

Characterisation of the mechanical and physical properties of rocks composing Azorean central volcanoes

Tese de Doutoramento

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Doutoramento em
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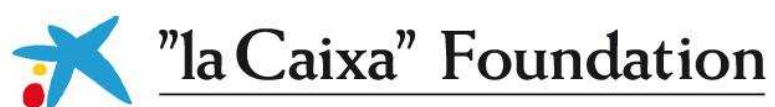


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Para aqueles que me mostraram o gosto por conhecer

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LIST OF ABBREVIATIONS

- μ CT – X-ray microtomography
- 2D – two dimensions
- 3D – three dimensions
- 4D – four dimensions
- AA – advanced argillic facies
- Adv. Sil – advanced silicic alteration
- Al – alunitic alteration
- Alb – albitic alteration
- alkali (content) - $\text{Na}_2\text{O} + \text{Si}_2\text{O}$
- Amp - amphibole
- Anort – anorthoclase
- ANOVA – analysis of variance
- arg – argillic facies
- asl – above sea level
- ASTM - American Society for Testing and Materials
- ATJ – Azores Triple Junction
- avg – average
- BDT – brittle-ductile transition
- BGD – Basic Geotechnical Description
- BSE – backscattered electrons
- Bt – biotite
- CIA – Chemical Index of Alteration
- CIW – Chemical Weathering Index
- CL – Cachaços-Lombadas
- CN – coordination number
- Cpx – clinopyroxene
- DTS – direct tensile strength
- DTS – direct tensile strength
- EAFZ – East Azores Fault zone
- EDS - energy dispersive spectroscopy
- EN – European norm

- EqDiameter or EqD – equivalent diameter
- EqRadius – equivalent radius
- Eu – Eurasia plate
- exp – exponential
- F – felsic
- FCUL – Faculdade de Ciências da Universidade de Lisboa
- FeMg – ferromagnesian(s)
- FMW – felsic-mafic-weathered
- Fp – feldspar
- Fp. Alk – alkali-feldspar
- GF – Gloria Fault
- GSI – Geological Strength Index
- H – hardness according to Mohs scale
- HB – Hoek-Brown
- IA – image analysis
- ICP – inductively coupled plasma
- IGEO – Instituto de Geociencias (Universidade Complutense de Madrid)
- INGV-OV – Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano
- ISRM – International Society for Rock Mechanics and Rock Engineering
- IST – Instituto Superior Técnico da Universidade de Lisboa
- ITS – indirect tensile strength (MPa)
- IUGS - International Union of Geological Sciences
- K – potassic facies
- KMO – Kaiser-Meyer-Olkin
- L/D – length-to-diameter ratio
- LOI – loss in ignition
- LSRM - lateral strain response method
- LVDT – linear variable differential transformer(s)
- M - mafic
- MAPE – mean absolute percentage error
- MAR – mid-Atlantic ridge
- max – maximum
- MC – Mohr-Coulomb
- min – minimum
- MIP – mercury intrusion porosimeter/porosimetry

- MS – mass spectroscopy
- N – number/ count
- NA – North America Plate
- Na – sodium
- NBC – neutral buoyancy condition
- NP – Portuguese norm (“norma Portuguesa”)
- Nu – Nubia plate
- O – direction parallel to pores/phenocrysts
- OES – optical emission spectroscopy
- Ol – olivine
- Op – opaque mineral(s)
- Oxi – oxidation
- PC – point counting
- PC1 – first principal component
- PC2 – second principal component
- PC3 – third principal component
- PCA – principal component analysis
- PCs – principal components
- Phy – phyllic facies
- Plg – plagioclase
- PNM – pore network model(s)
- prop – propylitic facies
- PSD – pore size distribution
- P-T – pressure-temperature
- Pyroclastics – pyroclastic rocks
- QAPF – quartz – alkali feldspar – plagioclase – feldspathoid
- RH – relative humidity
- RMR – Rock Mass Rating
- RMSE – root mean square error
- RSS – residual sum of squares
- S – sulfur
- s.l. – sensu lato
- San – Sanidine
- SE – secondary electrons
- SEM – scanning electron microscope

- SF – Sharp Front
- SG – strain gauge(s)
- Si - silica
- Sil – silicic alteration
- SPT – standard penetration test
- std.dev – standard deviation
- TAS – total alkali-silica
- TR – Terceira Rift
- trans – transitional facies
- UCS – unconfined/ uniaxial compressive strength (MPa)
- UTAD – Universidade de Trás-os-Montes e Alto Douro
- VAF – variance accounted for
- var - variance
- VRS – Volcanic Rock Mass System
- X – direction in-between parallel and perpendicular to pores /phenocrysts
- XRD – X-ray diffraction
- Δ – direction perpendicular to pores/ phenocrysts

LIST OF VARIABLES AND SYMBOLS

- ∇P – gradient pressure
- μ – coefficient of internal friction
- A – surface area
- $A(C_{EN})$ – anisotropy of C_{EN} .
- $A(V_p/V_s)$ – anisotropy of V_p/V_s
- A' – cross-sectional area
- C – capillary water absorption coefficient
- c – cohesion
- C_{EN} – standard capillary water absorption coefficient
- C_a – intermediate anomalous capillary water absorption coefficient
- C_e – initial capillary water absorption coefficient
- C_m – late/ matrix capillary water absorption coefficient
- c_{rm} – cohesion of the rock mass
- d – distance
- D – disturbance factor
- E – Young's modulus or stiffness
- E_{avg} – average Young's modulus (static)
- E_d – dynamic Young's modulus
- E_i – intact rock Young's modulus
- E_{rm} – rock mass Young's modulus
- E_s – static Young's modulus
- E_{sec} – secant Young's modulus (static)
- E_{tg} – tangent Young's modulus (static)
- ϵ_a – axial strain
- ϵ_l – lateral strain
- ϵ_v – volumetric strain
- g – gravitational acceleration
- G – shear modulus
- h – height
- H – Mohs hardness scale
- H_{slope} – slope height

- K – bulk modulus
- k – permeability (or absolute permeability)
- K_c – fracture toughness
- M_1 – dry mass
- M_2 – submerged mass
- M_3 – saturated mass
- M_4 – mass of rock covered by parafilm
- M_5 – mass of the setup water filled pycnometer + rock covered with parafilm
- M_6 – mass of the water filled pycnometer
- m_b , s and a – Hoek-brown constants for the rock mass
- M_f – final mass
- m_i – Hoek-Brown constant
- M_i – initial mass
- m_r – modulus ratio
- n – porosity
- n_{cc} – capillary-connected porosity
- $n_{eff_μCT}$ – effective porosity from $μCT$ images
- $n_{eff_adp.ISRM}$ – effective porosity determined by an adaptation of ISRM (2007) method using prisms of smaller dimension
- n_{eff_Hg} – effective porosity determined by mercury porosimeter
- n_{eff_ISRM} – effective porosity determined by ISRM (2007) method for irregular lumps
- n_{isol} – isolated porosity
- $n_{isol_μCT}$ – isolated porosity from $μCT$ images
- $n_{T_μCT}$ – total porosity determined from $μCT$ images
- $n_{T_2D; IA}$ – total porosity determined on a thin section by image analysis (IA)
- $n_{T_2D; PC}$ – total porosity determined on a thin section by point counting (PC)
- $φ$ - angle of internal friction
- P – pressure
- P_c – capillary pressure
- P_{conf} – confining pressure
- P_{eff} – effective pressure
- $Ph_{μCT}$ – percentage of phenocrysts determined from $μCT$ images
- $Ph_{2D; IA}$ – percentage of phenocrysts determined on a thin section by image analysis (IA)

- $Ph_{2D, PC}$ – percentage of phenocrysts determined on a thin section by point counting (PC)
- ϕ_{rm} – angle of internal friction of the rock mass
- r – mean pore radius
- R^2 – coefficient of determination
- r_M – mean pore-throat radius
- T - temperature
- t – time
- T – tortuosity
- $T_{cut-off}$ – tension cut-off
- u – fluid flow
- V – volume
- V_p – P-wave velocity
- V_t – bulk volume of the rock
- V_s – S-wave velocity
- V_v – volume of the total void space
- Y – water absorption
- z – depth
- γ – dry unit weight
- $\Delta\rho$ – difference of density
- η – viscosity
- θ - contact angle
- ν – Poisson's ratio
- ν_{avg} – average Y Poisson's coefficient/ ratio (static)
- ν_d – dynamic Poisson's coefficient/ ratio
- ν_s – static Poisson's coefficient/ratio
- ν_{sec} – secant Poisson's coefficient/ ratio (static)
- ν_{tg} – tangent Poisson's coefficient/ ratio (static)
- ρ – bulk density
- $\rho_{adp.ISRM}$ – dry bulk density determined by an adaptation of ISRM (2007) method using saturation and buoyancy techniques on prisms of smaller dimension
- ρ_{dry} – dry bulk density
- ρ_{dry_pyc} – pycnometric bulk density
- ρ_{ISRM} – bulk density determined by ISRM (2007) method using saturation and buoyancy techniques on irregular lumps

- ρ_s – grain density
- ρ_{sat} – saturated bulk density
- σ – normal stress/ strength
- σ_1 – maximum principal stress
- σ'_1 – maximum effective principal stress
- σ_2 – intermediate principal stress
- σ'_2 – intermediate effective principal stress
- σ_3 – minimum principal stress
- σ'_3 – minimum effective principal stress
- σ_{3max} - upper limit/maximum confining stress
- σ_c – compressive strength (confined)
- σ_{c_UCS} or UCS – unconfined compressive strength
- σ_{cd} - crack damage stress
- σ_{ci} - crack initiation stress
- σ_{ci_HB} - fit of unconfined compressive strength to Hoek-Brown criterion
- σ_{ci_MC} – fit of unconfined compressive strength to Mohr-Coulomb criterion
- σ_H – horizontal stress
- σ_p – peak stress
- σ_{rm} – rock mass global strength
- σ_{ST} – surface tension
- σ_t or ITS – indirect tensile strength
- σ_v – vertical stress
- σ_y – yield stress
- τ – shear stress
- l_0 – original axial length
- Δl – variation of the axial length
- x_0 – original lateral length
- Δx – variation of the lateral length

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This thesis aims to determine the physical and mechanical properties of volcanic rocks from the central volcanoes of S. Miguel Island (Azores, Portugal), with a focus on Fogo (Água de Pau) and Sete Cidades. Research follows a two-fold approach: (a) characterisation of fresh Azorean lava rocks, and (b) assessment of the effects of hydrothermal alteration. The work addresses a gap in the knowledge of Azorean volcanic rocks, which are typically studied from geochemical and petrographic perspectives but remain underexplored in terms of their mechanical and physical behaviour, especially when hydrothermally altered.

The first part of the thesis establishes a comprehensive intact rock study of lavas with varying compositions and textures. Using standardised laboratory methods, the following properties were determined: connected porosity, density, capillary water absorption coefficients, ultrasonic wave velocities, indirect tensile strength, confined and unconfined compressive strength, Young's modulus, Poisson's ratio, cohesion, and angle of internal friction. Microstructural features, such as pore size distribution, mean pore radius, and porosity, were analysed with advanced imaging techniques, including X-ray microtomography and scanning electron microscopy, as well as with mercury intrusion porosimetry.

Results reveal that the mechanical behaviour of Azorean lavas is influenced by microstructure. Massive lavas, with low-to-medium-porosity, display a broad range of stiffness and strength due to variable distribution of fissures and, possibly, microcracks. On the other hand, vesicular lavas are weaker, less stiff, and have moderate capillary water absorption, with strength and hydraulic properties governed by pore size. Localised porous bands and medium porosity in massive lavas promote a transitional behaviour between low-porosity and vesicular textures, which associates with weakening and higher capillary water absorption. Mineralogical composition also plays a role, albeit to a lesser extent than porosity. Trachytic lavas have lower density, ultrasonic velocities, and stiffness, earlier crack initiation, but reach variable peak stresses depending on textural and alteration features. All studied lavas remain brittle up to confining pressures of 30 MPa, with failure occurring by tensile splitting. Microstructure observations show that fracture propagation is favoured by the boundaries of phenocrysts and pores, particularly those of larger size. Vesicular specimens display post-yield plasticity at 10 MPa confinement, though developing fractures. Triaxial testing provides new shear strength parameters for Azorean lavas determined via

the Mohr-Coulomb criterion. The application of the Hoek–Brown criterion demonstrates that even "hard" geotechnical units undergo substantial strength and stiffness reduction when moderate rock mass fracturing is considered. Collectively, the findings emphasise that Azorean lava rocks, though mechanically competent, are sensitive to microstructural heterogeneity, affecting their resistance to seismic, volcanic, and rainfall-related hazards. For instance, saturation of lavas has revealed a 33 % decrease in the tensile strength.

The second part of the thesis addresses hydrothermal alteration, which produces contradictory findings, depending on the local conditions of volcano-hydrothermal systems. A critical analysis using data from worldwide geothermal systems and volcanoes was conducted to contextualise local results. This review highlights that argillic and zeolitic alteration, even if subordinate, tends to weaken rocks, whereas silicic and high-temperature propylitic alteration may enhance strength, always depending on whether the host rock is fragmental or dense.

To assess alteration in Azorean rocks, a field experiment attempted to induce alteration in the previously characterised fresh lavas by inserting them in a diffuse soil degassing zone (Caldeiras da Ribeira Grande, Fogo Volcano). Microstructural and chemical data indicate limited changes after four months due to the massive structure of the lavas. Alternatively, drill cuttings from the Ribeira Grande geothermal field were analysed using pycnometry and X-ray microtomography. Results show that reservoir lavas, despite hydrothermal alteration within the chlorite zone, retain a low-porosity matrix, with system permeability maintained primarily by large-scale discontinuities. In contrast, caprock tuff breccias display impermeability due to an infill by secondary minerals, which significantly reduces pore connectivity.

The findings of the thesis expand the understanding of the physical and mechanical behaviour of Azorean volcanic rocks across fresh and altered states. By integrating intact rock testing with microstructural analyses, this research delivers novel data for Azorean lavas and provides benchmarks for volcanic rock properties globally. The obtained values serve as input variables to future volcanic models, relevant to both slope instability and magma transport. As a result, the work has direct implications for future geotechnical and geothermal reservoir characterisations, volcanic hazard assessment, and slope stability analysis in volcanic settings, both locally and globally.

Keywords: intact rock, mechanical properties, physical properties, lava rocks, brittle failure, microstructure, rock digital physics, volcanic rocks, hydrothermal alteration

A presente tese tem como principal objetivo determinar as propriedades físicas e mecânicas das rochas vulcânicas constituintes dos vulcões centrais da Ilha de S. Miguel (Açores, Portugal), em particular do Fogo (Água de Pau) e Sete Cidades. A investigação segue uma abordagem dupla, dividindo-se na: (a) caracterização de lavas açorianas inalteradas, e (b) avaliação dos efeitos da alteração hidrotermal. O trabalho desenvolvido procura colmatar uma lacuna no conhecimento das rochas vulcânicas dos Açores que são tipicamente estudadas do ponto de vista geoquímico e petrográfico, permanecendo pouco caracterizadas relativamente ao seu comportamento mecânico e físico, sobretudo quando alteradas hidrotermalmente.

A primeira parte da tese estabelece um estudo abrangente de rocha intacta em lavas com diferentes composições e texturas. Utilizando métodos laboratoriais padrão, foram determinadas as seguintes propriedades: porosidade efectiva, massa volúmica seca e saturada, coeficientes de absorção capilar de água, velocidades de ultrassons, resistência à tracção indirecta, resistência à compressão confinada e não confinada, módulo de Young, coeficiente de Poisson, coesão e ângulo de atrito interno. As características microestruturais, como a distribuição do tamanho de poros, o raio médio dos poros e a porosidade, foram analisadas com recurso a técnicas avançadas de imagem, incluindo microtomografia de raios-X e microscopia electrónica de varrimento, bem como porosimetria por intrusão de mercúrio.

Os resultados revelam que o comportamento mecânico das lavas açorianas é influenciado pela sua microestrutura. As lavas de textura maciça, com porosidade baixa a média, exibem uma ampla gama de valores de deformabilidade e resistência devido à variabilidade na distribuição de fissuras e, possivelmente, de microfissuras. Por outro lado, as lavas vesiculares são menos competentes, menos rígidas e apresentam absorção capilar de água moderada, sendo a resistência e as propriedades hidráulicas controladas pelo tamanho dos poros. Bandas porosas localizadas e porosidades médias nas lavas maciças promovem um comportamento transicional entre o apresentado para texturas de baixa porosidade e vesiculares, associado a um enfraquecimento global da rocha e a uma maior absorção capilar de água. A composição mineralógica também desempenha um papel, embora menos significativo do que a porosidade. As lavas traquíticas apresentam menor densidade, velocidade de ultrassons e rigidez, iniciam a fracturação mais cedo, contudo atingem

tensões máximas distintas em função de componentes texturais e de alteração. Todas as rochas lávicas estudadas mantêm um comportamento frágil até pressões de confinamento de 30 MPa, apresentando uma rotura por tracção. As observações microestruturais demonstram que a propagação de fracturas é favorecida pelas fronteiras de fenocristais e de poros, em especial aqueles com maiores dimensões. Os provetes vesiculares, confinados a 10 MPa, exibem plasticidade após atingirem a tensão de cedência, embora preservando o carácter frágil. Os ensaios triaxiais fornecem novos parâmetros de resistência ao corte das lavas açorianas, determinados através do critério de Mohr-Coulomb. A aplicação do critério de Hoek-Brown demonstra que mesmo unidades geotécnicas consideradas “duras” sofrem uma redução substancial de resistência e de módulo de deformabilidade quando se considera uma fracturação moderada do maciço rochoso. De forma geral, os dados obtidos evidenciam que as lavas açorianas, embora mecanicamente competentes, são sensíveis à heterogeneidade microestrutural, o que afeta a sua resistência perante a perigos sísmicos, vulcânicos e associados a eventos de forte precipitação. Por exemplo, a saturação das rochas lávicas levou a uma diminuição de 33 % na resistência à tracção.

A segunda parte da tese aborda a alteração hidrotermal, que produz resultados contraditórios, dependendo das condições locais dos sistemas vulcânico-hidrotermais. Foi realizada uma análise crítica com dados de sistemas geotérmicos e vulcões globais para contextualizar os resultados locais. Esta revisão de literatura evidencia que a alteração argílica e zeolítica, mesmo que subordinada, tende a enfraquecer as rochas, enquanto a alteração silícica e a propilítica de alta temperatura podem aumentar a resistência, dependendo sempre se a rocha hospedeira é fragmentária ou densa.

De forma a avaliar a alteração em rochas açorianas, foi realizada uma experiência no campo que procurou induzir alteração de lavas frescas previamente caracterizadas, enterrando-as no solo numa zona de desgaseificação difusa (Caldeiras da Ribeira Grande, Vulcão do Fogo). Os dados da microestrutura e químicos indicam alterações limitadas após um período de quatro meses devido à estrutura maciça das lavas. Em alternativa, foram analisados os detritos de furação (*cuttings*) do campo geotérmico da Ribeira Grande através de picnometria e microtomografia de raios-X. Os resultados demonstram que as lavas do reservatório, apesar da alteração hidrotermal na zona da clorite, mantêm uma matriz de baixa porosidade, com a permeabilidade do sistema assegurada através de descontinuidades à escala do maciço rochoso. Por sua vez, os tufos brechóides da *caprock* apresentam impermeabilidade que advém do preenchimento dos poros por minerais secundários, o que reduz significativamente a conectividade porosa.

Os dados obtidos nesta tese ampliam a compreensão do comportamento físico e mecânico das rochas vulcânicas açorianas em estados inalterados e alterados. A integração dos ensaios em rocha intacta com análises microestruturais providencia novos dados sobre as rochas lávicas dos Açores e estabelece referências para as propriedades de rochas vulcânicas a nível global. Além disso, os valores obtidos servem como variáveis de entrada para futuros modelos vulcanológicos, relevantes tanto para a instabilidade de vertentes vulcânicas como para o movimento do magma em profundidade. Como resultado, o trabalho tem implicações directas em futuras caracterizações geotécnicas e de reservatórios geotérmicos, na avaliação de perigos vulcânicos e na análise de estabilidade de vertentes em contextos vulcânicos, tanto localmente como globalmente.

Palavras-chave: rocha intacta, propriedades mecânicas, propriedades físicas, rochas lávicas, rotura frágil, microestrutura, análise física de rocha digital, rochas vulcânicas, alteração hidrotermal

Resumo escrito de acordo com o antigo acordo ortográfico.

*Fui rocha, em tempo, e fui, no mundo antigo,
Tronco ou ramo na incógnita floresta...
Onda espumei, quebrando-me na aresta
Do granito, antiquíssimo inimigo...*

*Hoje sou homem – e na sombra enorme
Vejo, a meus pés, a escada multiforme
Que desce, em espirais, na imensidade*

*Interrogo o infinito e às vezes choro...
Mas, estendendo as mãos no vácuo, adoro
E aspiro unicamente à liberdade.*

Evolução; Antero de Quental

Antero de Quental was a notable Portuguese poet and thinker of the XIX century, born in Ponta Delgada. Much could be said about his poetry and philosophical thought, but this poem has spoken to me the deepest as a student.

In *Evolução*, the poet portrays the human journey as an evolutionary process: once rock, branch, or wave, we become conscious beings, placed between the multiform staircase of nature and the infinite horizon of freedom. The poem suggests that humanity is both shaped by material evolution and drawn toward a higher, spiritual destiny.

This image resonates with the path where PhD students stand - between the rigor of scientific reasoning, empiricism and logic, and the uncertainty of the unknown. Though daunting at first, this space is what allows us to grow as spiritual beings, thinkers and aspire towards the freedom of mind, ultimately surpassing the challenges of this journey.

Chapter

Introduction



1.1. General considerations: Problematic and contextualisation

Rock mechanics, the study of rock behaviour under stress, extends its application to volcanic intact rocks and rock masses by contributing to the understanding of volcanic processes and assessing the stability of volcanic structures. Determining the mechanical and physical properties of volcanic rocks, such as strength and porosity, is essential for evaluating hazards (e.g., landslides), designing resilient infrastructure in volcanic environments, and improving eruption forecasting.

In volcanic systems, host rocks are a domain of volcanic systems alongside magma, influencing processes that control the system's evolution. Host rocks affect magma genesis and are often brittle, experiencing elastic deformation and fracturing. At shallow crustal levels, these processes are associated with dyke intrusion, magma emplacement, and the maintenance of volcano-hydrothermal systems. At the surface, they can compromise the stability of volcanic slopes or entire edifices. Although these mechanisms are time- and scale-dependent, their investigation primarily begins with laboratory characterisation of the volcanic rock.

Over the past decade, numerous studies have applied rock mechanics principles to volcanological problems, as reviewed by Heap and Violay (2021) and Lavallée and Kendrick (2021). Significant advances have been made in characterising volcanic rocks, yet the influence of microstructure and hydrothermal alteration on their mechanical behaviour remains poorly understood. Furthermore, volcanic rocks have been far less studied than other lithologies such as granites, limestones, and sandstones. On São Miguel Island (Azores, Portugal), where volcanic rocks constitute the stratigraphy and subsurface geology, such research remains limited.

São Miguel Island, located in the central North Atlantic Ocean near the Azores Triple Junction, is the largest volcanic island in the Azores Archipelago, hosting several volcanic systems and experiencing significant seismicity. All its central volcanoes are polygenetic stratovolcanoes that have erupted progressively lower volumes of trachytic magmas over the past thousand years, following early emissions of primitive magmas and accompanied by major summit collapses. Meanwhile, mafic magmas have erupted along faults

intersecting the edifices of Sete Cidades and Fogo volcanoes, with the most recent events occurring offshore at Sete Cidades in 1811 and at Fogo in 1563. Despite the current quiescence of these volcanoes, episodes of unrest have been recorded on the island.

Physical and mechanical research remains limited compared to petrological and geochemical studies. The existing geotechnical work, mostly conducted for the construction sector, is sometimes restricted to the private domain. The available data lacks several mechanical and physical properties that have not yet been established.

In addition, the available altered rock materials correspond to drill cuttings obtained from the Ribeira Grande geothermal field (Fogo Volcano). The existing data from this system are limited to *in situ* physical measurements obtained during drilling, microscopic characterisation and chemical analyses.

The characterisation of local volcanic materials can be addressed in two main research scopes. The first focuses on fresh lava rocks, providing baseline data for the region and supplying input parameters for future volcanological models. Such characterisation also enables comparisons with global datasets on lava rocks and serves as a reference for evaluating the effects of hydrothermal alteration. The second area addresses hydrothermal alteration, which in the São Miguel is related to the high-temperature, active Ribeira Grande geothermal field on the northern flank of Fogo Volcano, currently exploited by two power plants. Heavy rainfall on São Miguel further amplifies the role of water transport in weathering and weakening processes on volcanic slopes.

Understanding the properties of the lava rocks forming the active volcanoes of Sete Cidades and Fogo is an important step toward improving volcanic monitoring and hazard assessment, with direct implications for nearby human communities.

1.2. Research question, aims and objectives

The present section defines the general research question, the aims (or general objectives) and the specific research objectives.

The research question is the following:

Regarding Azorean (São Miguel Island) volcanic rocks, what is the full set of physical and mechanical properties, and how do they relate to the microstructure and hydrothermal alteration?

The aims define the main goals of the thesis and are divided according to the two main research areas defined above, being as follows:

- 1) This thesis seeks to comprehensively assess a range of lava rocks as intact rock materials, encompassing diverse chemical and mineralogical compositions and a variety of textures. The focus is on determining how microstructural features influence their physical and mechanical behaviour, while providing novel variables from the intact rock study. This aim is addressed through a detailed laboratory programme employing both conventional and advanced techniques, enabling characterisation from the microscale to the intact rock scale.
- 2) This thesis also aims to provide new insights into the physical and mechanical properties of altered volcanic rocks by inducing alteration of fresh samples in a natural diffusive degassing site at Fogo Volcano. To complement the existing X-ray diffraction (XRD) data for the RG5 well, its drill cuttings are analysed for physical properties using a combination of pycnometry and X-ray microtomography.

The research objectives specify how the thesis will reach the aims and answer the research question, by breaking it down into smaller research questions. These are as follows:

1. *Does the mineral composition and porosity influence the density of lavas to the same extent?*

Conduct physical tests in different lava rock specimens, with distinct sizes and shapes. The tests are conducted according to standardised procedures, such as the buoyancy technique with water saturation under vacuum described by the International Society for Rock Mechanics (ISRM) suggested methods.

2. *How can void space be characterised at the microscale? What is the influence of the porous system in the intact rock?*

Define a multi-method approach to characterise lava rocks, utilising several techniques, like X-ray microtomography (μ CT), mercury intrusion porosimeter (MIP), thin-section analysis, and conventional physical tests. Characterise lava rocks at a pore-scale by integrating MIP

results (pore size distribution curves and mean pore radius) with pore network models obtained from 3D μ CT images.

3. *What is the water capillary absorption in Azorean lavas? How do capillarity and other water transport mechanisms relate to the pore size distribution of the analysed lavas?*

Combine MIP data with capillary absorption coefficient determined using standardised methods (e.g., European Standards for natural stone testing), along three orthogonal directions in cubic samples, spanning from massive (low-to-medium porosity) to vesicular (high porosity) lavas.

4. *Can P-wave velocity (V_p) be used as an indirect precursor measure to predict mechanical properties and the results of destructive techniques?*

Determine V_p before mechanical testing in cylinder specimens. Further investigate the heterogeneity of lava rocks by integrating V_p with S-wave velocity measures for cubic samples.

5. *What are the crack initiation and damage stress thresholds in lava rocks, and how do these relate to peak strength for distinct Azorean lava rocks?*

Calculate crack thresholds based on the stress-strain curves of the unconfined compressive testing in distinct lava rocks. Compare the new results with ratios to the peak stress from other igneous rocks covered in the literature.

6. *What are the connected porosity thresholds that define unconfined compressive strength and water absorption capillarity of the several lava rocks?*

Determine the relationship between n_{eff} with capillary absorption and unconfined compressive strength for lava rocks with varying texture and composition.

7. *How do pre-existing microstructural defects, such as pores and phenocrysts, affect the mechanical strength of volcanic rocks?*

Visualise in real-time and through post-deformation 3D imaging obtained via μ CT the fracture patterns developed due to brittle failure in unconfined conditions on representative lava rock samples.

8. *Are the selected lavas brittle under confining pressures that are representative of the depth of the Azorean volcanic system?*

Develop a conceptual schematic model calibrated with triaxial data (compressive strength, cohesion, internal friction angle), “upscaled” to the rock mass with the Hoek-Brown criterion. Define several confining pressures for the triaxial test to mimic the depths at which lavas occur in the Fogo Volcano (Cachaços-Lombadas sector), where several drilling campaigns characterise the site.

9. *How does saturation influence the indirect tensile strength (σ_t) of lava rocks? Is it similar to sedimentary rocks?*

Quantify the impact of vacuum saturation on the tensile strength of lavas tested via the Brazilian test.

10. *What is the effect of hydrothermal alteration on the physical and mechanical behaviour of volcanic rocks?*

Build a dataset with literature data concerning the properties of distinct rocks. Define potential property trends according to the lithology, type and degree of hydrothermal alteration.

11. *Can the collected Azorean lavas be altered in situ in a place of diffuse degassing?*

Induce alteration in the field by exposing lava rock specimens tested previously in a fresh state to hot volcanic gases produced in a diffusive degassing area from Fogo Volcano. The rocks are buried in the ground for four months.

12. *What are the properties of distinct volcanic rocks affected by the hydrothermal alteration produced in the Ribeira Grande geothermal field (Fogo Volcano) with increasing depth?*

Provide novel microstructural insights using μ CT imaging on the RG5 well cuttings, previously analysed at the binocular microscope and through XRD by Pereira et al. (2022).

1.3. Impact and novelty

The thesis presents the first comprehensive integration of intact rock mechanical data with microstructural investigations for Azorean lavas. Such an approach is rare, particularly locally, and allows a more complete understanding of the materials composing São Miguel’s volcanic systems, which are widely used as building stone and aggregates in the region.

The study fills gaps in existing data by determining key engineering properties that are seldom reported for these lavas, including confined compressive strength, shear parameters, and the absorption coefficient for water capillarity. In addition, the thesis broadens the existing knowledge by providing new petrophysical and mechanical data that may be incorporated into reference databases and serve as a benchmark for studies on lava rocks worldwide.

In practical terms, the results can be used in models of magma transport and emplacement, volcanic slope stability, and volcano–hydrothermal systems. They also provide a valuable resource for geotechnical applications in São Miguel and other volcanic islands. Overall, by bridging rock mechanics and volcanology, this research investigates volcanic rocks as both volcanological and geotechnical materials.

1.4. Thesis scope and organisation

The thesis focuses on the properties of intact lava rocks, complemented by a microscale characterisation of selected samples. The study of intact rock represents a fundamental first step toward more extensive geomechanical classifications. Field inspections of volcanic outcrops on São Miguel Island and numerical model simulations on volcanic processes were beyond the scope of this work. It is also worth noting that the research was made possible through multiple national and international collaborations, in some cases supported by external funding programmes.

The thesis is organised into two main parts and comprises ten chapters, including the present one. The first part provides a general framework common to all chapters. It includes the introduction, a literature review considered as background for all sections, the integrated results and general discussion, and the conclusions. The other part consists of the “publication” chapters, which can be regarded as standalone chapters presenting results and discussion, each framed by a preliminary note, a concise description of methods and materials (or references to the dedicated sections in Chapter 3), and specific conclusions. These are distributed in two thematic areas:

1. *Azorean fresh lava rocks* – three chapters addressing the physical and mechanical characterisation of fresh lavas from São Miguel Island.
2. *Effects of hydrothermal alteration* – two chapters examining the effects of hydrothermal alteration on volcanic rocks.

The thesis was originally conceived as a compilation of published works. However, as the third paper had not been published by the submission date, the document was instead structured as a monograph, following the conventional format of a PhD dissertation. Nevertheless, the published and submitted papers produced within the scope of this thesis form the foundation of the work and are included here in an adapted form. Additional research outputs, presented at one national and two international conferences, provide complementary findings to those reported in the journal articles.

The chapters of the thesis are as follows:

- *Chapter 1. Introduction*

Corresponds to the present chapter. It includes a general view of the problematic, further explored in the following chapters. The Introduction also defines the main research questions, the general and specific objectives, and the thesis's roadmap and impact.

- *Chapter 2. Literature review*

The literature review chapter outlines the theoretical framework necessary to follow the thesis, while critically assessing the existing literature and exploring the main research gaps. The chapter is divided into three sections. The first part (Part A) is introductory and presents important concepts and definitions used throughout the thesis body. The second part (Part B) briefly establishes the volcanological context in which the assessment of the physical and mechanical properties is relevant. The third part (Part C) focuses on petrophysics and rock mechanics theory applied to the volcanic rocks, including the current state-of-the-art.

- *Chapter 3. Materials and methods*

The section of the materials comprises the geological setting of the Azores, São Miguel Island, and the two target volcanoes – Sete Cidades and Fogo. The Materials Section also provides details on the sampling and sample organisation according to the macroscopic features of the collected lavas. The Methods Section describes the research methods used for the lava rock investigations.

The following chapters are included in the *fresh Azorean lava rocks'* theme.

- *Chapter 4. Characterisation of the physical and mechanical properties of Azorean lava rocks with distinct microstructure through a multi-method approach*

Chapter 4 investigates the interactions between microstructure and intact rock physical properties, using a multi-method and multi-scale research strategy on selected lava rock samples. This research is adapted from a journal publication and covers aspects presented in an oral communication at an international conference, whose references are:

Pereira, M.L., Pappalardo, L., Buono, G., Cueto, N., Vázquez-Calvo, C., Fort, R., Costa e Silva, M., Fernandes, I., Zanon, V., and Amaral, P., 2025, A multi-method approach in the physical and mechanical assessment of lava rocks with distinct microstructure: *Engineering Geology*, v. 346, 107907, <https://doi.org/10.1016/j.enggeo.2025.107907>.

Pereira, M.L., Pappalardo, L., Buono, G., Zanon, V., and Fernandes, I., 2023, Microstructural, textural, and physical characteristics of volcanic rocks from Fogo volcano – S. Miguel Island (Azores), Portugal: Paper presented at *MedGU 2023*, 26–30 November, Istanbul, 5 p.

- *Chapter 5. Engineering properties of Azorean lava rocks: Insights from a laboratory campaign*

This chapter includes a comprehensive intact rock study of all lava samples collected in São Miguel, defining several novel physical and mechanical properties, establishing new empirical equations to estimate strength and shear parameters, and upscaling triaxial data to develop a schematic conceptual model of the Cachaços-Lombadas sector of Fogo Volcano. This research is adapted from the following publication, currently under review:

Pereira, M.L., Fernandes, I., Costa e Silva, M., Pappalardo, L., Zanon, V., and, Amaral, P. 202X. Engineering properties of lava rocks and empirical correlations for geotechnical applications: Insights from laboratory testing. Paper submitted to *Rock Mechanics and Rock Engineering* on the 4/04/2025.

- *Chapter 6. Pore-scale heterogeneity and its impact on the physical and mechanical properties of different Azorean lava rocks*

This chapter expands the work developed in Chapters 4 and 5 by further assessing the role of heterogeneity in lava rocks. Cubic specimens are tested for ultrasonic wave velocities and capillary water absorption along three orthogonal directions, and time-resolved tests are conducted with the μ CT to assess mechanical variability. This chapter extends the research presented as a poster at EGU25:

Pereira, M.L., Cueto, N., Pappalardo, L., Buono, G., Falasconi, A., Moreira, M., Zanon, V., and Fernandes, I., 2025, Characterisation of the heterogeneity of vesicular lava rocks from Fogo Volcano (Azores, Portugal) combining conventional laboratory methods with X-ray microtomography: *EGU General Assembly 2025*, Vienna, Austria, 27 Apr–2 May, Abstract EGU25-9505, <https://doi.org/10.5194/egusphere-egu25-9505>.

The following chapters are included in the *Effects of hydrothermal alteration* theme

- *Chapter 7. Hydrothermal alteration influence on properties of rocks in a volcanic environment: A critical analysis*

This chapter includes a critical analysis of the effects of the type and degree of hydrothermal alteration on the properties of several altered lithologies present in worldwide geothermal fields and volcanoes. The chapter discusses the average values from the literature-built dataset and is adapted from the following publication:

Pereira, M.L., Zanon, V., Fernandes, I., Pappalardo, L., and Viveiros, F., 2024, Hydrothermal alteration and physical and mechanical properties of rocks in a volcanic environment: A review: *Earth-Science Reviews*, 104754, <https://doi.org/10.1016/j.earscirev.2024.104754>.

- *Chapter 8. Alteration in Azorean volcanic rocks: Preliminary insights*

This chapter covers the aspects of hydrothermal alteration in Azorean volcanic rocks. It is divided into two parts, one related to an attempt to induce alteration in the field and investigate its effectiveness, and a second part where selected drill cuttings from RG5 well were characterised for the physical properties and microstructure.

- *Chapter 9. Results integration and final discussion*

This chapter presents the main relatable findings of the thesis and critically assesses the potential contributions and limitations of the work, drawing on the theoretical framework defined in Chapter 2.

- *Chapter 10. Conclusion*

The general conclusions of the thesis are presented as answers to the specific objectives/research questions defined in this chapter, while also addressing the potential outcomes of the proposed future research.

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- Pereira, M.L., Matias, D., Viveiros, F., Moreno, L., Silva, C., Zanon, V., and Uchôa, J., 2022, The contribution of hydrothermal mineral alteration analysis and gas geothermometry for understanding high-temperature geothermal fields—the case of Ribeira Grande geothermal field, Azores: *Geothermics*, v. 105, 102519, <https://doi.org/10.1016/j.geothermics.2022.102519>.

“Nas mãos da ciência está o molde; ela só fundirá a estátua da futura sociedade. (...) A consciência, na sua constante evolução, passou do estado intuitivo, maravilhoso, para uma fase superior, reflectida, eminentemente positiva e naturalista”

Antero de Quental, Filosofia, p.61.

The Azorean poet and philosopher, Antero de Quental, saw science as a foundation of future society. For him, science offered not only progress but also a new code of harmony with the universe, grounded in “a deep and rigorous knowledge of realities, of nature, and of the soul.”

Chapter

Literature Review



Volcanoes are characterised by heterogeneous structures with alternating layers of lava and pyroclastic rocks, which can influence edifice stability (Voight, 2000; Rodríguez-Losada et al., 2009), affect subsurface processes, such as dyke propagation and hydrothermal fluid migration (Gudmundsson, 2002; Gudmundsson et al., 2006), and create favourable conditions for geothermal energy exploitation.

Volcanic rocks represent the solidified products of magma that have been emplaced onto the Earth's surface, subsequently cooling and solidifying into either lava flows or pyroclastic deposits. Their varied textures, which range from porphyritic or volcaniclastic to glassy and aphanitic, reflect their intricate cooling and depositional histories. This thesis primarily focuses on lava rocks, also referred to as lavas, while pyroclastic materials are only briefly considered.

Lavas are widespread in volcanic continental regions and on oceanic islands such as the Azores, where they exert a significant role in both natural and engineered settings. They intersect construction sites, inform rock engineering design (e.g., González de Vallejo et al., 2008; Lourenço et al., 2010; Miranda et al., 2018; Villeneuve, 2021), and appear in geotechnical hazard assessments, such as rockfall susceptibility mapping (e.g., Fernández-Hernández et al., 2012; Sarro et al., 2020; Fernández et al., 2024). Furthermore, lavas are frequently used as building stone and aggregates (e.g., Braga et al., 2000; Medeiros et al., 2021), highlighting their economic impact on volcanic islands.

Understanding volcanic rocks would benefit from a multidisciplinary approach, with assessments varying across the fields of petrology, petrography, geochemistry, petrophysics, and rock mechanics. At the intersection of these domains, particularly when addressing complex and heterogeneous materials like lavas, comprehensive characterisation must draw from all. This thesis positions itself at this interdisciplinary juncture, adopting a classic engineering geology perspective to provide a robust physical and mechanical characterisation of Azorean lavas. These data aim to support both geotechnical applications and volcanological studies, offering insights that can inform hazard assessment, geothermal exploitation, and structural stability analyses.

This review lays the ground for the experimental work and its subsequent interpretation. The purpose of this chapter is twofold:

1. to provide a theoretical framework that informs the reader with the fundamental concepts and definitions necessary to follow the thesis.
2. to critically review existing literature and highlight the research gaps.

The literature reviewed in this chapter supports the research strategy outlined in Chapter 3 and positions this study within the existing body of knowledge. Research was conducted using a range of online databases and search tools, including Google Scholar, ResearchGate, Web of Science, and Elicit.

The chapter is structured into three main parts:

Part A| Lava rocks – from the intact rock to the rock mass

Explains how lava rocks are assessed as geological and geotechnical materials. It covers the concepts of intact rock and rock mass and provides classic classification systems used in rock mechanics and petrography for lava rocks.

Part B| Lava rocks – from the crust to the volcanoes

Places lavas in the context of geology and volcanology. The chapter clarifies the role of their properties in volcanic, hydrothermal, and magma transport and emplacement processes, as well as in the crust and magmatic systems.

Part C| The properties of volcanic rocks

Describes several physical and mechanical properties and contextualises them to volcanological settings. For each property, whether physical or mechanical, after presenting the theoretical framework, the available data from the existing literature is presented. The structure of Part C enables the identification of the limitations of the current state-of-the-art, outlining the knowledge gaps and indicating the future research directions for Azorean rocks addressed in this thesis.

Part C covers both volcanic and lava rocks. Parts A and B focus mainly on lava rocks, which are the main topic of the thesis.

Lava rocks – from the intact rock to the rock mass

This study focuses on intact lava rocks, with the following chapter outlining the theoretical framework for assessing lavas as a geotechnical material. Noteworthy, many geotechnical classifications tend to be overly simplistic from a geological standpoint, which presents limitations when characterising complex lithologies such as volcanic rocks. Consequently, this chapter also considers lavas from a petrographic and microstructural perspective, which provides evidence of the volcanological processes subjacent to their formation. This integrated approach enables a deeper understanding of their intrinsic properties and how these influence the mechanical behaviour of lava rocks.

2.1. Lava rock as a geological material

Magma crystallisation, whether occurring at depth or at the surface, and the cooling rate influence the final rock texture. In parallel, the magma composition determines the mineralogical and chemical characteristics of the rock (e.g., Winter, 2014). Eruption, transport, emplacement, and cooling processes further affect texture and structure of lavas, particularly dictating the distribution and characteristics of vesicles (Cashman et al., 1994). Therefore, lavas have a complex origin and are affected by several post-eruption events that make them *heterogeneous* for compositions, textures, and structures. The concept of heterogeneity is detailed in Sections 2.2 (Part A) and 2.2.5. (Part C), while texture and composition are explored in the present section.

Petrologists commonly use the term *texture* to define the microscopic characteristics of the rock's mineral grains, such as the size, shape, spatial orientation, arrangement, and degree of crystallinity (MacKenzie et al., 1983; Vernon, 2018) up to the hand specimen scale (Philpotts, 1989; Smith, 2002). However, the term *microstructure* is gaining popularity, as among most material scientists and some structural geologists, texture refers to a preferred orientation (Vernon, 2018). The International Union of Geological Sciences (IUGS) Subcommission on the Systematics of Metamorphic Rocks has recommended substituting the term texture by microstructure (Passchier and Trouw, 2005). Yet, the term texture remains widely used in the suggestions of the IUGS Subcommission on the Systematics of

Igneous Rocks (Le Maitre et al., 2002). Following Barker (1998), this thesis uses these terms interchangeably for rock' characterisation. Specifically, texture is generally used to describe both pore space and mineral grain arrangements, while microstructure refers more narrowly to the pore system of the studied rocks.

The term *structure* is used to describe features that are only observable on the hand sample to outcrop scale (e.g., flow banding, layering, jointing; Phillpotts, 1989). However, as noted by Smith (2002), many features, like vesicularity, are present on a range of scales. In this thesis, texture and structure may be used interchangeably when describing the overall appearance of hand specimens, while structure is preferentially restricted to the outcrop scale.

In the structure of lava rocks, *vesicles* (or more generically pores) are important features that significantly dictate their physical and mechanical properties. Vesicles document gas exsolution processes that are governed by magma decompression and changes in volatile saturation, expansion, and escape, which drive most volcanic eruptions (Shea et al., 2010). Thus, primary vesicular textures reflect the rates of bubble nucleation and growth, which depend on intrinsic magma properties (e.g., volatile content and melt viscosity) and system-wide processes (e.g., magma ascent rate, fragmentation, and quenching) (Shea et al., 2010). Further modifications on the texture are produced by bubble deformation, coalescence, expansion, or gas escape, as reviewed by Shea et al. (2010).

Regarding the voids in rocks, vugs and vesicles have been distinguished by size and shape in basalts, with vugs referring to "irregularly shaped, long, and narrow cavities, whereas vesicles are spherical or ellipsoidal" (Wilbur et al., 2023). More broadly, the term vug is applied to cavities in various rock types formed through tectonic activity, mineral dissolution, or volcanic processes (Lagat, 2009; Allaby, 2020), commonly associated with vuggy porosity, which is typical of carbonate rocks (Lucia, 2007). Since this thesis focuses on volcanic materials, where pores are predominantly primary in origin, the terms vesicles and vesicular are used instead. In opposition to vesicular texture, the denomination massive texture is used to describe compact and coherent lavas. In the present thesis, *massive* refers to unfractured rock samples, characterised by minor macroscopic voids, most of which are smaller than 1 mm in diameter.

Petrology is a discipline that aims to understand the nature and origin of rocks based on petrographic data (modal, composition, and fabric) combined with field, chemical,

experimental, and isotopic analyses. This thesis primarily focuses on petrographic analysis, including mineralogy and modal analysis, combined with chemical data of major elements to perform a classification of the lavas.

Lavas are petrographically described regarding their degree of crystallinity, which ranges from holocrystalline (> 90 % crystals) to glassy (< 90 % crystals), depending on the glass-to-crystal proportion. Regarding granularity, lava rocks are often aphanitic (crystals not observed by the naked eye) and commonly display two grain-size populations (porphyritic texture): large crystals (phenocrysts) embedded in a fine-grained groundmass/matrix. If the crystals have a continuous size range, the texture is referred to as seriate.

The chemical and mineralogical composition is vast, resulting in numerous classifications that are reviewed by Le Maitre (2002). Minerals are commonly divided into felsic (feldspar/feldspathoids + silica minerals; F) and mafic (ferromagnesian minerals; M), which affect the colour index of igneous rock, often varying from leucocratic to melanocratic for 0–30% and 60–100% modal mafic minerals, respectively. Silica content (SiO_2 weight percentage, wt. %) also distinguishes igneous rocks as: acid (> 66 wt.%), intermediate (52–66 wt.%), basic (45–52 wt.%), ultrabasic (< 45 wt.%).

The IUGS developed a quantitative characterisation of igneous rocks – the QAPF diagram – based on the modal volume of silica minerals (Q), alkali feldspar (A), plagioclase (P), and feldspathoid (P) (Le Maitre, 2002). There are several diagrams for the different igneous rocks and mineral volumetric proportions are determined by modal analysis, either by visual estimation or point counting (Le Maitre, 2002). The QAPF diagram for volcanic rocks is presented in Fig. 2.1a. An accurate classification of extrusive rocks makes use of chemical criteria, which consider the content of the total alkali ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) and silica (SiO_2) represented in the TAS diagram (Le Bas et al., 1986; Fig. 2.1b).

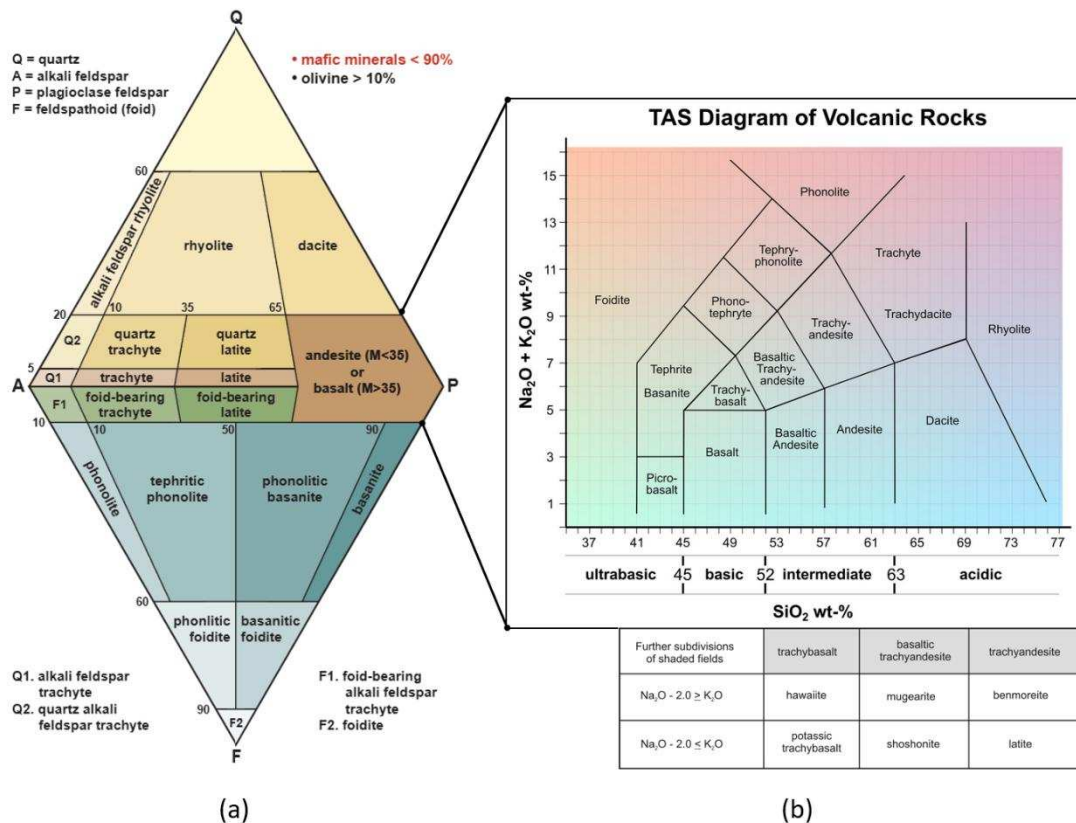


Fig. 2.1. Classification of lava rocks (a) based on the amount of minerals, using the IUGS diagram for volcanic rock classification with olivine > 10 %; and (b) chemically, using the TAS (total alkali versus silica) diagram, with further subdivisions regarding the sodic (Na_2O) and potassic (K_2O) content. Obtained online from Brady (n.d.), <https://www.science.smith.edu/~jbrady/petrology/index.php>, licensed under CC BY-NC-SA 4.0.

Magma series carry a genetic connotation that allows for understanding the petrogenesis of rocks and their geodynamic context (Winter, 2014). Magma series are divided into alkaline (subsaturated in SiO_2) and alkaline (saturated in SiO_2). Volcanic rocks are further classified based on the potassium oxide (K_2O) and silica (SiO_2) content, using the Peccerillo and Taylor diagram (1976). This diagram distinguishes volcanic rocks within the subalkaline series (tholeiitic and calc-alkaline) into different magma series, such as low-K, medium-K, high-K calc-alkaline, and shoshonitic series.

The geological classification of volcanic rocks helps in defining the geodynamic setting and eruption style associated with their formation. Petrophysical and engineering applications, particularly in rock design projects and the selection of materials for construction and decorative purposes, benefit from this petrographic and geochemical characterisation, as rock properties are known to depend on mineralogical composition (e.g., González de Vallejo and Ferrer, 201; Hencher, 2015).

2.2. Lava rock as an engineering material

2.2.1. Intact rock

Intact rock refers to the unfractured blocks between the discontinuities of a rock mass (Fig. 2.2). These blocks may range from a few millimetres to several meters in size (Hudson and Harrison, 2000). Theoretically, intact rock corresponds to an isotropic and homogeneous material, where the effect of fractures is diminutive, with their physical and mechanical properties depending on the rock itself, including the mineralogy and structure effects.

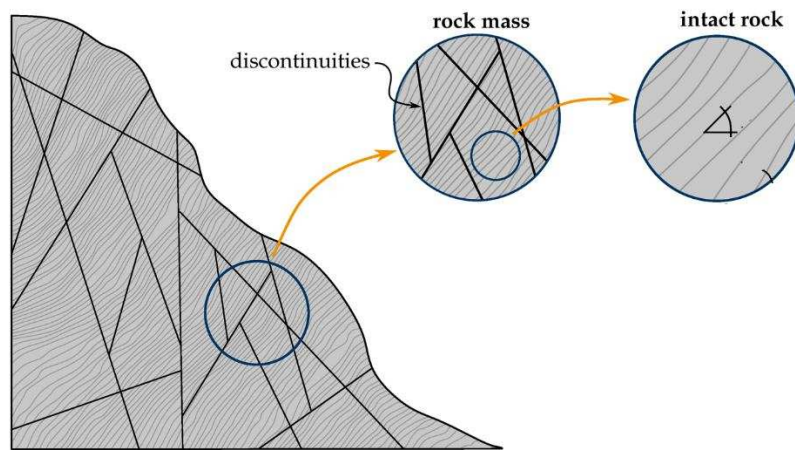


Fig. 2.2. Intact rock shown as unfractured blocks, characterised by inherent foliation/ stratification. The blocks are separated by discontinuities within the rock mass. Adapted from Mader et al. (2022) licensed under CC BY 4.0.

The concept of intact rock encompasses both geological and geotechnical significance. Its description typically includes the rock type, colour, texture, grain size, structure, and minor lithological characteristics (e.g., weathering, fossils), along with physical and mechanical properties like density, porosity, strength, hardness, and deformability (ISRM, 1978; Hencher, 2015). Among these, strength and deformability are critical, as they control when rock failure occurs (e.g., Hudson and Harrison, 2000). These mechanical properties are intrinsically linked to the mineralogical, textural, and physical properties of the rock (González de Vallejo and Ferrer, 2011; Hencher, 2015).

Laboratory testing of intact rock is crucial for geotechnical investigations, as it supports the classification of rock masses, provides a measure of rock quality, and defines other important properties through empirical correlations (Pereira, 2018). While *in situ* testing is

important, it is often costly and, therefore, less frequently employed than laboratory methods. However, the study of intact rock alone offers only a partial understanding of rock mass behaviour, particularly regarding the influence of discontinuities. Thus, laboratory assessments are combined with field observations in engineering practice. To enhance the representativeness of laboratory tests, international standards, such as those of the American Society for Testing and Materials (ASTM) and the suggested methods of the International Society for Rock Mechanics and Rock Engineering (ISRM), recommend a minimum number of specimens with a dimension suitable for the specific test being conducted (see Section 2.2.5. of Part C). Obtaining the required specimens of lava rocks is often difficult given their variable structure and common presence of defects, including vesicles/pores, microcracks, phenocrysts, corroded crystals, weathered/altered components.

Microcracks, used as a synonym to microfissures or microfractures, are defects that frequently coexist with pores to form the void space in many volcanic rocks (Guéguen and Kachanov, 2011). Microcracks are used in this work to describe a narrow, elongated void, recognised at the microscopic level. Although not quantified in size throughout the thesis, microcracks are described as having a width-to-length ratio of less than 10^{-2} by Simmons and Richter (1976) and Anders et al. (2014). Pores or vesicles correspond to more equidimensional voids (Walsh and Brace, 1966), varying from spherical to spheroidal in shape.

This leads to the concept of *heterogeneity*, defined as an intrinsic characteristic of materials with different properties at different locations. Differently, anisotropy describes the directional dependence of properties, such as deformability, strength, brittleness, permeability, or ultrasonic velocity, and it is often challenging to quantify in practice. For instance, the elastic behaviour of an intact rock sample may be described by up to 21 elastic constants, which encompasses all possible types of elastic anisotropy (Hudson and Harrison, 2000; Paterson and Wong, 2005). Heterogeneity is commonly assessed at the rock mass scale in volcanic terrains composed of interlayered lithologies with distinct mechanical and physical properties (e.g., González de Vallejo et al., 2008; Rodríguez-Losada et al., 2009). In contrast, heterogeneity on intact rock has received comparatively less attention. Nonetheless, it is widely recognised as a defining feature of volcanic rocks, where it significantly influences their behaviour (e.g., Mogi, 2006; Heap and Violay, 2021). Limited studies have been conducted in this sense through numerical modelling (Heap et al., 2016;

Griffiths, 2017) or a combination with experimental measurements (Bubeck et al., 2017; Vairé et al., 2024), further explored in Section 2.2.5. (Part C).

2.2.2. Rock mass

The description of a *rock mass* involves understanding both the materials that comprise it and the discontinuities that intersect it (Bell, 2007; Fig., 2.2). *Discontinuities* is a collective term for joints, fractures, bedding planes, contacts, and faults (ISRM, 1978). Discontinuities are planes of weakness that result from a sequence of geological events under specific stress conditions, dictating their mechanical behaviour and geometry (Hudson and Harrison, 2000). Among these, joints are fractures without measurable displacement, while faults (or shear fractures) involve relative movement. Hydrofractures, on the other hand, are fluid-driven fractures that include solidified magma-filled fractures (dyke, sill, sheet) and mineral veins (Gudmundsson, 2020). Throughout this thesis, the terms joints, fractures, and discontinuities are used interchangeably, following Hencher (2015).

Discontinuities control the strength, deformability, and permeability of rock masses, directly influencing the stability of any rock surface or excavation (Hudson and Harrison, 2000). The fracture spacing and weathering grade are routinely assessed in the field and drill cores (ISRM 1981, 2007; Anon 1995; Tuğrul and Gürpınar, 1997), offering preliminary estimations of the rock mass quality. Weathered and/or fractured rocks are generally less competent and resistant.

Several geotechnical and geomechanical classification systems have been developed to assess the quality of rock masses. These systems, while useful, often oversimplify geological complexity. Among the most widely applied is the Basic Geotechnical Description (BGD) proposed by the ISRM (1980), which combines granularity, major mineralogy, weathering grade, fracture spacing, and unconfined compressive strength to provide a broad characterisation. The Rock Mass Rating (RMR) system (Bieniawski, 1989) is based on intact rock strength and discontinuity characteristics, assigning numerical values to evaluate rock mass quality. Recognising the limitations of conventional geomechanical classifications when applied to volcanic terrains, Miranda et al. (2018) proposed the Volcanic Rock Mass System (VRS) as a tailored adaptation of RMR.

Similarly, the Geological Strength Index (GSI; Marinos and Hoek, 2000; Marinos et al., 2005) describes the rock mass quality by considering both structural characteristics and surface conditions, assuming that intact rock dictates the overall strength and that blocks are free

to rotate or slide under stress solicitations. Moreover, the GSI index is integral to the Hoek-Brown failure criterion (Hoek, 1968; Hoek and Brown, 1997; Hoek et al. 2002; Hoek and Brown, 2019). In volcanic environments, typical GSI values hover around 55, based on field observations (e.g., Miranda et al., 2018), a value recommended in the absence of site-specific data (Heap et al., 2020a; Villeneuve and Heap, 2021).

Characterisation of discontinuities is an integral part of most geotechnical assessments, with discontinuities in volcanic rocks originating from both primary geological processes and secondary structural modifications, which results in different types of fractures with distinct geometries (Hencher, 2015). Primary discontinuities in volcanic environments include cooling joints associated with extrusive and shallow intrusions, such as lava flows, dykes, sills, sheets, or with larger plutons. The typical columnar joints contribute to the permeability of igneous intrusions and lava flows and may facilitate dyking (Gudmundsson, 2020). Secondary discontinuities arise from an external stress field, creating faults and tectonic joints in the brittle crust. For instance, large-scale tension fractures and normal faults may align with pre-existing lava flows and intrusions (Gudmundsson, 2011). Tertiary discontinuities, like sheeting joints and exfoliation fractures, develop near the Earth's surface.

Discontinuities in volcanic rock masses have two roles. They weaken the performance of the rock mass, depending on the joint frequency, and dictate the mechanical behaviour by influencing the initiation and propagation of larger fractures. Furthermore, discontinuities in volcano-hydrothermal systems volcanoes allow for the storage and transport of fluids, even in low porosity rocks, such as intrusive units and lava flows, contributing to their potential as geothermal reservoirs or fractured aquifers at lower depth (Gudmundsson, 2002).

In addition to discontinuities, volcanic caves represent another source of heterogeneity, posing a geotechnical risk (Malheiro et al., 2015). Despite lava's classification as a moderately competent rock type, its structural variability introduces unpredictability in mechanical behaviour, especially under external stresses, such as those produced by seismic activity.

2.3. New approaches to lava rocks assessment

Although intact rock is traditionally assumed to be a homogeneous material free of defects, recent studies suggest that representative samples should be large enough to incorporate natural defects, even if their collection and preparation remain challenging (Hoek and Brown, 2019). By considering lava rocks that include such defects, new results would reflect their inherent heterogeneity, ultimately contributing to geotechnical and petrophysical databases (e.g., Zhang et al., 2012; Bär et al., 2020).

Another research direction involves exploring diverse strategies to analyse lava rock microstructure to constrain their mechanical and physical behaviour better. Some microstructural features act as stress concentrators and planes of weakness, dictating the mechanical response of lavas. Often, in response to loading and unloading cycles and weathering, these features originate at the microscopic scale. Microcrack patterns often are precursors of visible joints and, eventually, open fractures (Hencher, 2015).

Geotechnical characterisation of intact rocks has traditionally focused on strength and deformability, while hydraulic properties are seldom addressed in engineering or risk assessment contexts. However, recent work by Cueto et al. (2018, 2024a, 2024b) has highlighted the importance of understanding degradation mechanisms in volcanic rocks for geotechnical applications. Based on test procedures commonly applied in natural stone studies, their research links water transport properties to rock deterioration processes such as freeze-thaw cycles, salt crystallisation, wetting and drying, and thermal shock. These degradation processes are strongly influenced by pore size, distribution, total porosity, and the connectivity of the pore network (e.g., Benavente et al., 2018; Çelik and Sert, 2020). Once again, microstructural analysis emerges as a key avenue for advancing the understanding of lava rock behaviour.

Lava rocks – from the crust to volcanoes

Lavas (s.l.) are the main component of volcanoes and volcanic structures. The behaviour of rocks, nevertheless, varies from surface to depth and from a local to a regional scale. The following chapter presents lava rocks in the context of the crust, both without and hosting magmatic systems, and within the framework of volcanoes, extending from depth to the surface, from magmatic intrusion through the hydrothermal domain to the volcanic flanks.

2.1 Lava rocks expression at depth

2.1.1 The crust profile

The crust structure, strength, and deformation change with depth. Overall, the rocks become denser and hotter with increasing depth. The profile depicted in Fig. 2.3 shows that the crust is divided according to its strength and failure mechanisms variation throughout depth. Noteworthy, at any point of the Earth's crust, the stress tensor is characterised by three principal stress directions (maximum – σ_1 ; intermediate – σ_2 , and minimum – σ_3).

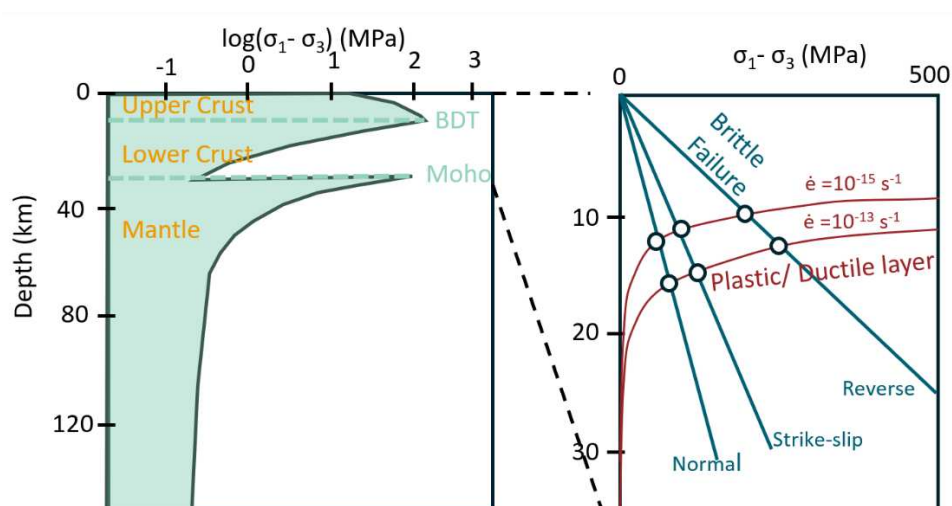


Fig. 2.3. Strength profile of the crust, with the shaded area representing the stress difference $\sigma_1 - \sigma_3$ (maximum and minimum principal stresses) that the rock can sustain before failure. The crust is divided into an upper and lower part. The upper crust corresponds to a layer where rocks respond to stress by failing, producing earthquakes. Brittle deformation under distinct tectonic regimes

(normal, strike-slip, and reverse) are represented in blue full lines. The lower crust is plastic and responds to stress mostly through viscous flow under different strain rates (red curves). The separation of the two crustal regions and the intersection of the two deformation regimes (white full circles) marks the brittle-ductile transition (BDT), whose depth varies according to several factors, such as the geodynamic context and strain rate. For instance, the upper crust thickness goes from a few kilometres in fast-spreading ocean-ridges to tens of kilometres in stable continental areas. Image adapted from Acocella (2021) with permission. License obtained by the author of the thesis.

The upper crust is characterised by brittle deformation and localised seismicity (Scholz, 1990), with rock strength typically increasing with depth (Fig. 2.3). Fracture mechanics and failure criteria dictate brittle deformation in this region (see Section A.2.2.1, Part C), with the development of new discontinuities or the reactivation of pre-existing ones. Brittle failure is a complex process that results from the interplay between the structure of the crustal rocks with the direction and relative magnitude of the principal stresses, which define the tectonic regime (Fig. 2.3). For instance, extensional tectonic regimes are associated with lower minimum principal stress (σ_3) and, consequently, with failure at lower stress levels (Fig. 2.3). The several types of fracture modes (Pollard and Fletcher, 2005), explain the typical discontinuities that form in the crust, which include extension, shear, and hybrid fractures (Gudmundsson, 2011), whose formation depend on several aspects, including the loading conditions, crustal depth, and fluid pressure.

At greater depths, with higher confining pressure and at higher temperatures, the brittle-ductile transition (BDT) marks a shift where ductile deformation becomes dominant over brittle failure (Fournier, 1999; Meyer et al., 2019) and where there is a significant strength contrast (Fig. 2.3). Moreover, in the BDT, a large fault zone (brittle), changes progressively into a ductile shear zone (Gudmundsson, 2011). In the middle and lower crust, deformation is generalised and primarily governed by viscous flow (Karato, 2008), with rock ductile strength decreasing with increasing temperature and depth (Fig. 2.3).

The depth of the BDT and the overall crustal strength profile are influenced by several factors (Karato, 2008; Lavallée and Kendrick, 2021; Acocella, 2021), including: (a) geothermal gradient and temperature; (b) tectonic regime; (c) fluid pressure (pore fluid pressure reduces friction); (d) varying mineralogical composition through the lithosphere; (e) porosity, and (f) strain rate. In fact, at higher confining stress and at high temperature at depth in the Earth's crust, the overstressing that generates brittle fractures at lower levels of the crust (usually up to ~10 km), might now lead to plasticity and a generalised deformation rather than fracturing. On the other hand, pore fluid pressure may reduce

effective stresses and favour fracturing or lead to plasticity by chemically active mechanisms (Carter and Tsenn, 1987; Noël et al., 2021).

2.1.2. Magmatic systems and the host rock domain

Magmatic systems evolve throughout the Earth's crust. Differentiation processes such as melt segregation and fractionation predominantly occur in the lower and middle crust, while the upper crust mostly constitutes a zone for magma accumulation and solidification (Annen et al., 2006; Cashman et al., 2017). As reviewed by Giordano and Caricchi (2022), the magmatic plumbing systems are long-lived at depth for more or less continuous magma feeding, but ephemeral in shallower portions of the crust. The dynamics of shallow magma systems and the processes related to the transfer and emplacement of magma in the brittle crust are governed by the fracture mechanics and failure criteria of the host rocks (Section 2.1.3 of Part B), which are the focus on this thesis.

The crust is structurally and thermally modified with the ponding and transport of magma, which develops a magmatic system, and by the tectonic regime (Acocella, 2021). The crustal profiles vary according to the magma system maturity (Fig. 2.4). The BDT becomes shallower when a high-temperature, mature magma system is installed, reducing the portion of the brittle crust and the density of the crustal rocks (full line of Fig. 2.4).

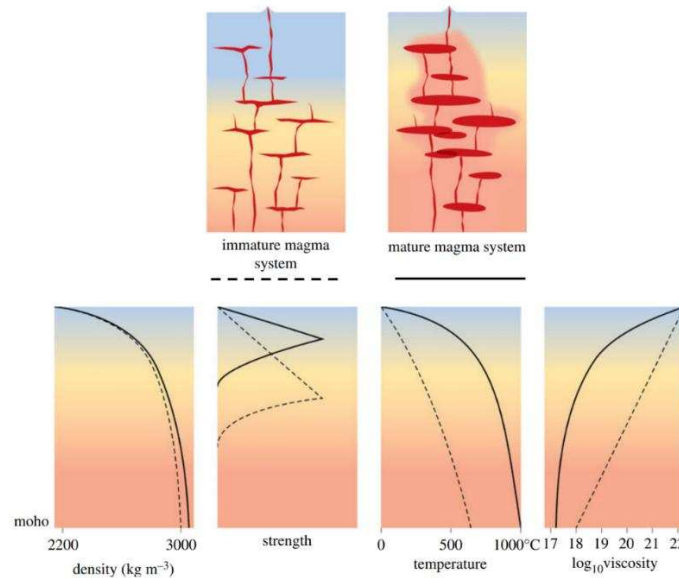


Fig. 2.4. Schematic crust density, strength, temperature and viscosity profiles, either for an immature magma system (early stages of magmatism or for a low magma flux – dashed lines) and mature magma system (heat and mass perturbing the crust – full lines). Adapted from Sparks et al. (2019) with permission. License obtained by the author of the thesis.

According to Sparks et al. (2019), magmatic systems comprise four interacting domains – *magma* (melt ± crystals and exsolved fluids), *mush* (a stiff network of crystals possibly entrapping some melt), and *host rocks*, that comprise the *super-solidus rocks* (hot rocks in a disturbed state) and the *sub-solidus rocks*, where no melt exists. The rheology of the various physical magmatic domains is governed by the amount of melt and interconnectivity between the melt pockets, with implications on magma ascent dynamics. Moreover, in this thesis the terms host rocks and the wall rocks are used as synonyms.

Magma reservoirs are composed by the crystal-dominated mush, where melt is present in only a few tens of percent of the magmatic system (Spark et al., 2019 and references therein), either on a microscale (crystal dimension) and mesoscale (veins, lenses, and pockets). On the other hand, a magma chamber consists in an ephemeral magma accumulation, either originated by successive intrusions or by the segregation and merging of melt-rich regions, forming a melt-dominated region (Sparks et al., 2019). Magma chambers may affect the propagation path of nearby dykes or nucleate into shallow-filled fractures that might feed eruptions, depending on the magma pressure and the minimum principal stress (σ_3 ; Gudmundsson, 2012; Pansino and Taisne, 2019).

Cold sub-solidus rocks, which correspond to older country rocks or plutonic rocks formed within the magmatic system, are often assumed as purely elastic, failing above a critical value of brittle failure (Bürgmann and Dresen, 2008). However, since they are in the vicinity or within active igneous systems, their rheology will be governed by the high temperature of the system and the mineralogy, water content, granularity, and strain rate of the host rock (Sparks et al., 2019; Fig. 2.4), with deformation involving both elastic (at short timescales) and viscous behaviour (Bürgmann and Dresen, 2008). In addition, despite not containing melt, sub-solidus host rocks can associate with fluids that affect their deformation, such as magmatic-hydrothermal fluids, magmatic volatile phases, or hypersaline brines; or fluids of external origin (Sparks et al., 2019).

2.1.3. Magma ascent through crustal rocks

The transport and accumulation of magma at the crust is discontinuous (Rivalta et al., 2015) and depends on the thermal evolution of the volcanic plumbing system overtime (Weber et al., 2020). As stated by Caricchi et al. (2021), this thermal evolution defines the capacity of magmatic systems to feed eruptions by controlling the accumulation rate of eruptible

magma and the changes in physical properties of the magma (e.g., viscosity) and host rocks (viscosity, shear modulus, relaxation time, fracture toughness, and tensile strength).

Critical values of pressurisation of a magma reservoir, leading to its destabilisation and initiating magma transport in the crust, depend on the aforementioned properties of the magma and surrounding rocks. For high strain rate (and short timescales), the host rocks behave elastically, with tensile failure promoting the crack nucleation and propagation in the wall rock. However, at slow strain rates promoted by magma supply and volatile exsolution, the host rock behaves viscously, inhibiting the fracturing of the wall rock. The several triggers for magma reservoir destabilisation and volcanic eruptions are reviewed by Caricchi et al. (2021), comprising factors like magma recharge, volatile exsolution, stress perturbations by loading and unloading, rainfall, and large earthquakes.

After a reservoir has reached a critical value, for an eruption to take place the magma needs to ascend through the crust. Moreover, sufficient magma volumes of low density and viscosity are required to ascend without solidifying in order to reach the surface, erupting (e.g., Taisne et al., 2011; Rivalta et al., 2015). Magma transport is a self-propagating and fluid-driven mechanism that occurs in the brittle host rocks (Lister and Kerr, 1991) as magma-filled fractures (or hydrofractures), most of which are planar and opening-mode fractures (Gudmundsson, 2002; Gudmundsson, 2011; Gudmundsson, 2022; Section 2.2.2 of Part A) that form distinct intrusion types: dykes, sills, and sheets (Fig. 2.5). Hydrofractures develop perpendicular to σ_3 and are controlled by the regional tectonic regime (Gudmundsson, 1990; Gudmundsson, 2006). On the other hand, they typically induce seismicity and/or ground deformation and can ultimately feed volcanic eruptions.

The connection between dyke initiation and magma reservoir failure remains poorly understood. As reviewed by Caricchi et al. (2021), most magma transport models consider the tensile failure of the wall rocks and the dilation and propagation in pre-existing fractures driven by magma overpressure, while shear failure criteria are less explored. Tensile failure is favoured by irregularities and spherical shape deviations of the magma chamber that act as stress concentrators, whereas pre-existing fractures favour the transport if with a suitable length and orientation. As pointed by Heap et al. (2013), both pre-existing discontinuities and percolating hot fluid weaken the host rock, possibly enhancing magma movement. Models representing longer timescale consider, instead, viscous deformation of the wall rocks as a possible trigger for reservoir failure (Caricchi et al., 2021 and references therein).

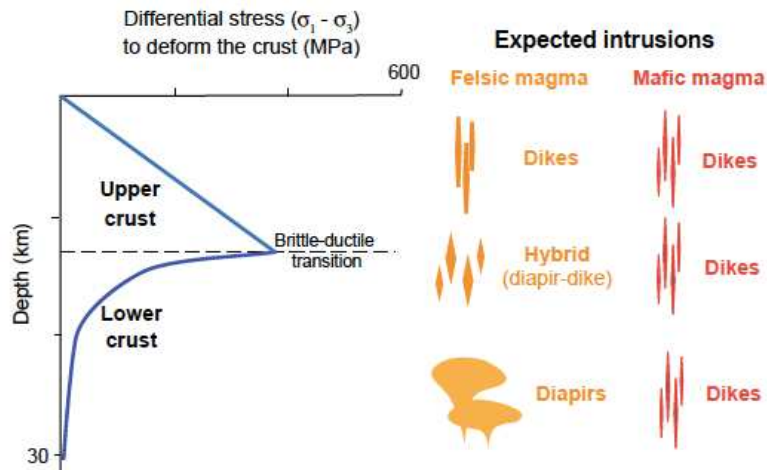


Fig. 2.5. Dominant type of intrusions with depth and for mafic and felsic magmas. In the upper brittle crust, dykes are the main structure, while for felsic magmas, hybrid structures and diapirs might occur in the viscous lower crust. Reproduced from Acocella (2021) with permission. License obtained by the author of the thesis.

Dyking, a mechanism similar to hydraulic fracturing (Rubin, 1995; Rivalta et al., 2015), is the predominant magma transfer mechanism in the upper brittle crust. Models on dyking (see Acocella, 2021) assume an elastic behaviour of the host rock, defined by solid mechanics, combined with the non-elasticity of the dyke tip, defined by fluid mechanics criteria. The propagation of magma implies a stress intensity on the dyke tip higher than the rock's fracture toughness (Kc), combined with an overpressure and viscous pressure drop of the magma. The temperature of the magma also plays a role in the vertical propagation, with mafic and/or hotter magma forming thinner dykes for higher distances (Fig. 2.5).

Pre-existing discontinuities do not affect the opening of dykes, but are often assumed to channel the ascending magma, forming sills or incipient magma reservoirs. However, if rock fracture is negligible in the overall force balance, then discontinuities are not mechanically advantageous to magma ascent (e.g., Gudmundsson, 2006). Because most faults are optimised to shear rather than opening, most dykes fail to occupy previous faults and rather create new paths (Caricchi et al., 2021 and references therein), whose orientation is dictated by the regional and/or local stress fields (Gudmundsson, 1990; Gudmundsson, 2006; Acocella and Neri, 2009).

Understanding the propagation of dykes in the crust helps in defining shallow magma transfer and forecast eruptions. However, most dykes become arrested in the crust, with

their stalling primarily controlled by the neutral buoyancy condition (NBC)¹, which is typically set on 2 to 4 km depth for mafic magmas at mid-ocean ridges (Hooft and Detrick, 1993). However, low density crustal rocks may reduce or nullify magma buoyancy (Acocella, 2021). Other factors contribute to dyke arrest (Acocella, 2021 and references therein), as following:

- a) limited or discontinuous supply rate from the source
- b) low regional deviatoric stress (e.g., compressive stress field) that hinders dyke propagation
- c) highly viscous magma
- d) pre-existing crustal anisotropies (layering, fractures, faults) in the host rocks
- e) mechanical heterogeneities within the crust (e.g., mush zones), which lead to stress barriers and/or rotational processes.

2.1.4 Hydrothermal systems

As described in the previous section, fracturing of crustal rocks is mostly associated with tectonic regime and the existence of magma reservoirs. Nevertheless, in volcano-hydrothermal settings, rock failure depends on other distinct but related processes (Wohletz and Heiken, 1992), such as hydrothermal circulation, magma degassing, and hydrovolcanic processes.

Conceptual model in intrusion-related systems

Hydrothermal systems are a key feature of the upper brittle crust, where structurally controlled permeability enables the circulation of fluids that transport heat and solutes. These systems require permeable host rock masses and a heat source, commonly resulting from magmatic activity, elevated geothermal gradients, radiogenic decay, or metamorphism, which are often linked to recent or ongoing volcanism (Pirajno, 2009).

Beyond their role in influencing the architecture of volcanic domains, hydrothermal systems contribute to the formation of valuable geological resources, including epithermal mineral deposits and geothermal energy (Stix et al., 2003; Stimac et al., 2015). Most factors

¹ The neutral buoyancy condition (NBC) occurs when the magma reaches isostatic equilibrium with the host rock, either in the crust or along large lithospheric discontinuities (e.g., Ida, 1995).

that constrain hydrothermal alteration are studied and defined for geothermal fields (Pereira et al., 2024a). Stimac et al. (2015) propose five geothermal resource categories - (1) intrusion-related systems; (2) tectonic systems; (3) deep sedimentary aquifers and geopressed systems; (4) hot dry rock systems or engineered geothermal systems; and (5) supercritical and/or magma tap systems – based on geological, hydrological, geophysical, and engineering characteristics. For example, the behaviour and evolution of intrusion-related systems are closely tied to the volcanic setting in which they occur, including features such as stratovolcanoes, lava domes, fissure vents, and calderas.

The crust can also be separated according to intrusion-related hydrothermal systems (Fig. 2.6; Stimac et al., 2015). The near-surface section is a groundwater domain, where meteoric waters or others of different origin (e.g., seawater) percolate and may intrude at higher depths, usually in peripheral zones of the hydrothermal domain.

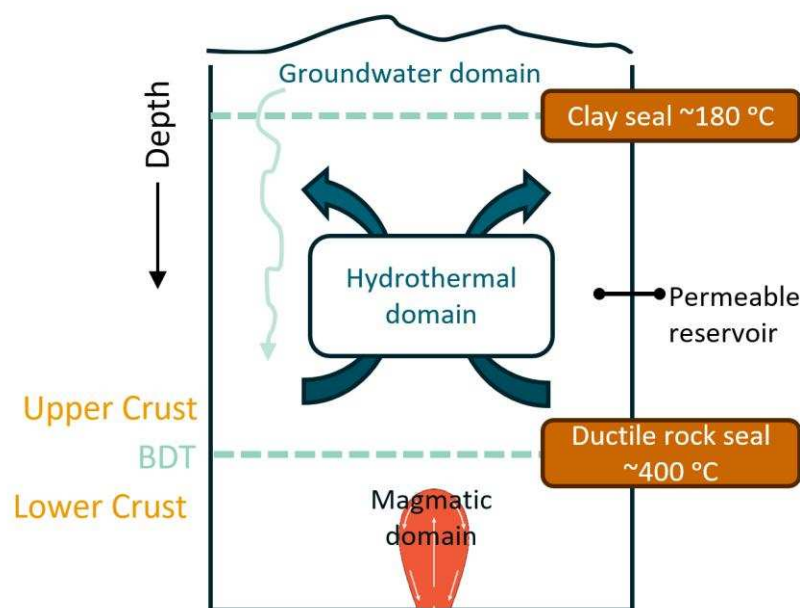


Fig. 2.6. Domains of crustal intrusion, hydrothermal system, and shallow groundwater along different crustal depths. The magmatic intrusion serves as a source of heat for the convective, percolating fluids in the hydrothermal domain, which is sealed at the bottom by the brittle-ductile transition (BDT) and at the top, typically by a clay seal. The zig-zag arrow represents the downward circulation of meteoric waters at peripheral zones. Based on Stimac et al. (2015).

In the upper crust, a hydrothermal domain prevails, where high temperatures ($> 200\text{ }^{\circ}\text{C}$) are maintained. Hydrothermal reservoirs often occur at depths between 1 and 4 km, and fracture networks guarantee high permeability (e.g., Scott et al., 2015; Stimac et al., 2015; Eggertsson et al., 2020). Geophysical and geodetic data point out the existence of

supercritical fluids and/or partial melt at depths of 2–10 km (e.g., Zollo et al., 2008) but maintaining permeability below 4 km in depth is challenging for high-temperature and high-enthalpy geothermal reservoirs (e.g., Eggertsson et al., 2020). Discontinuities in hydrothermal system are commonly accompanied by hydrothermal alteration products (e.g., Pirajno, 2009) and are necessary to preserve and rejuvenate hydrothermal activity, as indicated by the thermal models that show that most conductive heat flow is limited to fault zones (Sibson, 1982).

The top of the hydrothermal reservoir is sealed by a caprock, often impermeable volcanoclastic materials altered into clay (Franzson et al., 2010). The bottom boundary corresponds to the brittle-ductile transition (BDT; ~ 400 °C), which acts as a natural and impermeable barrier that limits at depth the seismicity and hydrothermal circulation in the crust (Sibson, 1982; Violay et al., 2012; Violay et al., 2015; Violay et al., 2017). The BDT may occasionally be breached, allowing magmatic water and volatiles to rise, which favour the failure of the host rocks and seismic events that affect the porosity, permeability and heat loss of the system (Fournier, 1999). The temperature of the system controls the depth of the BDT, with decreasing heat brittle phenomena in the host rock, such as faulting, brecciation, and vein genesis (Fournier, 1999).

At depths > 8 km and higher temperatures (> 400 °C), seismic anomalies probably represent zones of partial melt (Kennedy et al., 2018) that already belong to the magmatic system, relating to the magmatic intrusions that provide the necessary heat to drive the fluid circulation in the hydrothermal domain (Stimac et al., 2015).

Hydrothermal alteration is ubiquitous to any hydrothermal system and varies in terms of intensity and type of alteration. It is a complex metasomatic process that embraces the mineralogical, textural, and chemical response of rocks to a changing thermal and chemical environment in the presence of hot aqueous fluids (Henley and Ellis, 1983).

Hydrothermal fluids

As mentioned, in intrusion-related geothermal systems, fluid circulation depends on the heat source and on the permeability of the reservoir rocks, which is related to the tectonic structures and local stress fields. Another factor to consider is the availability of hydrothermal fluids with mineralising potential (Pirajano, 2009; Stimac et al., 2015). Hydrothermal fluids are hot aqueous solutions, typically ranging from 50 °C to over 500 °C,

with dissolved solutes that precipitate when the solution changes its physical or chemical properties, such as solubility, pH, redox potential, chemical potential, or fugacity. These modifications result from variations in temperature, pressure, or fluid density over time and space (Pirajno, 2009).

The water from hydrothermal fluids can originate from various sources (seawater, meteoric, connate, metamorphic, juvenile, or magmatic) but is typically of mixed origin. Dissolved solutes may include electrolytes, which dissociate into charged ions and conduct electric current, or non-electrolytes, which remain as molecules and are not conductive (Lagat, 2009).

Fluid–rock interactions play a crucial role in shaping the degree and type of hydrothermal alteration, with the chemical composition of both the circulating fluids and the surrounding host rocks evolving over time and space (Browne, 1978). Longer fluid-rock interaction tends to uniformise the composition and properties of the hydrothermal system (e.g., Frolova et al., 2010). The degree of alteration tends to diminish with increasing distance from both the discharge zone and any mineralised body (Pirajno, 2009).

The alteration and petrophysical properties of the wall rocks vary with the temperature of the fluids. Deep and high-temperature fluids ($> 200\text{ }^{\circ}\text{C}$) commonly decrease porosity and permeability, while increasing strength, density, and seismic wave velocities of the host rocks (Frolova et al., 2014). Conversely, hydrothermal alteration developed at lower temperatures ($> 150\text{ }^{\circ}\text{C}$) by subsurface fluids is complex and variable, depending on the initial lithology, pressure, temperature, and fluid-rock interaction (Ladygin et al., 2000; Frolova et al., 2010, 2011; Frolova et al., 2014).

Hydrothermal alteration mineral and mineral assemblages

Secondary mineral phases can precipitate directly from hydrothermal fluids into the voids of rocks, such as vugs and fractures. Fractures infilled by hydrothermal precipitates (veins and veinlets) can also be regarded as hydrofractures (Section 2.2.2 of Part A). These mineralised veins serve as geological records of former zones of high permeability, providing insights into hydrothermal system dynamics through their petrographic and geochemical characteristics (Wohletz and Heiken, 1992). Their orientation and spatial distribution are dictated by the crustal strength profile and the prevailing tectonic regime (Karakas et al., 2017). Many vein systems exhibit a spatial and genetic relationship with

igneous intrusions, frequently forming within or near the brittle-ductile transition (BDT) zone or at shallower depths where temperatures typically range between 200 °C and 350 °C (Pirajno, 2009 and references therein).

In intrusion-related systems, secondary mineral formation results from (Stimac et al., 2015): (1) the loss of magmatic volatiles from shallow intrusions and degassing in an active magmatic conduit; (2) the development of a magmatic-hydrothermal fluid envelope; and (3) the formation of a structurally controlled peripheral hydrothermal system governed by meteoric water and episodic input of magmatic fluids.

A complex interplay of different factors governs the genesis of hydrothermal mineral assemblages (Browne, 1970; 1978, 1984; Lagat, 2009), including temperature, pressure, wall rock composition (i.e., primary mineralogy), host rock permeability, fluid chemistry (pH, Eh), solute concentration, and the duration and intensity of the associated geodynamic processes. These factors, which are described below, vary from one geothermal field to another, resulting in distinct hydrothermal alteration signatures.

Mineral assemblages are often used as temperature indicators, particularly those that occur for a narrow temperature range (e.g., epidote) (Henley and Ellis, 1983; Reyes, 1990). Clay minerals are typically associated with lower temperature conditions. Yet, the type of clay can constrain the temperature range and distinguish between the type of fluid flow – channelised or diffusive – in the host rock (diffusive or channelised; Harvey and Browne, 1991; Utami and Browne, 1999).

Pressure dictates mineral solubility (Browne, 1984), and boiling zones are frequently associated with adularia, calcite, quartz, and sometimes wairakite (Browne, 1970; Browne and Ellis, 1970; Keith and Muffler, 1978). Depth affects the pore space characteristics of the host rock, with increasing depth and pressure favouring compaction, primarily in fragmental rocks, which affects the development of hydrothermal alteration (e.g., Durán et al., 2019). On the other hand, denser rocks, such as lavas, are more resistant to compaction. However, they fracture at depth, thereby increasing permeability and making them more sensitive to pore fluid pressure (Pereira et al., 2024a, and references therein).

The permeability of the host rocks determines the extent of water-rock interaction, the type of fluid flow, and the mineral assemblage that precipitates. Veins and alteration to quartz, anhydrite, wairakite, illite, adularia, hyalophane, celadonite, abundant pyrite and calcite indicate zones of former high permeability (Keith et al., 1978; Reyes, 1990), in opposition

to mixed-layer clays, prehnite, pumpellyite, pyrrhotite, abundant laumontite, abundant sphene, that form under low-permeability conditions (Reyes, 1990; Harvey and Browne, 1991).

Primary mineralogy primarily influences hydrothermal alteration that develops at temperatures below 280 °C (Frolova et al., 2014). As for high temperatures, the assemblage chlorite ± albite ± adularia + calcite + quartz ± illite ± pyrite is often reported for distinct rock types (Henley and Ellis, 1983; Browne, 1978; Cox and Browne, 1998). For igneous rocks, glass and ferromagnesian minerals are more reactive and prone to dissolution, while crystalline rocks with rhyolitic composition are more resistant to alteration (e.g., Browne, 1984; Cathelineau et al., 1985; Lagat, 2009; Frolova et al., 2010).

In sum, the study of hydrothermal minerals is fundamental for the exploration, characterisation, and sustainable development of geothermal resources. As outlined by Reyes (1990), hydrothermal alteration minerals can serve multiple purposes: (a) geothermometers; (b) defining the depth at which production casing is set during drilling; (c) estimating fluid pH and other chemical characteristics; (d) predicting the potential for corrosion and scaling; (e) indicating permeability and identifying zones of cold water inflow into wells; (f) guiding interpretations of field hydrology; and (g) providing approximate estimates of the thickness of eroded overburden.

Classification of hydrothermal alteration

Hydrothermal alteration is characterised and classified based on the identified mineral assemblages and associated chemical modifications. Over time, a variety of terminologies have emerged in the literature related to both geothermal and ore-deposit exploration to describe alteration (Wohletz and Heiken, 1992). The terms “pervasive,” “selectively pervasive,” and “non-pervasive” are frequently employed to express the intensity and extent of alteration within the host rock. To capture the complexity of hydrothermal alteration in volcanic rocks, Gifkins et al. (2005) proposed a multi-dimensional classification that incorporates four descriptive variables:

1. Mineral assemblage – a list of minerals arranged in order of decreasing abundance;
2. Texture – including shape, grain size, fabric, and alteration style (e.g., selective, pervasive, or vein halo);
3. Distribution – spatial extent and setting (e.g., local or regional, footwall, hanging wall, pipe, or stratabound); and

4. Mineral intensity – qualitative assessment of alteration strength, ranging from slight to intense.

Alternatively, hydrothermal alteration can be quantified through chemical analyses (Mathieu et al., 2018). One commonly applied metric is the Chemical Index of Alteration (CIA), which evaluates the extent of alteration by leveraging the relative immobility of aluminium during weathering processes. Originally developed for the study of sediments and sedimentary rocks (Nesbitt and Young, 1982), the CIA has more recently been applied to volcanic rocks to characterise alteration intensity (Pola, 2014; Weydt et al., 2022; García-Soto et al., 2024). High CIA values (>80) are indicative of intense and recent weathering or hydrothermal alteration, particularly associated with feldspar destruction and the development of chloritic or advanced argillic assemblages.

In addition to CIA, the Na_2O content is often used as a complementary indicator to infer feldspar abundance and alteration intensity (Gifkins et al., 2005). Another widely utilised geochemical parameter is Loss on Ignition (LOI), which quantifies volatile content and allows for detecting hydration or calcification of mafic minerals in altered volcanic rocks (Pandarinath et al., 2023; García-Soto et al., 2024).

Table 2.1 provides an overview of the principal types of hydrothermal alteration observed in geothermal systems and mineral ore deposit settings. The main alteration zones/ facies are usually defined by temperature and the main mineral assemblages.

Despite not being on the table, hydrolytic alteration is particularly prevalent. It typically represents the initial stage and precedes more specific alteration types, such as propylitic, argillic, sericitic or phyllic, and potassic alteration (Pirajno, 2009). Hydrolytic alteration is characterised as a hydrogen ion metasomatic process. It involves chemical transformations driven by water-rock interaction, including hydrolysis (the dissociation of H_2O into H^+ and OH^-), hydration, and dissolution.

Most productive geothermal systems are associated with the argillic ($< 140\text{ }^\circ\text{C}$), transitional ($140\text{--}220\text{ }^\circ\text{C}$) and propylitic ($> 220\text{ }^\circ\text{C}$) alterations with increasing temperature. Argillic and transitional zones typically affect the low permeability caprocks, while the permeable reservoir itself is altered to the propylitic facies. Propylitic alteration can be subdivided (Frolova et al., 2010; 2011; 2014) into low temperature, comprising clay minerals, zeolites, and calcite, and medium-high-temperature, often combines with advanced silicic alteration,

which causes a strengthening, porosity, and permeability reduction of host rocks (e.g., Frolova et al., 2014). Furthermore, when close to a magmatic intrusion, this facies often combines with the potassic alteration (biotite-adularia $\pm$ amphibole $\pm$ tourmaline) (Heald et al., 1987).

Fig. 2.7, reproduced after Pereira et al. (2024a), provides a cross-section of a hydrothermal system associated with an intrusion, integrating information from Fig. 2.6 with the main hydrothermal facies that form in response to the heat source and thermal and fluid compositional gradients.

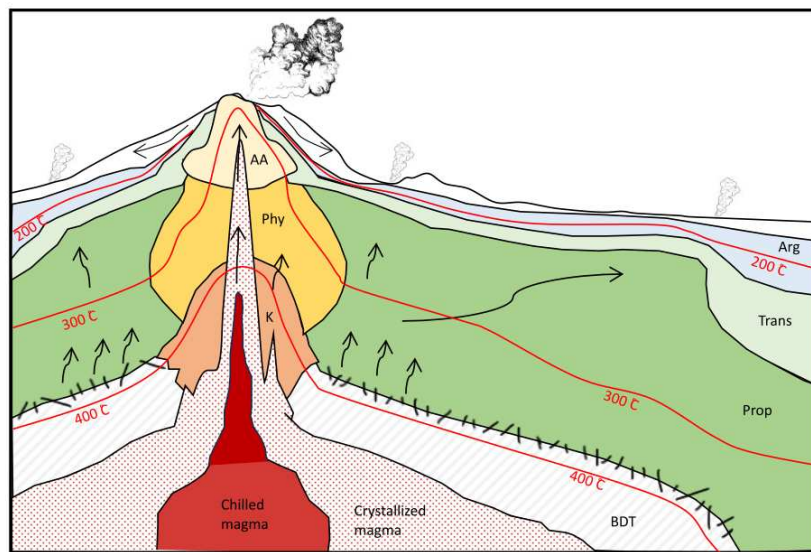


Fig. 2.7. Cross-section of a subvolcanic hydrothermal system reproduced from Pereira et al. (2024a). Main hydrothermal facies with increasing depth and temperature - argillic (Arg), transitional (Trans), and propylitic (Prop). With increasing depth, potassic (K), phyllic (Phy), and advanced argillic (AA) alterations occur around the magmatic intrusion. The brittle-ductile transition (BDT) overlies a crystallised magma carapace and is breached by rising magmatic fluids (arrows). Red lines represent the isotherms. At the surface, manifestations of geothermal systems include fumaroles, hot springs, cold CO₂-rich springs, and diffuse degassing areas. Licensed under CC BY 4.0.

Table 2.1. Main hydrothermal alteration assemblages of geothermal settings (based on Heald et al., 1987; Gifkins et al., 2005; Lagat, 2009; Pirajno, 2009). Minerals in italics are the most common secondary phases.

	Mineral Assemblage	Description
Propylitic	<i>Epidote + chlorite + albite</i> ± carbonates ± pyrite ± Fe-oxides ± sericite ± montmorillonite ± zeolite ± amphiboles (actinolite and tremolite) ± apatite ± anhydrite ± chalcopyrite	Typically, a high-temperature and regional alteration. Results from the decomposition of Fe-Mg-bearing minerals or from the replacement of feldspar by the addition of H ₂ O and CO ₂ , and locally S. Outward grades into unaltered rocks or greenschist facies rocks.
Potassic	<i>K-feldspar (orthoclase) + biotite + quartz</i> ± chlorite ± mica type minerals ± adularia (epithermal) or anhydrite (porphyries) ± magnetite ± albite ± rutile ± epidote ± pyrite ± chalcopyrite ± anhydrite	Typically, a high temperature and potassium-rich alteration, with possible occurrence of adularia. Common replacement of plagioclase and mafic silicate minerals (T = 450–600 °C).
Sericitic	<i>Sericite + pyrite + quartz</i> ± biotite ± K-feldspar ± carbonates ± chlorite ± andalusite ± albite ± pyrrhotite	Forms at low pH conditions and results from the decomposition of feldspars. It is structurally controlled, occurring near veins. It is common in geothermal and other mineral deposit systems. Sericitic alteration usually evolves to a potassic type (by adding K-feldspar and/or biotite) or argillic type (by adding clays).
Phyllic	<i>Sericite + pyrite + quartz</i> ± biotite ± chlorite ± rutile ± leucoxene ± chalcopyrite ± illite/mixed layer illite ± kaolinite ± apatite	It is also designated as sericitic alteration, being typical of acidic environments in porphyry copper deposits. If the amounts of topaz, tourmaline, quartz and zunyite increase, then it is called greisen-type alteration. As sericitic, it commonly evolves to potassic and argillic alteration types.
Argillic	<i>Kaolinite ± montmorillonite</i> ± sericite (or muscovite) ± chlorite	Argilic alteration is typical of lower temperatures. For higher thermal regimes, kaolinite is replaced by chlorite and pyrophyllite. The advanced argillic alteration
Intermediate Argillic	<i>Chlorite ± sericite</i> ± kaolinite ± montmorillonite ± illite-smectite ± calcite ± epidote ± biotite ± pyrite	reflects extreme acid attack and high sulfidation. Overall, argillic alteration results from intense H ⁺ metasomatism and acid leaching at T = 100–300 °C. Inwardly evolves to phyllic zones and outwardly to propylitic alteration. Typical either from porphyries or epithermal environments. It can also be graded into silicic zones. Clays typically
Advanced Argillic	<i>Pyrophyllite ± kaolinite</i> ± quartz ± sericite ± andalusite ± diasporite ± alunite ± topaz ± zunyite ± enargite ± tourmaline ± pyrite ± chalcopyrite ± hematite	alter plagioclases and mafic silicates (hornblende and biotite). In geothermal fields, argillic and intermediate argillic alteration are common.

Table 2.1. (continued) Main hydrothermal alteration assemblages of geothermal settings (based on Heald et al., 1987; Gifkins et al., 2005; Lagat, 2009; Pirajno, 2009). Minerals in italics are the most common secondary phases.

Other types of alteration typically combined/included in the former types of alteration		
	Mineral Assemblage	Description
Albitic	<i>Albite</i>	Typical of high temperatures and reflects Na enrichment of the system.
Silicic/ Silicification	<i>Quartz ± silica minerals</i> (e.g., chalcedony; opal)	Characterised by secondary silica addition. Wall rocks are typically silicified, and chalcedony occupies empty spaces. Common to a wide range of geological settings and temperatures.
Carbonation	<i>Carbonates</i> (calcite, dolomite or ankerite) ± talc ± sericite ± albite	Typically associated with propylitic alteration. Dolomitisation involves loss of volume, which leads to an increase in porosity and consequent fluid flow.
Chloritic/ Chloritisation	<i>Chlorite</i>	Origin of chlorite, usually as a vein mineral or in vugs. Commonly associated with intermediate argillic alteration.
Alunitic	<i>Alunite</i>	Typical from high SO ₄ environments, possibly as the result of sulfide minerals oxidation. It can be considered as part of the advanced argillic alteration.
Zeolitic	<i>Zeolite minerals</i>	Typical of volcanic environments as replacements of the glass matrix or as infills in vugs and fractures. Zeolites occur for low temperatures, except wairakite. Zeolites are effective indicators of temperature and pressure, suggesting the proximity of a heat source and a potential boiling zone. Often superimposes to argillic alteration.
Serpentinisation and talc alteration	<i>Serpentine and Talc</i>	This alteration is restricted to mafic and ultramafic host rocks and is typical of low temperatures. Serpentine, talc, and talc associated with chlorite are formed as pyroxene is exposed to H ₂ O and CO ₂ .
Oxidation	<i>Oxides</i> (e.g. hematite, magnetite)	Formation of any oxide mineral, mostly in or near the surface, due to oxygen presence. It develops under a wide range of temperatures.

In intrusion-related geothermal systems, hydrothermal alteration is further categorised based on fluid composition and structural context. According to Wohletz and Heiken (1992), two primary types are recognised:

- Acid-sulfate alteration, typically occurring in the uppermost parts of a volcanic edifice or along caldera ring faults, where cool groundwater interacts with volcanic gases, resulting in acidic conditions. As a result, alunite and kaolinite are used as indicators of acidic steam-heated zones at the subsurface and fractures. This type of alteration is associated with argillic to advanced argillic alteration (Table 2.1), either being pervasive or cut by propylitic alteration associated with zones of discontinuities (Heald et al., 1987; Stimac et al., 2015).
- Adularia-sericite alteration is associated with deeper portions of geothermal systems, where mixed meteoric and magmatic fluids produce alkali-chloride waters of near-neutral pH, often above or adjacent to a deep-seated magmatic heat source. These neutral fluids are also the source of the argillic propylitic facies (Table 2.1).

Additionally, Heald et al. (1987) link the alteration produced by volcanic-geothermal systems with their spatial evolution in wall rocks regarding the mineralised hydrothermal veins (see Fig. 2.8), offering further insight into the thermal and chemical gradients operating within these systems. According to Mayer et al. (2016), near fracture zones, high permeability and acidic conditions ($\text{pH} < 2$) favour the genesis of amorphous silica, while towards the periphery of the system where permeability is lower, alunite and amorphous silica form at $2 < \text{pH} < 4$ and kaolinite at $\text{pH} > 4$.

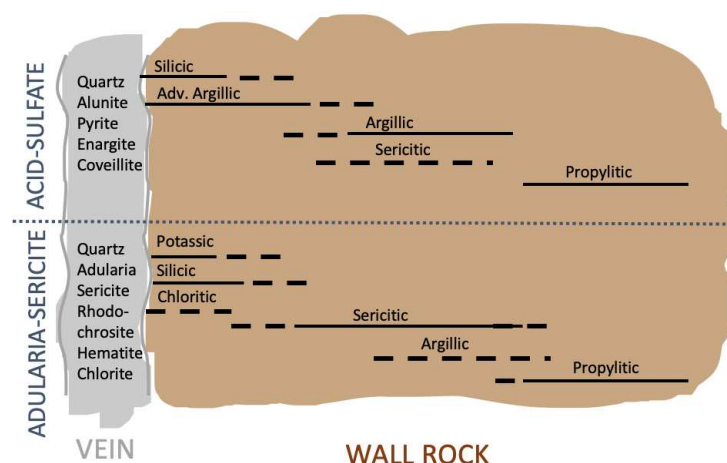


Fig. 2.8. Schematic representation of acid-sulfate and adularia-sericite alteration in volcanic rocks. Vein mineral assemblage and alteration zones in the wall rock concerning the vein source. No scale (based on Heald et al., 1987).

2.2. Lava rocks expression at the surface

2.2.1. Stratovolcanoes with calderas

Stratovolcanoes are composite volcanoes with the interlayering of lava flows and pyroclastic deposits, each possessing distinct physical and mechanical properties. These differences primarily relate to the diverse textures and structures that result from various petrogenetic processes and deformation histories during emplacement and post-eruption evolution (e.g., Cashman et al., 1994).

As the volcanic edifice grows, the internal stress field becomes increasingly compressive, inhibiting dyking (Pinel and Jaupart, 2000; Gudmundsson et al., 2006). Additionally, rocks buried beneath newer volcanic materials differ from their surface equivalents (Eggertsson et al., 2020), often experiencing shear-enhanced compaction, decreasing porosity and permeability (Heap et al., 2015a), which in turn affects fluid flow and mechanical responses within the edifice.

The progression of these structural and mechanical transformations may contribute to the gravitational instability of the volcanic system. In many cases, this leads to edifice collapse and the formation of caldera structures, which can develop either at the summit or within the original stratovolcano. Furthermore, the different mechanical responses of the interlayered volcanic materials might deviate and arrest propagating dykes/sheets in the upper part of the edifice (Gudmundsson, 2020).

Calderas consist of topographical subcircular depressions formed by the subsidence due to a partly drained magma reservoir (Branney and Acocella, 2015). Subsidence follows from the explosive eruption of magma from the chamber or lateral intrusion of magma, which feeds a minor to moderate distal effusive eruption (e.g., Cole et al., 2005; Acocella, 2007). Caldera-forming eruptions are among the most catastrophic natural events on Earth (e.g. Acocella et al., 2015; Okumura et al., 2019), which pose severe societal and economic risks. Notwithstanding, caldera structures often host conditions to create favourable economic resources like geothermal energy and ore deposits (Stix et al., 2003; Stimac et al., 2015; Section B.2.1.4). However, their inherent complexity complicates the understanding of post-collapse events and hinders reliable forecasting of future eruptions in active calderas (e.g., Kennedy et al., 2018). Episodes of unrest are frequently driven by the interplay between magmatic, hydrothermal, and tectonic processes. (e.g., Kennedy et al., 2018).

At depth, the volcanic rocks within caldera systems tend to compact over time, leading to microfracture closure and subsequent reductions in both porosity and permeability (Lamur et al., 2017; Eggertsson et al., 2020). The structure and development of calderas are independent of the regional tectonics, as evidenced by modelling (Acocella, 2007; Acocella, 2021). However, tectonic regimes and local stress fields influence caldera morphology, fault reactivation, and collapse timing. Although it is defined that the evolution and the geometry of caldera plumbing systems depend on the geodynamic setting, their understanding remains incomplete (e.g., Kennedy et al., 2018).

Fractures (see also Section 2.2.2. of Part A) are ubiquitous in stratovolcanoes, with or without calderas, resulting from mechanical (Heiken et al., 1988) and thermal stresses (Aydin and DeGraff, 1988). The low tensile strength of rock relative to its compressive strength promotes the development of extensive/tensile fractures at depth (Jaeger et al., 2007) that counteracts the effects of compaction in volcanoes. Volcanic tensile fractures include microscopic cooling cracks, polygonal joints in lava flows and domes, hydrofractures, tuffisites, crease structures, dome-related fractures, and large surface fissures (Heap et al., 2016; Heap et al., 2021a). These fractures play two main roles: reducing the structural integrity of the edifice and acting as conduits for fluid migration (Voight, 2000; Heap et al., 2016, 2021a; Gudmundsson, 2020). For example, they can enhance the outgassing of magma within conduits (Castro et al., 2014) and, when extensively developed, become efficient pathways for hydrothermal and magmatic fluids circulation (Heiken et al., 1998; Gudmundsson et al., 2002; Gudmundson, 2020).

When solidified magma-filled fractures form a cohesive network at depth, they may enhance the overall strength of the volcano (Gudmundsson, 2020). However, if sheet intrusions associate with stress concentrations along the border with the host rock, brittle failure and weakening may take place instead. Veins and pervasive alteration also contribute to the weakening of a volcano-caldera system, as the clays formed by argillic alteration have lower stiffness and facilitate the rock's deformation.

2.2.2. A brief note on volcanic landslides

As previously noted, stratovolcanoes and volcanic edifices are composed of interbedded units that often include mechanically weak layers, such as poorly consolidated pyroclastic deposits, fractured lava flows, weathered horizons, and argillic alteration zones. The structural stability of volcanoes can be reduced by a combination of factors, including intense rainfall, hydrothermal alteration, volcano-tectonic activity, and deformation associated with magmatic intrusions,

which may lead to a loss of rock strength, increased pore pressure, and enhanced deformation and loading, both static and seismic (van Wyk de Vries and Francis, 1997; van Wyk de Vries and Davies, 2015). Even in periods of volcanic quiescence, volcanic landslides pose a significant hazard, potentially resulting in flank or sector collapse that can disrupt both hydrothermal and magmatic systems (van Wyk de Vries and Davies, 2015). Structural weakening may be driven by either rapid, short-term triggers or a long-term event related to the volcano's lifetime. Lava-dominated units are particularly vulnerable to rockfalls, as documented across various volcanic islands (Whitchurch, 2012; Darmawan et al., 2020; González de Vallejo et al., 2020; Massaro et al., 2024).

The properties of lava rocks

This chapter focuses on the physical and mechanical properties of lava rocks, offering a theoretical framework and a synthesis of the current literature. These properties are traditionally assessed within the scope of rock mechanics but also intersect with the field of petrophysics.

Rock mechanics is the theoretical and applied science focused on the mechanical behaviour of rocks under various stress conditions, linking the rock mass to a first intact rock study (Jaeger et al., 2007). Rock mechanics is governed by structural geology and engineering principles that operate across distinct scales and conditions, such as time, pressure, and temperature (Pollard and Fletcher, 2005).

Petrophysics, defined as “the petrographic interpretation of the physical properties of rocks” (Montoto, 1983), overlaps rock mechanics by assessing the porosity and permeability of rocks. These properties control the fluid storage and transport and have geomechanical implications for the intact rock and rock mass.

The principles of rock mechanics and petrophysics have wide-ranging applications across civil engineering, natural stone quarrying, and resource extraction (oil, gas, water, geothermal). They also support geological investigations regarding the origin and age of rocks, stratigraphy, and the development of structures such as folds, faults, joints, and dykes, as well as processes like weathering and mineralisation (Hencher, 2015).

Rock mechanics has historically been understated in volcanology. However, its integration with field observations has significantly advanced the knowledge of processes such as magma transport and emplacement, caldera formation (Gudmundsson, 2006; Acocella, 2007), and volcanic slope stability (Voight, 2000).

2.1. Physical Properties

Porosity, permeability, and density in volcanic rocks arise from a range of processes linked to their formation (see Section 2.1, Part A), and their study is part of both petrophysics and rock mechanics. This chapter focuses on these properties by first establishing their theoretical framework, then examining their contribution to volcano-hydrothermal systems, and finally, providing a brief review of the existing data on volcanic rocks.

2.1.1. Density

Density (ρ) is the ratio of the mass (including of the solids and natural moisture) per volume of rock, representing the mean density of the considered rock volume, including the effect of both the pores and the rock's matrix (Schön, 2015). The conventional thinking is that density depends on the mineral composition (mineral density and volume fraction) and the rock's porosity (pores and fractures). For example, compact and low-porosity rocks tend to have higher density, in particular those with heavy minerals (e.g., ferromagnesian and opaque minerals). On the other hand, increasing porosity and decreasing water saturation decrease the density. The density of pore fluids also plays a role, but in this research, only distilled water is used (1 g/cm³). kg/m³ is the SI unit, but g/cm³ is commonly used and adopted in the thesis.

2.1.2. Void space characteristics

There are several fundamental physical properties of the pore space of a rock. Porosity corresponds to the volume fraction of pores (and microcracks), capillary pressure is associated with the fluid distribution in the pore space, and permeability describes the fluid flow in a rock under pressure (Schön, 2015).

2.1.2.1. Porosity

Porosity is a fundamental volumetric property in several geological applications. Total porosity (n_T) represents the ratio of the total void space volume (V_v) in the rock to the bulk volume of the rock (V_t), varying between 0 to 1 (e.g., Amyx et al., 1960; Eq. 2.1). Porosity can also be calculated via the density and grain density (ρ_s) (Eq. 2.2), and it is reported in percentage.

$$n = \frac{V_v}{V_v + V_t} \quad 2.1.$$

$$n = \frac{(\rho_s - \rho)}{\rho_s} \quad 2.2.$$

Only a portion of the total pore space in a rock is interconnected, referred to as open, effective, or connected porosity (n_{eff}), which encompasses both pores and microcracks (see terms in Section 2.1.1, Part A). n_{eff} is a key parameter that links fluid transport properties to other petrophysical characteristics, playing a central role in predictive models of capillarity and permeability, as well as in understanding the overall physical properties of rocks (Cueto, 2020; Hall and Hoff, 2021).

Pore size classification varies across studies (Table 2.2). The categories compiled by Mann et al. (1997) report to low-permeability sedimentary rocks, whereas Franzson et al. (2010) define micropores at larger dimensions to reflect the characteristics of volcanic rocks better. Pore size distribution and pore geometry influence the rock's mechanical behaviour and failure patterns (e.g., Heap et al., 2014a; 2014b; Bubeck et al., 2017; Heap and Violay, 2021). Furthermore, the size and connectivity of the pores dictate the fluid movement within the rock matrix, which depends on three competing forces—viscosity, capillarity, and gravity—that occur at different observation scales (Mann et al., 1997).

Table 2.2. Pore size classification according to the pore radius for sedimentary (Mann et al., 1997) and volcanic rocks (Franzson et al., 2010).

Mann et al. (1997)		Franzson et al. (2010)	
Type of pore	Size (radius)	Type of pore	Size (radius)
Rough pore	> 1 mm	Macropore	$\geq 15 \mu\text{m}$
Macrocapillary	$25 \mu\text{m} - 1 \text{ mm}$		
Capillary	$1 \mu\text{m} - 25 \mu\text{m}$		
Microcapillary	$25 \text{ nm} - 1 \mu\text{m}$		
Macropore	$1 \text{ nm} - 25 \text{ nm}$	Micropore	< $15 \mu\text{m}$
Mesopore	$0.4 \text{ nm} - 1 \text{ nm}$		
Micropore	< 0.4 nm		

The porosity of pyroclastic rocks is used as an indicator of the character of a volcanic eruption (Mueller et al., 2011). In turn, lava flows are composed typically of low-porosity rocks with varying degrees of porosity and primary fractures, which are influenced by the properties of the magma and the emplacement process (Couves et al., 2016; Becker et al., 2019). Processes such as hydrothermal alteration, weathering, and tectonic stress can modify the micropore network and introduce late-stage discontinuities (secondary and tertiary – Section 2.2.2. of Part A).

2.1.2.2. Fluid movement in the rock: Capillary absorption and permeability

The water mobility in the porous system of rocks changes the saturation degree over time (Cueto, 2020), depending on the initial saturation. The water moves through permeability or capillary absorption, both of which are addressed in this research. While *capillarity* describes the water distribution within a rock, considering an initial unsaturated medium, permeability assumes a saturated one (Cueto, 2020).

Sorption Processes

Water uptake into the rock by capillarity promotes *sorption kinematic processes* (or *transport mechanisms*). Sorption mechanisms are triggered by distinct mobilising forces and correspond to fluid molecules that either attach to the rock's surface or enter the rock matrix. Sorption, which is further detailed below, can either occur on the surface (adsorption), within the rock (absorption) or through a combination of transport mechanisms (capillary condensation) (Benavente, 2011; Benavente et al., 2015; 2018). These processes occur under subaerial exposure conditions and depend on a set of intrinsic and extrinsic parameters, including *pore size* (Fig. 2.9), *pore size distribution* (PSD), and *relative humidity* (RH) (Cueto, 2020).

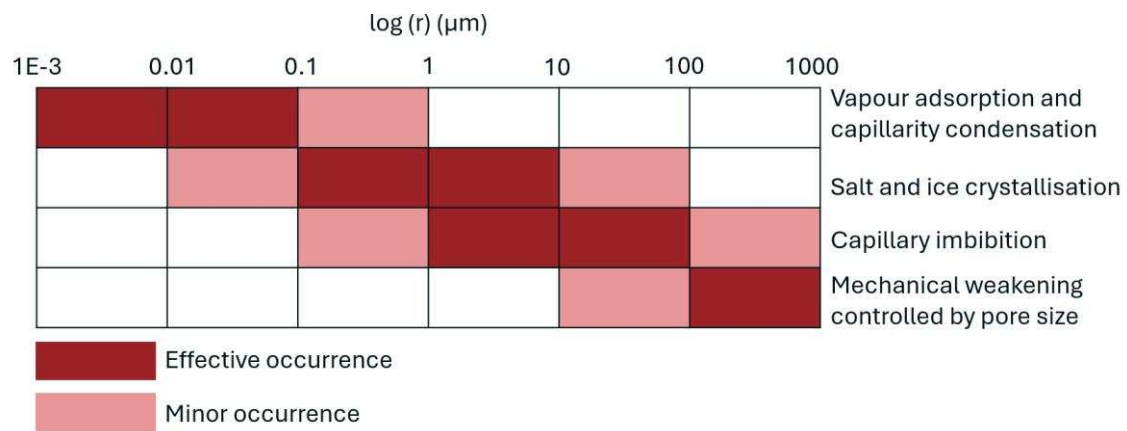


Fig. 2.9. Water transport mechanisms and deterioration processes in building stones according to the pore size (radius in μm). Adapted from Benavente et al. (2018) with permission. License obtained by the author of the thesis.

○ Adsorption and capillary condensation

At the initial molecular stage and for pore radius $< 0.01 \mu\text{m}$, fluid *adsorption* to the rock's surface molecular adhesion is driven by Van der Waals electrostatic forces, forming a monomolecular layer at low RH ($\sim 20\%$) that flows via individual molecule diffusion. *Diffusion* corresponds to the

slow movement of water molecules due to concentration gradients and is governed by Fick's Law (e.g., Hall and Hoff, 2021). Then, as RH increases (~40–60 %), the adsorbed fluid changes into a multimolecular layer that moves via surface flow (Rose, 1963), which transports water more efficiently than individual molecule diffusion.

When RH is ~75–85%, the pore radius is ~0.1 μm , and the temperature of the porous medium is lower than the dew point of the air, water transport shifts to a combination of diffusion and capillarity, known as capillary condensation. In this sorption process, capillary forces bind liquid fluid layers together, increasing the water content to maximum RH limits of ~98 % for a maximum 1 μm pore radius.

- Capillary absorption

Capillary absorption follows the origin of a continuous phase of liquid along the rock's surface, comprising adhesion and cohesion processes. The predominant transport mechanism is *capillarity*, where fluid is driven by pressure due to a surface tension (Benavente, 2003; Hall and Hoff, 2021). Capillarity is one the most important mechanisms in distributing the fluid within the rock, depending on the properties of the void space and fluid, as well as on the interactions between the fluid and the pore surface and between the distinct fluids (Schön, 2015).

Capillary forces consist of *wetting* and *surface tension*. Wetting occurs whenever the dry solid/air surface is replaced by a solid/liquid interface that reduces the energy of the system (Hall and Hoff, 2021 and references therein) and describes the property of one fluid to adhere to a rock surface (Schön, 2015). Surface tension controls the water behaviour at the surface, namely the formation of droplets and the water-free level.

The fluid distribution by capillarity, represented by water absorption capillary curves, induces changes in the saturation degree of the rock, resulting in different saturation zones (Schön, 2015). The water zone corresponds to the volume where the rock is saturated. In the transition zone, saturation is variable and depends on the uniformity of the pore size. For instance, water uptake is facilitated by the presence of abundant and larger pore throats (pore radius < 1 mm in size). Above the transition zone, water uptake is made via grain-to-grain contacts and in the small pores through a capillary bounding between the water and the pore contact.

Regarding mechanisms, capillary absorption takes place through:

- *spontaneous imbibition*: driven by the spontaneous tendency of liquid to distribute in a rock material in all directions through absorption (e.g., Hall and Hoff, 2021).
- *capillary rise*: the liquid rises a capillary tube (or narrow void space), counteracting gravity (Schön, 2015).

In both mechanisms, the pressure in the liquid phase is lower than the ambient pressure, which creates a negative gauge pressure. The capillary pressure (P_c) acts at the curve liquid/air interface (meniscus), where a surface tension (σ_{ST}) is created and makes the water rise, depending on the capillary radius (r) and the contact angle (θ). This phenomenon corresponds to the Laplace equation (Eq. 2.3; in Schön, 2015).

$$P_c = \frac{2 \sigma_{ST} \cos\theta}{r} \quad (2.3)$$

In capillary rise, both capillary and gravity forces intervene in the saturation of a rock, which proceeds according to its height (h ; Eq. 2.4). The liquid rises until the capillary pressure equals the gravitational pressure, and smaller pore radius (r) enhance a higher capillary rise (Schön, 2015).

$$h = \frac{2 \sigma_{ST} \cos\theta}{g \Delta\rho r} \quad (2.4)$$

where g is the earth acceleration, and $\Delta\rho$ is the difference of density between the wetting and non-wetting fluid.

Rocks can have similar porosities but considerable differences in permeability that result from microstructural differences. The porous network characteristics, specifically the pore and throat radii, dictate the connectivity and influence the P_c , with a large pore-throat radius contributing to high permeability and low capillary pressure and vice versa (Schön, 2015). For instance, according to Jurin's law for a wetting liquid, in a pore radius of 1 mm, the capillary rise achieves only a height of ~1.5 mm. As a result, pore system characterisation is important to constrain the overall physical properties of the rocks, as previously suggested by Hall and Hoff (2021).

In porous rocks, capillary imbibition can be measured considering the variation of the free water level ($y(t)$) that is dictated by the capillary pressure over time (Eq.2.5). In alternative, spontaneous imbibition is obtained via the mass of water ($M(t)$) that is absorbed by the superficial area (A) of the rock along the time (t) (Eq.2.6). The constant C is the *coefficient of capillary absorption* ($\text{g}/\text{m}^2 \cdot \text{s}^{0.5}$).

$$y(t) = \sqrt{\frac{2 \sigma \cos\theta}{r} t} = \sqrt{P_c t} \quad (2.5)$$

$$\frac{M(t)}{A} = C \sqrt{t} \quad (2.6)$$

Capillary imbibition is a crucial phenomenon in porous rocks, influencing their durability over time (Fig. 2.9). Deterioration by salt and ice crystallisation, as well as other processes, such as mineral hydration and oxidation, can be prompted by capillary absorption (Benavente et al., 2018; Cueto, 2020). The imbibition kinetics is activated from pore sizes > 0.1 µm but reaches maximum water absorption rates for pores between 1–100 µm (Fig. 2.9; Benavente, 2011; Benavente et al., 2018).

- Sharp Front model

The cumulative absorption kinetics (i) over time ($t^{1/2}$) in rocks with a non-uniform pore size distribution are best described by the Sharp Front (SF) model (Philip, 1957; Ioannou et al., 2008, 2009), which accounts for distinct stages of imbibition kinetics. In this model, sorptivity (rate of fluid absorption by capillarity) is considered equivalent to capillary imbibition, making sorptivity a direct measure of the capillary imbibition rate (Philip, 1957; Hall and Hoff, 2021).

During the initial stage, imbibition kinetics (i) is linear with respect to $t^{1/2}$, and the slope of this relationship represents the early sorptivity of the rock. In the subsequent transitional phase, absorption deviates from this linear behaviour due to the presence of larger pores. Eventually, in a later stage, linearity in $t^{1/2}$ is reestablished, albeit with a reduced slope corresponding to the matrix sorptivity. The process reaches its final stage when the wetting front approaches the end of the specimen, and water absorption slows substantially (Hall and Hoff, 2021).

These stages are linked to pore size distribution. During the transitional phase, water is primarily absorbed through larger pores (or aeration pores, with ~0.1–1 mm in diameter – Hall and Hoff, 2021), which exhibit low capillary suction and are not adequately described by the standard $t^{1/2}$ sorptivity law. Instead, this behaviour is captured by an intermediate anomalous absorption coefficient (C_a). If gravitational effects are significant during this stage, equilibrium between gravity (downward force) and capillary forces (upward force) is reached rapidly. In the later stage, water absorption shifts to the finer matrix pores, where capillary forces dominate, and the kinetics follow the typical capillary absorption behaviour, described by the matrix absorption coefficient (C_m).

- Sorption processes in volcano-hydrothermal systems

Depending on their size and connectivity, vesicles may control the escape of volcanic gases and, therefore, influence the explosivity of an eruption (Sparks, 1997; Edmonds et al., 2003). Most intrusive rocks and lava flows have a low-porosity matrix. However, their porosity dictates their capability to store fluids (Lu et al., 2023). If vesicles are interconnected by throats of varying sizes lower than 1 mm in radius, limited fluid transport can occur via capillary absorption at lower rates.

On the other hand, impermeable volcanic rocks with negligible connected vesicles have a fluid movement restricted to molecular-scale processes, such as diffusion or capillary condensation, depending on the RH. These rocks can act as effective impermeable barriers, trapping fluids such as hot water, steam, or magma at depth.

Permeability

For pore sizes > 1 mm (Fig. 2.9), fluid transport is governed by hydrodynamic principles, with gravity becoming increasingly significant (Hall and Hoff, 2021). The permeability of rocks determines the various types of fluid flow depending on connectivity, including matrix-driven flow, fracture flow, and conduit flow (Jamtveit and Yardley, 1996).

Permeability (k) represents a rock's ability to transmit fluid. Unlike porosity, which is a scalar quantity, permeability is a tensor and can be anisotropic. It links the laminar flow of a non-reactive fluid through a rock's cross-section area (A) with the fluid's viscosity and pressure. Absolute permeability describes the flow of a single-phase, non-reactive fluid, whereas effective permeability applies to multiphase systems (e.g., Schön, 2015). Fluid flow (u) is described by Darcy's law (1856), with permeability (k , in m^2) derived based on flow velocity, dynamic viscosity (η), and the pressure gradient (∇P), as shown in Eq. 2.7. While Darcy's law operates at a macroscopic scale, void space properties such as capillary radius and length are assessed at a microscopic level (Schön, 2015). Tortuosity quantifies the complexity of pore channels and is influenced by both porosity and the rock's microstructure.

$$k = \frac{u \eta}{\nabla P} \quad (2.7)$$

k is in m^2 (SI unit), but the industry often uses Darcy (D; $1 \text{ D} = 0.9869 \times 10^{-12} \text{ m}^2$) and millidarcy (mD). In this thesis, permeability values are reported in mD.

As a property of the porous system, k is influenced by n_{eff} pore size, and fracture width (Schön, 2015). Intra- and intergranular pores may store large fluid volumes but often provide limited connectivity, with fluids percolating under pressure gradients. In contrast, fractures and channels enhance fluid flow. However, not all fractures contribute to permeability, as some may be sealed or disconnected from the flow network.

Hölting's classification (Hölting, 1989; Fig. 2.10) provides a permeability-porosity relationship for porous building stones, defining three groups based on mean pore-throat size. Each group reflect the correlation between water transport coefficients and pore size distribution in materials with $n_{eff} > 10\%$ (Benavente et al., 2015). From high to low permeability, the categories are: (1) non-vuggy pores visible to the naked eye, with pore-throat radii > 1 mm; (2) pore-throat radii between 1 mm and $0.5 \mu\text{m}$; and (3) pore-throat radii $< 0.5 \mu\text{m}$.

In addition to influencing fluid transport, pores larger than 1 mm also compromise the mechanical strength of the rock (Fig. 2.9). Consequently, the durability of stone materials may be implicated, whereas the renewal of permeability in volcano-hydrothermal systems may be facilitated by brittle failure.

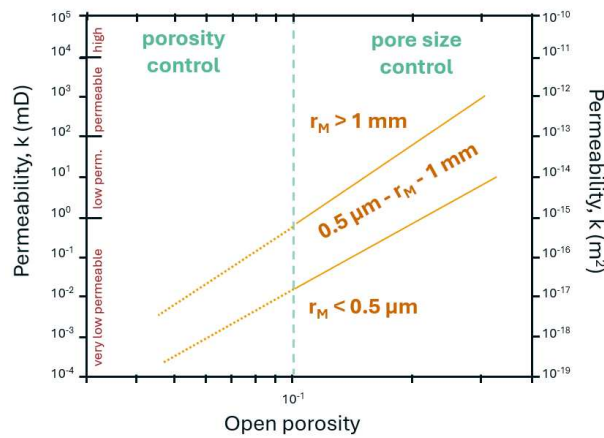


Fig. 2.10 Hölting's classification (Hölting, 1989) of rocks based on the relationship between open porosity, mean pore-throat radius (r_M), and permeability (k). Adapted with from Benavente et al. (2018) with permission. License obtained by the author of the thesis.

The contribution of fractures to permeability in volcano-hydrothermal systems is scale-dependent and relies on factors, such as porosity and fracture-sealing (Lamur et al., 2017). Large-scale discontinuities can facilitate the upward migration of magmatic and hydrothermal fluids, even through low-porosity lavas or intrusive rocks. Thus, the fracture networks enable heat

transfer and fluid flow, potentially facilitating an eruption (Gonnermann and Manga, 2007; Fairley, 2009; Stimac et al., 2015; Heap et al., 2019; Lavallée and Kendrick, 2021).

By sustaining the reservoir permeability and allowing for the circulation of fluids, discontinuities favour hydrothermal alteration. In this scenario, dissolution and precipitation are two competing processes. The dissolution of primary phases creates or rejuvenates fracture networks, with the extent of dissolution depending on pressure, temperature, and fluid chemistry (e.g., Farquharson et al., 2019). On the other hand, mineral precipitation seals the fractures, decreasing the porosity and permeability of the system. As a result, the fault-fracture networks dictate the distribution of secondary minerals within the upper crust (Callahan et al., 2019; Kennedy et al., 2020). With increasing sealing, the fluid pressure within the pores increases until new fractures are developed, restarting the cycle (Siratovich et al., 2016; Kennedy et al., 2020).

2.1.3. Ultrasonic wave velocity

Although considered dynamic, ultrasonic or acoustic wave velocities are also classified as physical properties. These velocities can be measured non-destructively in the laboratory using transducers at high frequencies, with calculations based on the specimen's length and the arrival time of ultrasonic waves.

Ultrasonic velocities include compressional or longitudinal P-wave velocities (V_p) and shear or transverse S-wave velocities (V_s). They are scale-dependent and influenced by the rock's crystallinity, mineralogy, porosity, and degree of saturation (e.g., González de Vallejo and Ferrer, 2011; Lesage et al., 2018). Denser and more compact rocks typically have higher ultrasonic wave velocities. However, the attenuation of ultrasonic waves is complex and linked to defects in the rock matrix (e.g., grain contacts, fractures), to the proportion and distribution of pores and fractures, and the fluids within them (Schön, 2015).

V_p and V_s are functions of the elastic properties of the rocks and can provide indirect insights into the stiffness of rock. They are used to derive dynamic properties, namely the dynamic Young's modulus (E_d ; GPa) and dynamic Poisson's ratio (ν_d), which typically double their static equivalents due to the nonlinear stress dependence of the static data (e.g., González de Vallejo and Ferrer, 2011). Additional moduli, such as the shear modulus (G) and the bulk modulus (K), can also be calculated using V_p and V_s . G reflects the resistance to shear deformation, while K expresses resistance to volumetric compression (e.g., Acocella, 2021). Dynamic elastic variables

also help in assessing rock anisotropy and heterogeneity (Hudson and Harrison, 2000), which is useful in analysing fractured rock masses (Hencher, 2015).

The P- to S-wave velocity ratio (V_p/V_s) is used for seismic subsurface characterisation due to its sensitivity to variations in rock and fluid properties, including porosity, mineralogy, fluid type, and effective stress (Bustos and Adam, 2023, and references therein). Indeed, in seismic tomography analysis, the V_p/V_s ratio along depth allows for the identification of magma and gas flows in volcanic settings (Vargas et al., 2017).

Laboratory V_p/V_s data provide complementary information to field-scale interpretations, clarifying the impact of other physical properties on the ratio, which is common in volcanic rocks due to their complex pore structures. V_p/V_s ratio varies markedly in fractured rocks, where the low aspect ratio of cracks leads to distinct behaviour compared to more equant (spherical) voids, which are less affected by increasing effective pressure (i.e., depth) (Bustos and Adam, 2023).

2.1.4. Physical properties data for volcanic rocks

This chapter incorporates data previously published by Pereira et al. (2024a)², developed within the scope of this doctoral research. Selected results and adapted excerpts are cited and integrated throughout this chapter following Universidade dos Açores rules, also aligning with the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0).

Pereira et al. (2024a) compiled data from the literature on both unaltered and altered rocks, mostly volcanic in nature. Fig. 2.11 presents average values for porosity (Fig. 2.11a), density (Fig. 2.11b), permeability (Fig. 2.11c), and ultrasonic wave velocities (Fig. 2.11d) in igneous rocks. Generally, low-porosity volcanic rocks have higher density and ultrasonic wave velocities, and lower permeability. These trends, consistent with previous studies (e.g., Pereira et al., 2021), are further supported by the biplots in Fig. 2.12, which displays the relationship among physical properties of fresh igneous rocks (Pereira et al., 2024a).

² Pereira, M.L., Zanon, V., Fernandes, I., Pappalardo, L., and Viveiros, F., 2024a, Hydrothermal alteration and physical and mechanical properties of rocks in a volcanic environment: A review: *Earth-Science Reviews*, <https://doi.org/10.1016/j.earscirev.2024.104754>. Licensed under CC BY 4.0

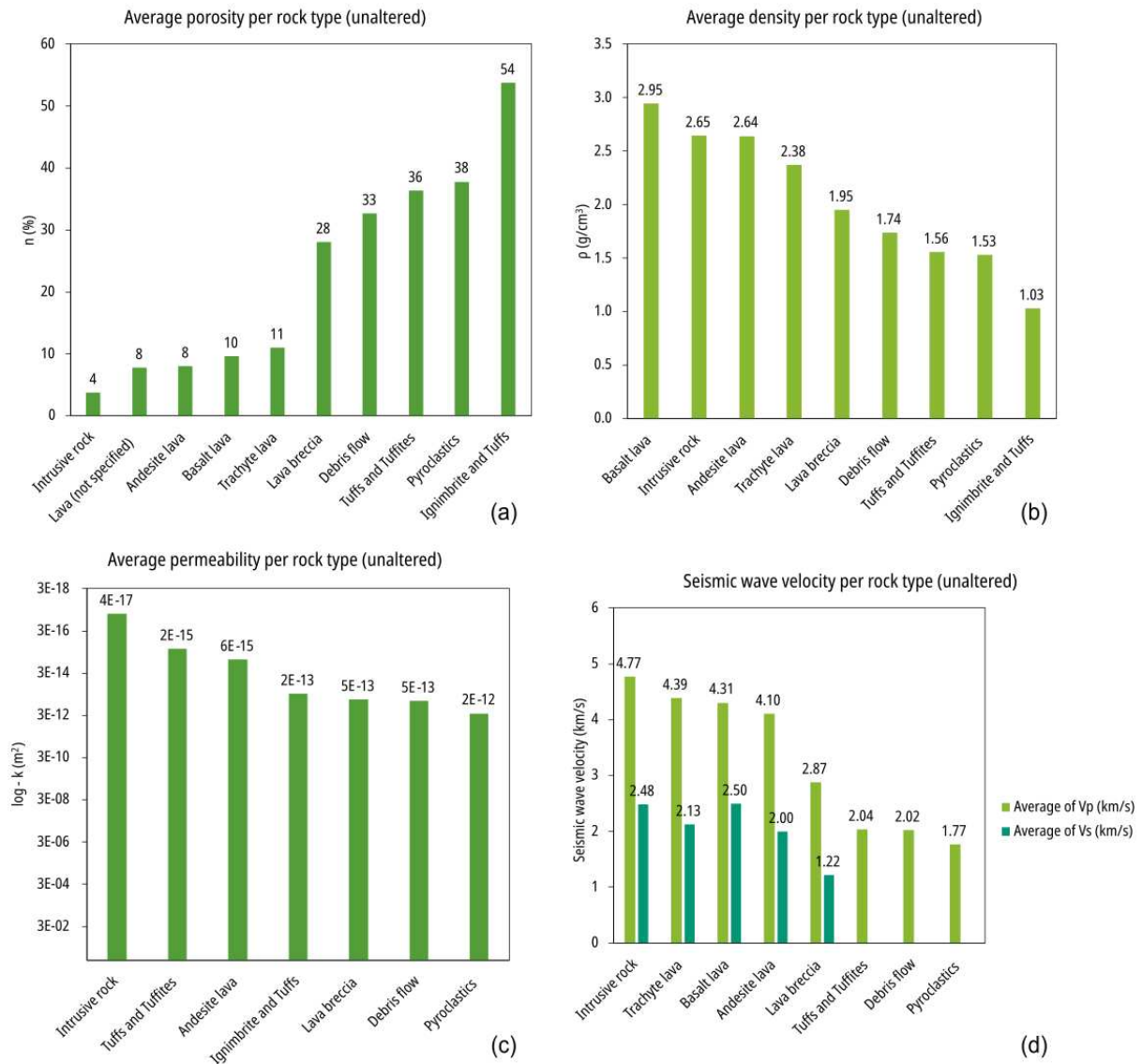


Fig. 2.11. Average values of physical properties – (a) porosity; (b) density; (c) permeability; (d) seismic wave velocity - for several types of fresh igneous rocks, including intrusive rocks, lavas and pyroclastic materials. The data was compiled by Pereira et al., (2024a) (see references therein). Reproduced from Pereira et al. (2024a). Licensed under CC BY 4.0.

Porosity has a linear negative correlation with density and V_p (Fig. 2.12a and Fig. 2.12d), whereas V_p increases linearly with increasing ρ (Fig. 2.12e) and V_s (Fig. 2.12c). Permeability has a nonlinear and positive relationship with porosity (Fig. 2.12b), as previously found (Kanakiya et al., 2022). However, the performance of the regression analysis, given by the coefficient of determination (R^2), is weak, indicating that permeability and porosity do not have a straightforward relationship.

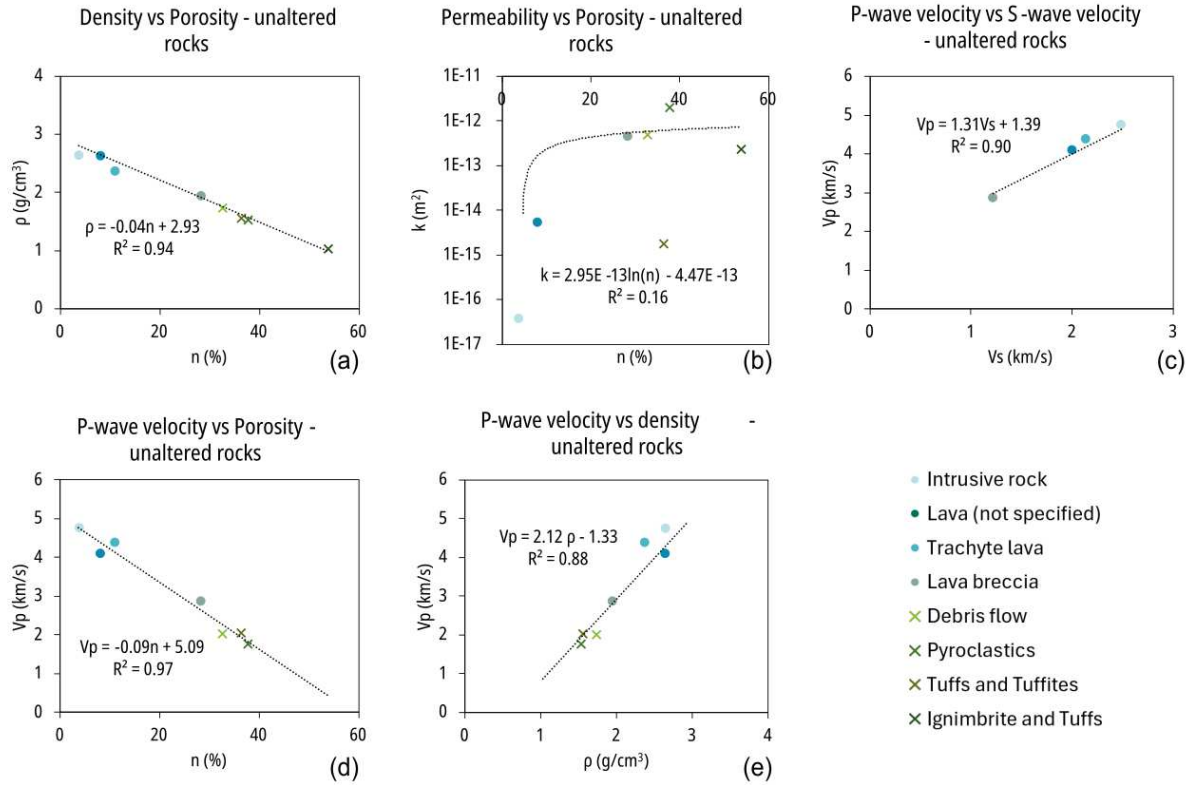


Fig. 2.12. Generalised correlation between physical properties for several rock types, including intrusive rocks, lavas, and pyroclastic rocks. (a) porosity vs. density; (b) porosity vs. permeability; (c) S-wave velocity vs. P-wave velocity; (d) porosity vs. P-wave velocity; (e) density vs. P-wave velocity. Reproduced from Pereira et al. (2024a). Licensed under CC BY 4.0.

Density

As shown by Pereira et al. (2024a), density (Fig. 2.11b) is generally higher in lava rocks, ranging on average from 1.95 to 2.69 g/cm³, than in fragmental materials, which typically span from 1.03 to 1.74 g/cm³. Lava breccias (1.95 g/cm³) represent an intermediate case due to their highly fractured nature. These values are consistent with previous studies reporting densities for volcanic rocks between 1.00 and 3.30 g/cm³ (Lavallée and Kendrick, 2021), reflecting their diverse compositions and complex pore structures, features also present in sedimentary rocks (Schön, 2015).

In igneous rocks, density tends to increase from felsic to mafic compositions. Basalts typically range from 2.40 to 3.20 g/cm³, while rhyolites are less dense, with a narrower range between 2.10 and 2.60 g/cm³ (Schön, 2015). These trends are corroborated by the average values in Pereira et al. (2024a), which report higher densities for basalts (2.95 g/cm³) compared to andesites (2.64 g/cm³) and trachytes (2.38 g/cm³).

Pore system: Porosity and permeability

Because of the complex origin processes, volcanic rock porosity spans from less than 1% to as high as 97% (Lavallée and Kendrick, 2021) because of the variable microstructure, which is classified into pore-dominated and microfractured types (Lamur et al., 2017; Cant et al., 2018). Pore-dominated rocks are generally less compressible and maintain their permeability under increasing confining pressure, whereas microfractured rocks experience a significant permeability reduction with burial depth due to fracture closure under stress (Nara et al., 2011; Cant et al., 2018).

Similar to other lithologies, fluid transport mechanisms in volcanic rocks depend on connected porosity, pore size, and pore geometry (Heap et al., 2014a; Heap et al., 2014b; Cant et al., 2018; Cueto, 2020). Rocks with a prevalence of isolated pores can exhibit low permeability despite having a high total porosity, which explains the weak correlation observed in Fig. 2.12b (Pereira et al., 2024a). Regardless of the volcanic rock type, the presence and connectivity of discontinuities and vesicles define their n_{eff} and k , as well as the subsequent fluid dynamics.

Data compiled by Pereira et al. (2024a) show that pyroclastic rocks display a broader porosity range (38 – 54%) compared to lava rocks (4 – 11%). Several research have proposed that porosity is less influenced by mineralogy than by the microstructure, which results from the different tectonic and volcanic processes, including vesiculation, fragmentation, and compaction (Kennedy et al., 2010; Lamur et al., 2017; Colombier et al., 2017a). Pyroclastic rocks also tend to be more permeable ($\geq 2 \times 10^{-13} \text{ m}^2$) than lava flows ($\leq 6 \times 10^{-15} \text{ m}^2$), although porosity reduction with depth is not always systematic due to processes like compaction (Wyering et al., 2014; Stimac et al., 2015; Cant et al., 2018; Durán et al., 2019).

Lava breccias and debris flows represent transitional rock types. Due to their significant fracturing, lava breccias display high porosity (~38%) and the highest permeability values among the analysed rock types, indicating a well-connected pore network (Pereira et al., 2024a). Such a unit can have potential in maintaining productive geothermal reservoirs.

Ultrasonic wave velocity

The wave velocity in igneous rocks increases from acidic felsic to basic/mafic members (Schön, 2015), which is also verified by Pereira et al. (2024a). Basalt has higher ultrasonic velocities ($V_p = 4.31 \text{ km/s}$ and $V_s = 2.50 \text{ km/s}$) than andesites ($V_p = 4.10 \text{ km/s}$ and $V_s = 2.10 \text{ km/s}$). In contrast, trachytes display the highest elastic wave velocities ($V_p = 4.39 \text{ km/s}$ and $V_s = 2.13 \text{ km/s}$), which

either indicates velocity reduction in andesites due to heterogeneities or favourable textures in the trachyte to wave propagation (Pereira et al., 2024a). However, average values of V_p and V_s presented by Pereira et al. (2024a) for fresh lavas are near or below the minimum values reported by Schön (2015) for basalts ($V_p = 4.5\text{--}6.2$ km/s and $V_s = 2.4\text{--}3.4$ km/s), andesites and trachytes ($V_p = 4.0\text{--}6.2$ km/s and $V_s = 2.4\text{--}3.5$ km/s).

The extensive fracturing in lava breccias led to reduction in ultrasonic wave velocity ($V_p = 2.87$ km/s and $V_s = 1.55$ km/s) in respect to lavas, and the fragmental rocks have $V_p < 2.25$ km/s in average (Pereira et al., 2024a). Thus, dynamic properties typically show lower values in rocks with higher porosity and lower density.

The variable types of porosities in volcanic rocks, especially fractures, scatter the data on ultrasonic wave velocities, as well as in V_p/V_s ratios (Bustos and Adam, 2023). V_p/V_s ratio of 1.6 to 1.8 was modelled for dry rocks (Wang et al. 2012), 1.8–2 and 1.5–2.4 was determined experimentally for basalts (Japsen and Mavko, 2006) and basaltic andesites (Lesage et al., 2018), respectively.

2.1.5. Physical properties in the scope of the doctoral research

In the Azores, the geology is composed of lava flows interlayered with pyroclastic deposits, resulting in different physical properties that lead to variable fluid flow. While permeability is often studied, capillary absorption remains poorly understood in volcanic rocks. Based on the state-of-the-art, it is concluded that in lavas, which have a wide range of pore sizes and porosities, capillarity likely participates in fluid transport. This knowledge gap is especially relevant, as sorption mechanisms are of interest in geothermal reservoir characterisation (e.g., Shang et al., 1995), and for hazard assessments, since water absorption can contribute to slope weakening (Heap et al., 2023) or to explosive eruptions (Thiéry and Mercury, 2009).

Additionally, connected porosity has been established as a crucial factor that constrains permeability (e.g., Lamur et al., 2017; Fig. 2.9), capillarity (e.g., Cueto, 2020), and mechanical strength (e.g., Pappalardo et al., 2017) of rocks. Defining its role on Azorean lavas with distinct textures and compositions would expand the current knowledge on these materials.

Understanding how fluids move through volcanic rocks begins with characterising their physical properties and assessing their capillary absorption. This work takes a step toward that goal by answering the research question presented in Chapter 1 and using Azorean lava rocks as a case study with broader global relevance.

2.2. Mechanical properties

Rock deformation and failure are fundamental topics of geomechanics. A rock, when deformed by a stress field, can produce different responses. The deformation of the rock occurs when its behaviour is controlled by the elastic properties of the rock, such as Young's modulus (E) and Poisson's ratio (ν). The rock can experience failure, which is dictated by strength properties, namely compressive strength (σ_c), tensile strength (σ_t), cohesion (c), and angle of internal friction (ϕ). The determination of these parameters is essential for solving geomechanical problems, including deformation and failure due to late stress fields, landslides, underground excavation, wellbore stability and fracturing, amongst others (e.g., Schön 2015). Each mechanical variable and the modes of rock deformation are first theoretically exposed in this chapter and then framed in the context of volcano-hydrothermal environments to clarify their importance.

2.2.1. Stress-strain curve

The stages of progressive deformation of the intact rock and its ultimate failure result from progressive damage accumulation, comprising nucleation, propagation, and coalescence of micro- and macrocracks (e.g., Li et al. 2024 and references therein). The stress-strain response under uniaxial compression is described in five stages (Fig. 2.13): i) crack closure; ii) linear-elastic deformation; iii) crack initiation and stable crack growth; iv) crack damage and unstable crack growth; and v) failure and post-failure response.

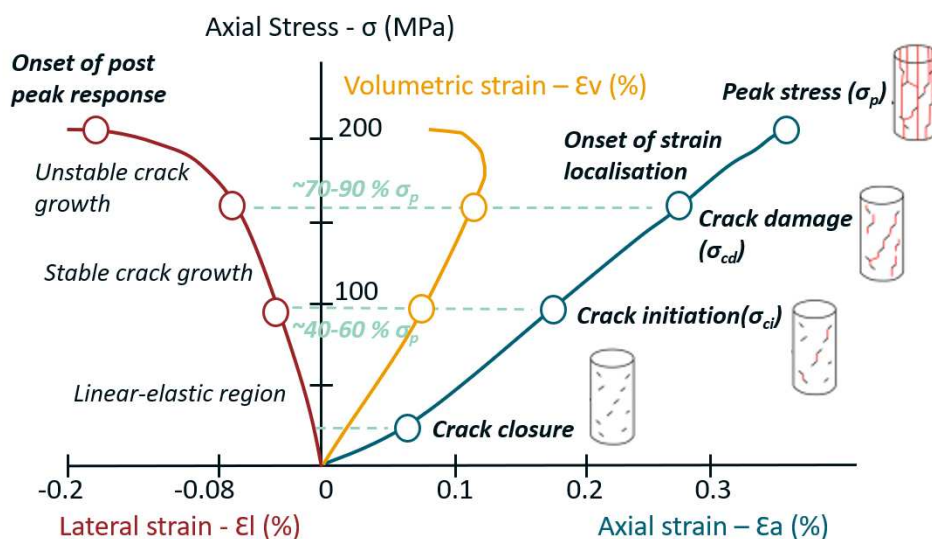


Fig. 2.13. Theoretical stress-strain curve from uniaxial compressive loading. Based on Hoek and Martin (2014) and Pepe et al. (2018), with permission. License obtained by the author of the thesis.

The closure of pre-existing cracks characterises the initial stage of the loading path and gives a concave shape to the stress-strain curve, given the gradual increase of axial strain. By further increasing the axial stress (loading), the rock deforms elastically, leading to a linear stress-strain region of the curve, which follows the principles of elasticity (Hooke's law). The stiffness of the rock, described by the Young's modulus (E), is obtained from this portion of the stress-strain curve. Then, the rock reaches the crack initiation stress (σ_{ci}), commonly ~ 40 - 60% of the peak stress (e.g., Martin and Christiansson, 2009), which corresponds to the nucleation and propagation of microcracks following a stable growth. Such microcracks are mostly oriented parallel to the axial loading, deriving from wing cracks (e.g., Ashby and Sammis, 1990). With increasing stress and around ~ 70 - 90% of the peak stress (e.g., Martin and Christiansson, 2009), the crack damage stress (σ_{cd}) marks the onset of strain localisation, corresponding to a dilatancy boundary that defines the long-term strength of the material (Martin and Chandler, 1994). Onwards, unstable crack growth starts to take place, with an increasing time-dependent damage propagation associated with the coalescence of fractures (e.g., Basu and Mishra, 2014). Increasing stress ultimately results in the failure of the rock at the peak stress (σ_p). The developed macroscopic fractures – shear (typically inclined at an angle of less than 45°) and extension (or axial splitting) - characterise the two principal modes of brittle failure (Griggs and Handin, 1960). Shear fracture prevails in triaxial tests, whereas extension fractures are more common in unconfined compressive tests (Paterson and Wong, 2015).

Crack stress initiation (σ_{ci}) and damage (σ_{cd}) restrict the development of damage in the rock (Li et al., 2024). Their determination in the literature is mainly limited to intrusive igneous rocks (Nicksiar and Martin, 2012; Nicksiar and Martin, 2013; Nicksiar and Martin, 2014) and metamorphic and sedimentary rocks (Pepe et al., 2018 and references therein; Peng et al., 2018 and references therein), which means that little is known regarding the crack thresholds for volcanic rocks. Crack threshold determination is often based on the volumetric strain (ϵ_v ; Eq. 2.8), which depends on the axial strain (ϵ_a ; Eq. 2.9) and lateral/transverse strain (ϵ_l ; Eq. 2.10). σ_{ci} corresponds to the point where ϵ_v departs from linearity, and σ_{cd} coincides with the reversal of ϵ_v . Nicksiar and Martin (2012) review other procedures for crack threshold determination.

$$\epsilon_v = \epsilon_a + 2\epsilon_l \quad (2.8)$$

$$\epsilon_a = \frac{\Delta l}{l_o} \quad (2.9)$$

$$\epsilon_l = \frac{\Delta x}{x_o} \quad (2.10)$$

where l_0 and x_0 are the original measured axial and lateral length, respectively, and Δl and Δx are their variation axially and laterally, respectively.

2.2.2. Deformation types and micromechanisms

The rock's deformation can be classified into *elastic* and *inelastic* (e.g., Jaeger et al., 2007). The elastic behaviour corresponds to the linear portion of the stress-strain curve (Fig. 2.13), where there is no explicit time dependence. A rock, when elastic, does not undergo internal, microscopic degradation during deformation, returning to its initial state when stresses are removed. For the *inelastic* behaviour, the rock deforms irreversibly, being considered plastic when it is not rate-dependent (Jaeger et al., 2007).

A finite yield stress (σ_y) must be reached to achieve plasticity, and its clear onset in the stress-strain curve depends on the rock and confinement (Mogi, 2006). Under unconfined conditions and brittle failure of rocks, σ_y is less perceptible compared to rock deformation with confining pressures. The post-peak behaviour of rocks also varies, either experiencing strain-softening (stress drop for a substantial inelastic strain - Fig. 2.14a) or strain-hardening (stress-strain curve continues to rise with a lower slope - Fig. 2.14b). The rock behaviour is elastic-perfectly plastic when strain continues to increase for a constant σ_y (see Jaeger et al., 2007).

Strain softening is more often observed in soft and less explosive rocks. A hard, competent rock, on the other hand, has an abrupt stress drop. Brittle rocks, such as lavas, can experience some extent of strain-softening when they are in a transitional deformation mode between the brittle and ductile. This process is observed for lavas with significant porosity, such as the trachyandesites represented in Fig. 2.14, with porosities ranging from 18 % to 21 %. Strain-softening is rather more common in pore-dominated rocks, such as tuffs, especially when altered (Marmoni et al., 2017).

The overall mechanical behaviour of rocks is usually classified as *brittle* and *ductile*. *Brittle failure* comprises the crushing and reorganisation of the grains and the coalescence of microcracks, forming a macroscopic and *localised fracture*, typically a shear fracture (Wong and Baud, 2012). Brittle failure commonly leads to an increase in porosity and permeability and induces *dilation* of the rock (Fig. 2.14A). Brittle fracturing is permanent, as distortion remains when stress is removed (e.g. Acocella, 2021). The micromechanisms subjacent to deformation are microcracking and frictional sliding (Heap and Violay, 2021).

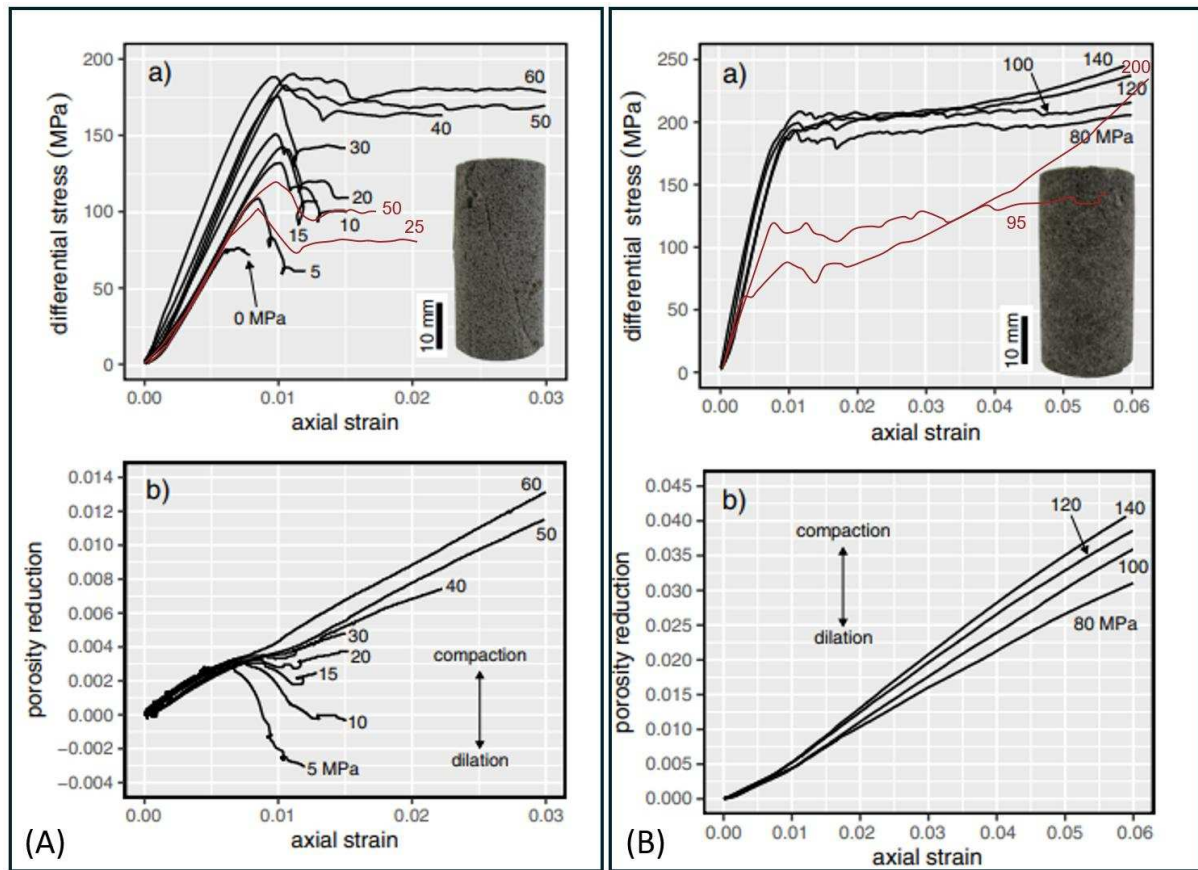


Fig. 2.14. Example of the behaviour of trachyandesites, with a deformation characterised as (A) brittle and (B) ductile. Plots from Heap and Violay (2021) regarding a Volvic trachyandesite with 21 % of porosity (black lines). The lavas are brittle up to 50 MPa forming a macroscopic shear fracture. From 40-60 MPa, the lava behaves in a transitional way (BDT). Above 60 MPa, the lava is ductile and presents strain hardening. A similar behaviour is found for a trachyandesite collected in the Azores ($n = 18\%$; represented by the red lines) tested by Loaiza et al. (2012), which only becomes ductile above 95 MPa. The values next to each curve correspond to the experimental effective pressure (in MPa). Figure adapted from Heap and Violay (2021). Licensed under CC BY 4.0.

Ductile behaviour is defined as “the capacity of a material to deform to a substantial strain without the tendency to localise the flow into faults” (Rutter, 1986), producing typically a pervasive deformation characterised by the absence of strain softening and with the compaction of the rock specimen (Fig. 2.14B). Ductile behaviour results from a series of microstructural deformation mechanisms, such as diffusional processes (or diffusional flow), crystal plasticity, and microcracking, which are known to depend on pressure, temperature and strain rate (e.g., Passchier and Trouw, 2005; Heap and Violay, 2021). For example, cataclastic flow, which is often associated with ductility, refers to a combination of microcracking and granular flow (Paterson and Wong, 2005). The definition proposed by Rutter (1986) lacks a mechanistic connotation in that microcracking can lead to either a brittle or ductile mode of failure. Therefore, ductile deformation can be perceived as a scale-dependent structural failure mode, as the microscale

deformation process is achieved through a range of deformation mechanisms, including brittle and plastic deformation (e.g., Acocella, 2021).

Alternatively, several authors prefer the terms *dilatant* and *compactant* (e.g. Heap et al., 2015a; Heap and Violay, 2021; Fig. 2.14b). Dilatancy is observed as a precursor to brittle faulting in both compact and porous rocks, while failure by cataclastic flow may be accompanied by a negative or positive change in volume, depending on the original porosity of the rock (Paterson and Wong, 2005).

Ductile deformation mechanisms have been extensively and first studied for sedimentary rocks, such as limestones and sandstones (Wong and Paterson, 2005; Wong and Baud, 2012). Noteworthy, ductile deformation can either be *distributed* and associated with the “flow” of the rock or *localised*.

The micromechanisms subjacent to distributed ductile deformation is *cataclastic flow* (i.e., microcracking or permanent strain due to distributed fracturing – Gudmundsson, 2011) for both limestones and sandstones or *grain crushing* in sandstones and *cataclastic pore collapse* in limestones (Wong and Baud, 2012 and references therein).

Localised ductile deformation is associated with the formation of compaction bands, which correspond to zones of lower porosity, typically with a thickness of 0.5–1.5 mm in porous materials (Wong and Baud, 2012). The type of compaction is thought to derive from the heterogeneity of the rocks, in particular grain size distribution (Wong and Baud, 2012). For instance, sandstones with wide grain size distribution deform through cataclastic flow and compaction, while sandstones with homogenous grain size distribution tend to form compaction bands. The failure mode of sandstones also depends on other microstructural parameters, such as grain size, clay content, cementation, bedding, pore size, type of porosity, and saturation degree (Wong and Baud, 2012). For limestones, there is an interplay between pore collapse, cleavage cracking, and twinning (see Wong and Baud, 2012).

Deformation of Lava Rocks

Understanding the failure mode of volcanic rocks, i.e., if they are ductile or brittle, has gained more notoriety in recent years, as such data may predict instability produced by faulting in a volcano (Lagmay et al., 2000) and volcano spreading (e.g., van Wyk de Vries and Francis, 1997). In addition, quantifying the strength and elastic properties is relevant for modelling the stability of a rock mass or a volcanic edifice containing such materials (e.g., Voight, 2000).

Lava rocks might start to transit from brittle to ductile under room temperature at confining pressures as low as 40 MPa, depending on their porosity (Fig. 2.14). Such pressures are relevant for volcanic edifices and volcano-hydrothermal settings, representing few kilometres of depth (Heap et al., 2015a). Research on the failure mode of lavas has focused on basalts (Adelinet et al., 2013; Zhu et al., 2016), trachyandesites to basaltic trachyandesites (Loaiza et al., 2012; Zorn et al., 2018; Heap and Violay, 2021), and andesites (Heap et al., 2015a). Heap and Violay (2021) present an important review on the subject. In general, volcanic rocks show similar stress-strain curves to those of porous sedimentary rocks (Heap and Violay, 2021).

Microstructural investigations of deformed lavas show cataclastic flow, collapse of pores and crushing of crystals (Shimada, 1986) or localised compaction bands (Loaiza et al., 2012; Adelinet et al., 2013; Heap et al., 2015a). High-pressure and high-temperature experiments on porous lavas reveal that increasing the temperature above the glass transition temperature changes the deformation mechanism from cataclastic pore collapse to viscous flow and the failure transitions from localised to distributed (Heap et al., 2017). Conversely, porous tuffs (Zhu et al., 2011; Marmoni et al., 2017) mostly experience cataclastic pore collapse. The various failure micromechanisms of volcanic rocks result from a combination of microstructural attributes, including microcrack density, porosity, pore size distribution, and pore shape (Heap et al., 2014a, 2014b, 2015a).

Porosity is a determinant factor in the rock mechanics of lavas that evolves and modifies throughout time and loading (Heap and Violay, 2021). Other factors, such as mineralogy, crystallinity, granularity, and preferred mineral orientation (e.g. Coats et al., 2018; Zorn et al., 2018), contribute to the variable mechanical behaviour of volcanic rocks. Moreover, porosity reduction is often used as a proxy for dilation or compaction in the rock (Heap et al., 2015a; Marmoni et al., 2017; Heap and Violay, 2021; Fig. 2.14).

The confining pressure also dictates the progress of deformation and failure mode. For low confining pressures (shallow depths), both low- and high-porosity rocks have a dilatant failure mode. With increasing confining pressure (depth), while low-porosity rocks will remain brittle, porous rocks will undergo compaction (Fig. 2.14).

As exposed in Section 2.1.1 (Part B), other external factors, such as temperature, strain rate, pore-fluid pressure, dominant stress field, large-seismic events, the influx of new magma and outgassing, and hydrothermal alteration, can promote a variation of the brittle-ductile transition at depth (Fournier, 1999; Meyer et al., 2019). Laboratory investigations on fresh and altered

volcanic rocks can help constrain these variations and predict the BDT depth at the base of volcanic edifices and calderas (Parisio et al., 2019). Moreover, high temperatures and high pressures cause lavas to deform through viscous flow, making them more prone to a greater extent of porosity reduction, with implications for increased pressure in volcanic systems (Heap et al., 2017).

2.2.3. Elastic properties

Young's modulus or modulus of elasticity (E) represents the stiffness of a rock and is defined as the ratio of the stress and the resulting axial strain (Eq. 2.11). E is calculated in the elastic regime of the stress-strain curve, corresponding to its slope, and is usually presented in GPa.

$$E = \frac{d\sigma}{d\epsilon_a} \quad (2.11)$$

There are several calculating methods for E in engineering practice (ISRM, 2007; ASTM D7012-23, 2023). The secant modulus (E_{sec}) is defined as the ratio of the total stress to the total strain (from the origin until a fixed percentage of the peak stress), containing the nonlinear initial part of the stress-strain curve. The tangent modulus (E_{tg}) commonly corresponds to the slope of the curve in a fixed percentage, usually 50 % of the peak stress. The average elastic modulus (E_{avg}) corresponds to the linear portion of the stress-strain curve. Young's modulus is also related to the modulus of rigidity (G) and bulk modulus (K), which are only assessed based on dynamic properties and, therefore, mentioned in Chapter 2.1.3 (Part C).

The scale effect also influences the Young's modulus, as the laboratory-measured E is higher than the Young's modulus of the rock mass (E_{rm}) affected by discontinuities. Upscaling laboratory measurements can be performed using the Hoek and Diederichs equation (Eq. 2.12; Hoek and Diederichs, 2006), which is based on the E of the intact rock and the GSI of the rock mass. D is the disturbance factor due to the excavation or natural slope features and null when no perturbations occur in the rock mass. In addition, Heap et al. (2020a) propose a "depth correction" of the E for the intact rock (Eq. 2.13) to account for crack closure and depth (z). Nevertheless, it remains unclear to what extent the Hoek and Diederichs equation is suitable for predicting E_{rm} at depth, at several kilometres (Heap et al., 2020a).

$$E_{rm} = E \left(0.02 + \frac{1 - \frac{D}{2}}{1 + e^{\left(\frac{60+15D-GSI}{11}\right)}} \right) \quad (2.12)$$

$$E_{(z)} = -6.07 \times 10^{-7} z^2 + 7.90 \times 10^{-3} z + E \quad (2.13)$$

According to Gudmundsson (2020), in a basaltic volcanic edifice, the several E vary by one or two orders of magnitude, while for a stratovolcano, between three and possibly four orders of magnitude. Stratovolcanoes are associated with heterogeneous local stress fields, which partly promotes the arrest of their dykes (Gudmundsson, 2006; Section 2.2.1, Part B). Moreover, static E are commonly considered for the modelling of dyke emplacement and other hydrofractures (Gudmundsson, 2011).

Poisson's ratio (ν) is described as the ratio of the lateral/transverse strain to the longitudinal/axial strain (Eq. 2.14). It represents the volumetric change of a rock, being less than 0.5 (Jaeger et al., 2007). In other words, ν measures the tendency of a rock to respond through dilation and shear or distortion when loaded, measuring the amount of shortening axially without thickening laterally (e.g., Acocella, 2021).

$$\nu = -\frac{\epsilon l}{\epsilon a} \quad (2.14)$$

The limited range of ν compared to E has important implications for rock behaviour and volcano-tectonic modelling (Gudmundsson, 2011; Gudmundsson, 2020). These models typically assume a uniform ν and variable E in a stratovolcano.

2.2.4. Strength properties

There are two modes of intact rock failure in the brittle field: tension (mode I) and shearing. The latter can be divided into "direct" or "in-plane" (mode II) and "simple" or "out-of-plane" (mode III) shear, a distinction commonly made in structural geology. As mentioned in Section 2.1.1 (Part B), extension fractures may develop in the Earth's crust, although shear fractures developed by shearing prevail (Hudson and Harrison, 2000; Gudmundsson, 2020; Section 2.2.2., Part A). The brittle failure in the crust governs processes of magma reservoir instability and magma transport, as exposed in Section 2.1.3 (Part B). Moreover, stiff rocks, such as lavas, typically associate with several types of discontinuities, such as columnar joints (Section 2.2.2, Part A). The role of discontinuities and hydrofractures in the stability of a volcano is variable, as stated in Section 2.2.1. (Part B), depending also on the host rock's strength.

Rock failure is described by strength envelopes, which can be derived either considering the minimum (σ_3) and maximum (σ_1) principal stresses (Fig. 2.15a) or the shear strength (τ) and normal stress (σ) (Fig. 2.15b). Rocks fail more easily through tension than through compression and González de Vallejo and Ferrer (2011) suggest that typically tensile strength is 5–10 % of the

uniaxial compressive strength. This chapter theoretically exposes the several types of strength (compressive and tensile) and includes a brief reference to the failure criteria commonly used in engineering practice, also with relevance for volcanic materials.

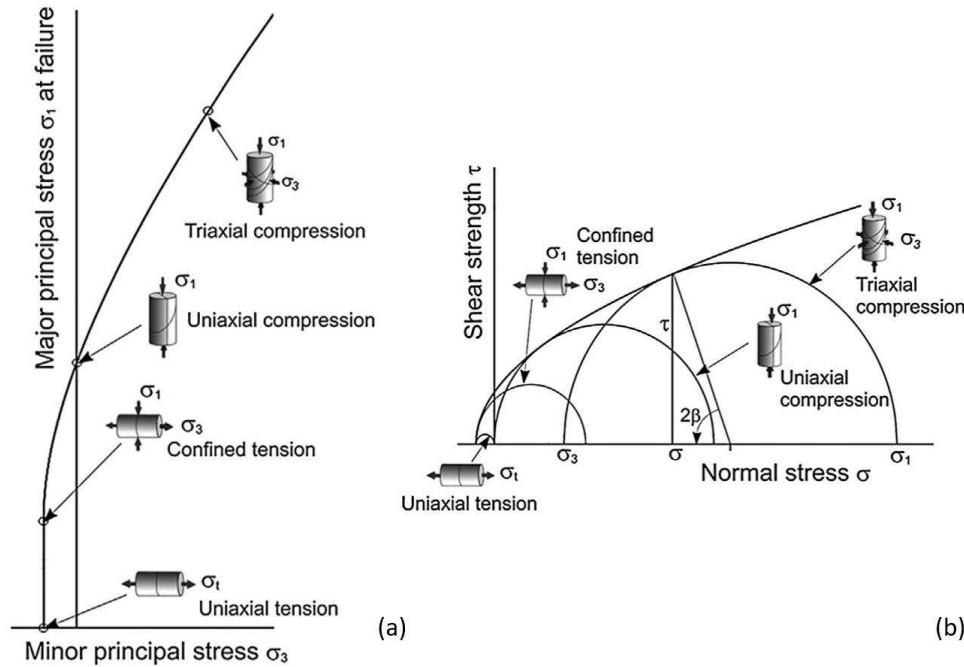


Fig. 2.15. Failure characteristics of intact rock plotted in terms of major (σ_1) and minor (σ_3) principal stresses (a) and Mohr circles (b) and respective envelopes. Figure from Hoek and Martin (2014) with permission. License obtained by the author of the thesis.

2.2.4.1. Compressive strength

Intact rock is frequently classified according to its compressive strength, which can be unconfined or confined. Failure occurs when the peak stress (σ_p) is reached, representing the compressive strength of the material and corresponding to the ratio of the loading force per the surface area subjected to the load.

Unconfined compressive strength ($\sigma_{c,UCS}$ or UCS) is one of the most common parameters considered in rock engineering practices and in strength determinations on rock cores (e.g., Xie et al. 2024) and is determined by the uniaxial test. Uniaxial tests consist of the loading of the specimen without confinement ($\sigma_2 = \sigma_3 = 0$) and are representative of the strength of the rock under such conditions. Thus, UCS is frequently used for slope stability analysis of volcanic rock masses (e.g., del Potro and Hürlimann, 2008; Schaefer et al., 2013; Villeneuve and Heap, 2021). At a larger scale, the brittle deformation of rocks is considered to dictate the stability of volcanic edifices and their flanks during unrest periods characterised by magma accumulation and dyking

(e.g., Voight, 2000). Together with E , the UCS is also an input in rock mass geomechanical classifications (Bieniawski, 1989; Miranda et al., 2018) and numerical models related to rock engineering problems (e.g., Abdelaziz and Grasselli, 2021 and references therein).

Despite the common determination of $\sigma_{c,UCS}$ in both structural and geotechnical practice, laboratory standards define strict requirements on the size and shape of the specimens to avoid stress concentrations (e.g., Hudson and Harrison, 2000). However, rocks can inherently contain defects (e.g., voids – pores and microcracks, phenocrysts, fossils, cleavage planes), which will affect the rock's strength. For instance, heterogeneity due to cleavage and schistosity is commonly considered in the UCS of schists and slates, respectively (e.g., Hencher, 2015). However, the role of heterogeneities is less explored for volcanic rocks despite their complex structures and textures, as discussed in Part A of the present work.

Triaxial tests are performed by applying confining pressures ($\sigma_2 = \sigma_3$; true triaxial tests are outside the scope of the thesis) while compressing axially (σ_1) the specimen. The tests are useful to assess and mimic, at least to some extent, the behaviour of rocks at depth, possibly establishing the confining pressures of the BDT in different geological settings (e.g., Violay et al., 2012) and for depths relevant to volcanic edifices and volcano-hydrothermal settings (Section 2.2.2, Part B). As pointed by Mogi (2006 and references therein), there are different mechanisms of the BDT for distinct rock types, explaining why silicate and carbonate rock have different fracture behaviour (brittle – little or no plastic deformation before collapse - or ductile – significant deformation before breaking) at different confinements.

Several rock specimens are tested at different confining pressures. If fluids are used, then effective pressures (difference between the confining pressure and the pore fluid pressure) are considered. Besides the peak stress that defines the compressive strength (σ_c) of brittle materials, shear parameters (c , ϕ) can be derived using the failure criteria (2.2.4.4, Part C). Considering isotropic rocks, σ_c increases with increasing confining pressure.

The failure of rock under triaxial conditions combines, at least at a microscale, tension and shear failure modes. Under the uniaxial test or triaxial test at low confining pressures, brittle rocks tend to fail through tensile splitting, developing fractures oriented parallel to the loading direction. Under moderate confining pressure, the axial fracturing is suppressed, and the plane of failure becomes inclined with respect to σ_1 , forming a shear fracture (Paterson and Wong, 2005). With increasing confining pressure, the rock eventually becomes ductile, and a network of small shear

fractures is formed, accompanied by plastic deformation of the rock grains (Jaeger et al., 2007). Shear fracturing can also be characterised by conjugate shear fractures (Basu et al., 2013).

2.2.4.2. Shear strength

Shear fractures, generated by shear stresses, correspond to faults forming at any crustal depth (Gudmundsson, 2011). The shear strength (τ) of a rock describes its ability to resist shear stress before failure, depending on the normal stress (σ), cohesion, and friction along the fracture plane. Data can be experimentally obtained from both triaxial tests and direct shear tests (e.g., Aydan, 2019) and failure criteria (e.g., Byerlee's law; Mohr-Coulomb – see Chapter 2.4.4.5, Part C) are used to derive the fitting parameters.

Cohesion (c) of the rock is a linear function of E and represents the internal force holding the particles of the rock together. The internal friction angle (ϕ) and the coefficient of internal friction (μ) describe how resistant a rock is to the shear failure produced by the internal friction between its grains, varying from 15° to 35° (Byerlee, 1978).

While c and ϕ are often reported in engineering practice, their assessment for volcanic remains less explored (Ball et al., 2018).

2.2.4.3. Tensile strength

The tensile strength (σ_t) describes the maximum stress a rock can sustain under tension. However, the determination of direct tensile strength is complex and time-consuming. The Brazilian test (ISRM, 2007; ASTM D3967–23) consists of an alternative, where disc specimens are loaded across their diameter under compression, allowing for more flexible size and shape requirements than the direct tensile test (e.g., Perras and Diederichs, 2014; Aydan, 2019). With the Brazilian test, the indirect tensile strength (ITS) is obtained, while for the conventional tensile tests, the direct tensile strength (DTS) is obtained.

The direct and indirect tensile strength (DTS and ITS, respectively) differ. Zhang (2016) obtained a DTS/ITS ratio of 0.60–0.71, but the commonly accepted ratio is 0.75 (e.g., Derek, 2014; Li et al., 2013). For igneous rocks, Matthew and Mark (2014) defined DTS/ITS = 0.80, while Rocha (1981) obtained DTS/ITS = 0.87 for trachytes and DTS/ITS = 0.62 for basalts.

Tensile strength is important to infer volcano deformation (Holohan et al., 2017). The value of σ_t can be used to estimate the necessary overpressure to induce dyke initiation and propagation

throughout the host rock, together with E and ν (e.g., Gudmundsson, 2006; Section 2.1.3., Part B). Tensile strength also allows to estimate the total volume and the rupture of a magma chamber (Browning et al., 2015), being an important input for eruption forecast modelling (Heap and Violay, 2021). However, these volcanic models have been developed for *in situ* tensile strength, measured from hydraulic fracture experiments in boreholes (Gudmundsson, 2006; Browning et al., 2015), where confining pressure and the length scale result in different σ_t values than those obtained in the laboratory, which are higher than the field σ_t . As explained in Section 2.2 (Part A), intact rock specimens are not affected by the discontinuities ubiquitous in volcanic rock masses. According to Gudmundsson (2011), *in situ* tensile strength mostly ranges between 0.5 and 6 MPa but can reach maximum strength up to 9 MPa.

2.2.4.4. Failure of brittle materials

“Failure is the stress condition by which a solid such as a rock begins to flow or break” (Gudmundsson, 2011). The theory of brittle failure of rocks, which predicts the stress for macroscopic fracturing, follows two classic approaches (Paterson and Wong, 2005). The first consists of empirically determining failure criteria based on the failure conditions for practical purposes. The available failure criteria are widely used in engineering practice despite their limitations. The Mohr-Coulomb criterion describes the failure of the intact rock, while the Hoek-Brown criterion is respective to the rock mass strength. The second approach is theoretical and involves establishing a physical model of the brittle fracture process, such as the Griffith’s theory.

Griffith’s theory

The Griffith’s theory refers to the initiation of tensile failure and constitutes the first step towards a realistic model of the failure process (see Paterson and Wong, 2005; Hoek and Martin, 2014). The original theory (Griffith, 1920) established a rock strength governed by the pre-existent small cracks, with tensile failure starting in the tips of flat elliptical cracks (penny-shaped) at lower stress than expected. Crack propagation occurs when the maximum tensile stress overcomes the cohesion of the material (Paterson and Wong, 2005). The original theory predicts a ratio of σ_c to σ_t of 8–12 %, and the intermediate principal stress (σ_2) does not intervene in the crack initiation. Griffith’s theory variation for closed cracks (e.g., closed microcracks, grain boundaries) considers the Mohr-Coulomb equation and compressive confining pressures (see Paterson and Wong, 2005 and references therein). Later, the Griffith theory was modified. This change combined the former Griffith fracture criterion (Eq. 2.15), which describes the tensile stress concentration around crack-like flaws (non-linear regime), with the Mohr-Coulomb criterion (Eq. 2.16), which

considers shear and compressive stresses (linear regime), together with the (see Paterson and Wong, 2005 and references therein; Fossen, 2010).

$$\text{Tension - parabola} \quad \tau^2 + 4T_{cut-off}\sigma - 4T_{cut-off}^2 = 0; \Delta\sigma \leq 4|T_{cut-off}| \quad (2.15)$$

$$\text{Compression - linear} \quad \tau = \mu\sigma + 2T_{cut-off} \quad (2.16)$$

where $T_{cut-off}$ tension cut-off, τ the shear strength, σ the normal strength, and μ the coefficient of internal friction.

Griffith's theory is frequently considered in fracture mechanics problems and volcano-tectonics research. In volcanic settings, during dyke emplacement, and under divergent regimes, tensile conditions prevail, sometimes combined with shearing (Acocella, 2021). However, under predominant compressive conditions (e.g., rock deformation experiments), fracture initiation occurs at lower stress than macroscopic failure (Fig. 2.13).

Byerlee's law

Byerlee's law (Byerlee, 1978) is often addressed in the geology literature. It defines two distinct shear failure envelopes for lower (Eq. 2.17) and higher (Eq. 2.18) normal stresses (σ). The law was derived from different rock types and defines the frictional resistance, represented by μ , on a pre-existing fault or fracture. Geologically, it shows that crustal rocks, regardless of their type, behave similarly in terms of friction under pressure, allowing for the prediction of the depth of the seismogenic zone (Fig. 2.3)

$$\sigma < 200 \text{ MPa} \quad \tau = 0.85\sigma \quad (2.17)$$

$$\sigma > 200 \text{ MPa} \quad \tau = 0.6\sigma + 50 \quad (2.18)$$

Byerlee's law assumes a null cohesion to pre-existing discontinuities in the rock. It can be regarded as a simplification of the Mohr-Coulomb criterion (established below) for a $c = 0$.

Mohr-Coulomb criterion

The Mohr-Coulomb (MC) criterion (e.g., Labuz and Zhang, 2012) describes the relation between the shear stress and the normal stress at failure. It establishes a failure envelope over different confining pressures. Triaxial results are plotted as Mohr circles (Fig. 2.15b) in the shear-normal stress regime and mathematically described by Eq. 2.19, depending on the c and ϕ of the intact

rock. According to Labuz and Zhang (2012), at least three triaxial experiments are required to derive the MC criterion.

c corresponds to the intersection of the envelope when $\sigma = 0$ and reflects that in the absence of a normal stress, a finite shear stress is still needed to initiate failure. The slope of the envelope is described by $\tan\phi$, which corresponds to μ .

This criterion assumes that the rock fails along a plane due to shear stress, while sliding is resisted by a frictional-type force associated with the normal stress and μ (Jaeger et al., 2007). The rock experiences shear failure when the Mohr circle, representing a stress state, is tangent and intersects the failure envelope. The intersection point indicates the orientation of the plane of failure.

$$\tau = c + \sigma \tan \phi = c + \sigma \mu \quad (2.19)$$

Paul (1961) modified the MC criterion by introducing the concept of tension cut-off (T), defined as the point where the Mohr envelope intersects the $\sigma\sigma$ axis (Fig. 2.15b). For negative values of σ_3 , failure is tensile (Fig. 2.15a). Fluids (water, melt, gas, oil) within the pores facilitate the failure of the rock and allow for chemical interactions between the rock and the fluid (Jaeger et al., 2007). Mechanically, pore pressure is subtracted from the principal stresses, which become effective stresses (σ_1' and σ_3'), moving the Mohr circle to the left (Fig. 2.15b).

MC criterion is effective in describing shear failure along pre-existing fractures, depending solely on μ . Moreover, it has the advantage of being mathematically simple and clear in its physical meaning, which makes it broadly used in engineering practice. Despite its successive modifications, the MC criterion has limitations in the tensional regime, where more realistic estimates are provided by Griffith's theory (see above).

Hoek-Brown criterion

The Hoek-Brown (HB) criterion was developed to estimate rock mass strength based on geological conditions, namely weathering and the characteristics of discontinuities (Hoek, 1968; Hoek and Brown, 1997; Hoek et al., 2002; Hoek and Brown, 2019).

The HB criterion was first developed using the parabolic Mohr envelope derived from Griffith's theory, establishing the shear and normal stress at fracture initiation (Hoek, 1968). Later, the criterion was derived by trial and error using triaxial data (Hoek and Brown, 1980),

corresponding to an empirical criterion based on a 'best-fit' to strength (Eberhardt, 2012). For an isotropic rock, the HB failure criterion considers a nonlinear increase in peak strength with increasing confining stress (Eq. 2.20) (Eberhardt, 2012)

$$\sigma'_1 = \sigma'_3 + \sigma_{ci_HB} \left(m_b \frac{\sigma'_3}{\sigma_{ci_HB}} + s \right)^a \quad (2.20)$$

where σ'_1 and σ'_3 are the major and minor effective principal stresses, respectively, at failure.

σ_{ci_HB} is an intact rock property that differs from σ_{c_UCS} because it represents the intersection of the σ_1 axis according to the algorithm used to fit the Hoek-Brown envelope. At least five triaxial tests (including σ_{c_UCS}) are necessary to derive the Hoek-Brown failure criterion (Hoek and Brown, 1997).

Eq. 2.20 refers to the “generalised” criterion to estimate the strength of the rock mass (Hoek et al., 2002; Hoek and Brown, 2019), considering s (Eq. 2.21), a (Eq. 2.22), and m_b (Eq. 2.23) as constants describing the rock mass.

$$s = \exp\left(\frac{GSI - 100}{9 - 3D}\right) \quad (2.21)$$

$$a = \frac{1}{2} + \frac{1}{6} \left(e^{-GSI/15} - e^{-20/3} \right) \quad (2.22)$$

$$m_b = m_i \exp\left(\frac{GSI - 100}{28 - 14D}\right) \quad (2.23)$$

The GSI characterises the quality of the rock mass based on discontinuities and D is the disturbance factor (see Section 2.2.2, Part A). m_i is the Hoek-Brown constant, which is a dimensionless intact rock property that depends on the frictional characteristics of the component minerals and the degree of particle interlocking (Marinos and Hoek, 2000).

The HB criterion was derived using several rock types, providing a straightforward empirical method to estimate rock mass properties and, therefore, frequently applied to geotechnical investigations (e.g., Jaeger et al., 2007) and more recently to volcanology (Villeneuve and Heap, 2021).

2.2.5. Factors affecting the strength of brittle materials

The strength of rocks is influenced by several external and intrinsic factors, which were summarised by Hudson and Harrison (2000), Paterson and Wong (2005) and Heap and Violay (2021) for unconfined compressive strength.

2.2.5.1. Specimen size

Standards and suggested methods for rock testing impose strict requirements on specimen size and geometry to minimise stress concentrations and ensure accurate results. Short specimens are prone to clamping effects at their ends, which can lead to erroneous and high σ_c (Mogi, 2006). An appropriate specimen length allows fractures to propagate within a uniformly distributed stress field. In contrast, long specimens are more susceptible to bending, potentially reducing the measured σ_c . To avoid the concavity effect at the start of loading, specimen ends should be flat and parallel.

Regarding diameter, it should be at least ten times the size of the largest grain to ensure representative sampling (ISRM, 2007; ASTM D7012-23, 2023; ASTM D3967-23, 2023). The ISRM (2007) recommends the NX core diameter (54 mm), commonly used in drilling. However, studies indicate that some rocks, particularly sedimentary types, require larger diameters (≥ 75 mm) to achieve consistent strength values (Xie et al., 2024). In practice, diameters ranging from 40 to 60 mm are typically used.

For uniaxial compression tests, a length-to-diameter (L/D) ratio between 2 and 2.5 is generally recommended (ISRM, 2007; ASTM D7012-23, 2023). Mogi (2006) observed that strength stabilises above an L/D ratio of 2.5 in rocks such as granite, dolomite, and trachyte. Exclusively for the trachyte, strength remained constant above a ratio of 2.

The fracture angle relative to the loading axis also depends on the L/D ratio. As the ratio increases, the angle decreases and eventually stabilises once a threshold is reached, indicating a transition to a uniform compressive stress field. While the L/D ratio affects the orientation of shear fractures, it does not influence microfracture orientation.

A ratio of 2 is commonly adopted in rock mechanics studies on lava rocks, where it is considered sufficient to ensure stress uniformity (Heap and Violay, 2021).

Lastly, while peak stress is sensitive to changes in the L/D ratio, the average Young's modulus remains relatively unaffected (Harrison and Hudson, 2000).

2.2.5.2. Loading conditions

The loading rate of the tests is also an important factor to consider, as higher loading rates result in higher peak stresses. Compressive strength tests typically adopt a strain rate of 10^{-5} s (see Heap and Violay, 2021), while ISRM methods (ISRM, 1007) consider appropriate the stress rate 0.5–1.0 MPa/s for the uniaxial (up to 10 min of loading) and triaxial (up to 15 min of loading) tests. Reducing the loading and strain rate of the tests increases the time available for time-dependent micromechanisms, with implications for the rock's deformation (Heap and Violay, 2021). It is also important to consider that brittle fracture mechanisms are generally less sensitive to variations in strain rate and temperature compared to ductile rocks (Paterson and Wong, 2005).

2.2.5.3. Heterogeneity and microstructure of the rocks

The heterogeneity of volcanic rocks is a key factor contributing to the variability of their mechanical properties. Different volcanic rock types cannot be reliably distinguished based on mechanical data alone (e.g., Heap and Violay, 2021). Microstructural characteristics, including the size and geometry of crystals and voids, control lava rock strength.

The inherent heterogeneity and complex microstructure of volcanic rocks limit experimental and numerical interpretations. For example, current micromechanical models are limited in capturing the interplay of deformation mechanisms, as they do not account for both vesicles and microcracks simultaneously (Heap et al., 2014a). Elastic damage models remain simplistic but provide insight into the influence of pore and crystal characteristics (Heap et al., 2016; Heap et al., 2021a). In turn, experimental data are essential for validating numerical models, although there is a scattering of results due to variable porosity, porosity type, and crystallinity among specimens.

Crystals

In general, finer-grained rocks tend to display higher peak stress (Paterson and Wong, 2005, and references therein). Numerical models show that crystal size (granularity) has a less significant impact compared to crystallinity (Section 2.1, Part A), which reduces strength when increased (Heap et al., 2016).

Porosity, pore size, and pore size distribution

Lavas display a broad range of porosity. The distribution and relative proportion of vesicles and microcracks vary significantly, even within a single rock type (e.g., Heap et al., 2014a; Cant et al., 2018).

Rocks with larger vesicles or higher connected porosity tend to be mechanically weaker (Heap et al., 2014b; Pappalardo et al., 2017). However, models indicate that rocks with low porosity (< 15 %) and small vesicle sizes can also have low competence, whereas rocks with a non-uniform pore size distribution are as weak as rocks with large pores (Heap et al., 2014b). Microstructural observation (see also below) of vesicular lavas with porosities exceeding 11/15 % support these model predictions, revealing that connected vesicles and microcracks create preferential pathways for failure and reduce the stress required to initiate macroscopic deformation (Heap et al., 2014a).

The spatial distribution of pores within the rock also affect strength. Larger pores and/or closer pores, even if small, reduce strength by promoting stress concentrations, which facilitate microcrack initiation and propagation (Heap et al., 2014b; Bubeck et al., 2017).

Pore shape

Numerical studies indicate that pronounced pore shape variation makes rocks stronger and stiffer than those composed by spherical pores (Bubeck et al., 2017). However, strength heterogeneity is less pronounced in rocks with sub-spherical pores than in those with elongated ones, i.e., with low aspect ratio (minor to major axis ratio).

Bubeck et al. (2017) further showed that the orientation of elongated pores relative to the loading axis affects unconfined compressive strength. Rocks loaded perpendicular to the major axis of the pores are weaker. These findings are supported by the numerical models from Griffiths et al. (2017) and Vairé et al. (2024), which also provide experimental data on strength, stiffness, ultrasonic velocity, permeability, and thermal properties.

Microstructural effects on tensile strength

Most research on microstructural controls in volcanic rocks has focused on UCS. More recently, Heap et al. (2021a) numerically investigated the effects of porosity, pore diameter, aspect ratio, and orientation on ITS. Their results show that increasing porosity and pore diameter reduce σ_t

and that elliptical pores oriented perpendicular to the loading axis further decrease strength. However, laboratory measurements yield lower σ_t values than numerical predictions, likely due to a wide range of pore size distribution in the tested samples.

Microstructural imaging

The microstructural analysis complements conventional mechanical testing by revealing the micromechanisms underlying brittle and ductile failure (Chapter 2.2.2., Part C; Paterson and Wong, 2005). In volcanic rocks, failure modes are commonly characterised using backscattered electron images (SEM-BSE) (e.g., Heap et al., 2014a; Zhu et al., 2016).

After unconfined deformation, lavas present vesicle-emanated microcracks that traverse both the matrix and crystals, often aligned parallel to the loading axis (Heap et al., 2014a). These microcracks generally remain open but may contain partial bridges of rock material (Zhu et al., 2016).

Under confining pressure, pre-existing cracks can reactivate, as demonstrated by the reopening of healed or sealed cracks in basalts (Zhu et al., 2016). Vesicles may collapse, and intragranular cracking is also observed. Despite the intragranular fractures and the grain-boundary fracturing, phenocrysts appear to inhibit crack propagation. At higher confining pressures, compaction bands may develop (Heap et al., 2015a).

Recently, advanced imaging techniques such as X-ray microtomography (μ CT) have enabled 3D visualisation and quantification of the pore network in undeformed lavas. Moreover, this technique provides imaging of the post-deformation microcrack patterns, as well as supports digital volume correlation to establish strain localisation within specimens (e.g., Bubeck et al., 2017; Heap et al., 2020b; Vairé et al., 2024). Despite its potential, μ CT remains overlooked in the study of lava rocks.

2.2.5.4. Temperature

Temperature significantly influences the strength and elastic behaviour of rocks. Although outside the scope of the thesis, it remains a relevant factor in volcanic and geothermal systems, where thermal cycles are common (e.g., Heap et al., 2013; Kendrick et al., 2013; Lavallée and Kendrick, 2021). Temperature variations can induce microcracking due to a mismatch in volume change between distinct mineral phases, which can progressively evolve into rock damage, weakening the rock and compromising its overall structural integrity (Heap et al., 2010).

The impact of thermal stressing has been extensively studied for volcanic rocks (e.g., Schaefer et al., 2015; Browning et al., 2016; Heap et al., 2017; Coats et al., 2018; Heap et al., 2018a; Ersoy et al., 2019; Li et al., 2019). Findings indicate that the response to temperature depends on the presence of pre-existing microcracks. In such cases, thermal effects may produce minimal changes in strength and permeability because of the Kaiser effect (see Vinciguerra et al., 2005; Heap et al., 2014c).

Both increases and decreases in UCS with increasing temperature have been observed for volcanic rocks (Heap and Violay, 2021 and references therein). Under triaxial loading, for increasing temperature, an incipient increase in the inclination of shear fractures with respect to the loading direction has been observed, particularly in ductile rather than brittle rocks (Paterson and Wong, 2005).

2.2.5.5. Saturation

An increase in the degree of saturation reduces both compressive and tensile strength of rocks (Hudson and Harrison, 2000). This water weakening effect is well established for volcanic rocks, particularly regarding unconfined compressive strength. Heap and Violay (2021) compiled data showing that the ratio of wet to dry uniaxial compressive strength ranges from 0.96–1.09 for basalts, 0.56–1.07 for andesites, 0.60–1.04 for dacites, and is approximately 0.92 for trachyandesites. These results indicate no systematic relationship between water weakening and porosity. Ratios greater than 1, which contradict the expected trend, may reflect incomplete saturation or sample variability.

In sandstones, feldspar has been associated with weakening due to saturation (Baud et al., 2000), while in saturated tuffs, strength reduction was attributed to the presence of zeolites and clays (Heap et al., 2012; Heap et al., 2014c; Wedekind et al., 2013; Heap et al., 2018b). Heap and Violay (2021) reported a wet-to-dry strength ratio of 0.87 for a block-and-ash flow. Additionally, Wedekind et al. (2013) found that microporous tuffs are deteriorated by moisture, even in the absence of swellable clays. The pore size and saturation degree play a fundamental role in determining the loss of strength.

The water weakening effect on tensile strength is less thoroughly investigated, especially for lava rocks, presenting a promising avenue for future research. Wong et al. (2016) observed an exponential decrease in tensile strength for fully saturated limestones and sandstones, with reductions exceeding 50%. Wedekind et al. (2013) reported decreases in indirect tensile strength

of 17–33% for saturated tuffs and up to 63% in anisotropic samples. On average, saturation resulted in a 30% reduction. Hashiba and Fukui (2015), studying granite, tuff, and andesite, confirmed that water weakening was more pronounced under tensile loading than in compression.

2.2.5.6. Hydrothermal alteration

Hydrothermal alteration may induce ductility in volcanic rocks (Mordensky et al., 2019), creating weak altered zones that might compromise the stability of a volcano (Heap and Violay, 2021 and references therein). However, as described by Pereira et al. (2024a), the effects of hydrothermal alteration on the mechanical properties of rocks remain elusive due to contradictory findings in the literature. A higher degree of hydrothermal alteration does not necessarily imply a weakening of the host rocks, which has prompted increasing research on this topic in recent years (e.g., Wyering et al., 2014; Frolova et al., 2014; Marmoni et al., 2017; Heap et al., 2020c; Scott et al., 2023).

In addition to the degree, the type of hydrothermal alteration (see Section B.2.1.4, Part B) differs from one volcano-hydrothermal setting to another, resulting in variable mechanical properties of the host rocks. Hydrothermal fluids modify the rock's porous system through dissolution or precipitation processes, ultimately affecting the strength and deformation of the host rocks and defining the stress field of the system (Frolova et al., 2014). Indeed, deformation- or alteration-induced changes in the stress field can either promote brittle failure or fracture sealing, thereby limiting the extent and distribution of hydrothermal fluids (Pereira et al., 2024a).

The type of secondary minerals that form also dictate the strength of the rock. For instance, clays are considered weakening secondary minerals (e.g., del Potro and Hürlimann, 2008). In contrast, secondary adularia and quartz are found to increase the uniaxial compressive strength of volcanic rocks (Heap and Violay, 2021 and references therein).

2.2.6. Mechanical properties data for volcanic rocks

This chapter incorporates data previously published by Pereira et al. (2024a)³, developed within the scope of this doctoral research. Selected results and adapted excerpts are cited and integrated throughout this chapter following Universidade dos Açores rules, also aligning with the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0).

Pereira et al. (2024a) compiled mechanical data on fresh rocks from volcanoes and geothermal systems worldwide. Fig. 2.16 presents the average for UCS and ITS (Fig. 2.16a), elastic properties (Fig. 2.16b), Poisson's ratio (Fig. 2.16c), and cohesion (Fig. 2.16d) in igneous rocks. Noteworthy, dynamic Young's modulus and Poisson's ratio are included in these plots to compare with their static counterparts.

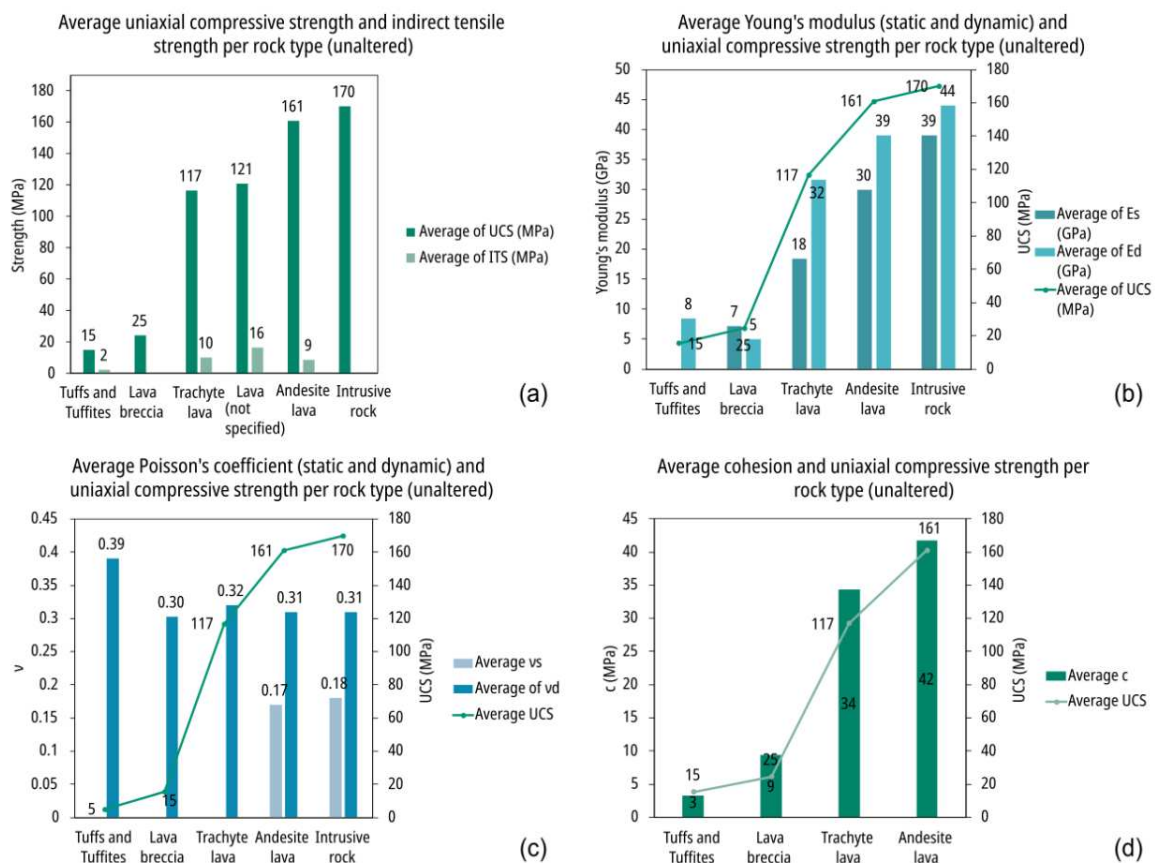


Fig. 2.16. Caption in the next page.

³ Pereira, M.L., Zanon, V., Fernandes, I., Pappalardo, L., and Viveiros, F., 2024, Hydrothermal alteration and physical and mechanical properties of rocks in a volcanic environment: A review: *Earth-Science Reviews*, <https://doi.org/10.1016/j.earscirev.2024.104754>. Licensed under CC BY 4.0

Fig. 2.16. Average values of mechanical properties – (a) unconfined compressive and indirect tensile strength; (b) static and dynamic Young’s modulus; (c) static and dynamic Poisson’s ratio; (d) cohesion – for several types of fresh igneous rocks, including intrusive rocks, lavas and pyroclastic materials. The data was compiled by Pereira et al., (2024a) (see references therein). Reproduced from Pereira et al. (2024a). Licensed under CC BY 4.0.

The discrepancies in strength and stiffness between dense and fragmental rocks are notorious in the compiled data (Pereira et al., 2024a). However, in general, dense and less porous lavas are more competent, stiffer, and have higher cohesion than pyroclastic rocks, in agreement with the observations of Heap and Violay (2021).

The correlations between several mechanical and physical properties of fresh volcanic rocks are depicted in Fig. 2.17 (reproduced from Pereira et al., 2024a). The authors show that, for the same rock type, σ_{c_UCS} or UCS decreases nonlinearly with porosity and increases nonlinearly with density, trends previously found by González de Vallejo and Ferrer (2011) and Heap and Violay (2021). Heap and Violay (2021) plotted data from several volcanic rocks (basalt, andesite, dacite and pyroclastic rocks), showing that similarly to UCS, σ_t and E_s decrease nonlinearly with increasing porosity. However, the data is significantly scattered, indicating that rocks may have lower σ_t , σ_{c_UCS} , and E than their porosity would suggest, probably due to the microstructural variability of volcanic rocks. As a result, lava rock types cannot be distinguished solely based on their σ_t , σ_{c_UCS} , and E , as microstructure induces variability in the mechanical properties (Heap and Violay, 2021).

The remaining variables of Fig. 2.17 (ITS or σ_t , Fig. 2.17b; E_s , Fig. 2.17c; V_p , Fig. 2.17f; c , Fig. 2.17e) correlate through a positive linear trend with UCS, which suggests that strength depends on the type of rock. For E_s , besides the linear regression, a nonlinear correlation is also obtained (Fig. 2.17b), displaying an R^2 greater than the linear trend. Nevertheless, the latter is more frequently established for volcanic rocks (e.g. Pereira et al., 2021).

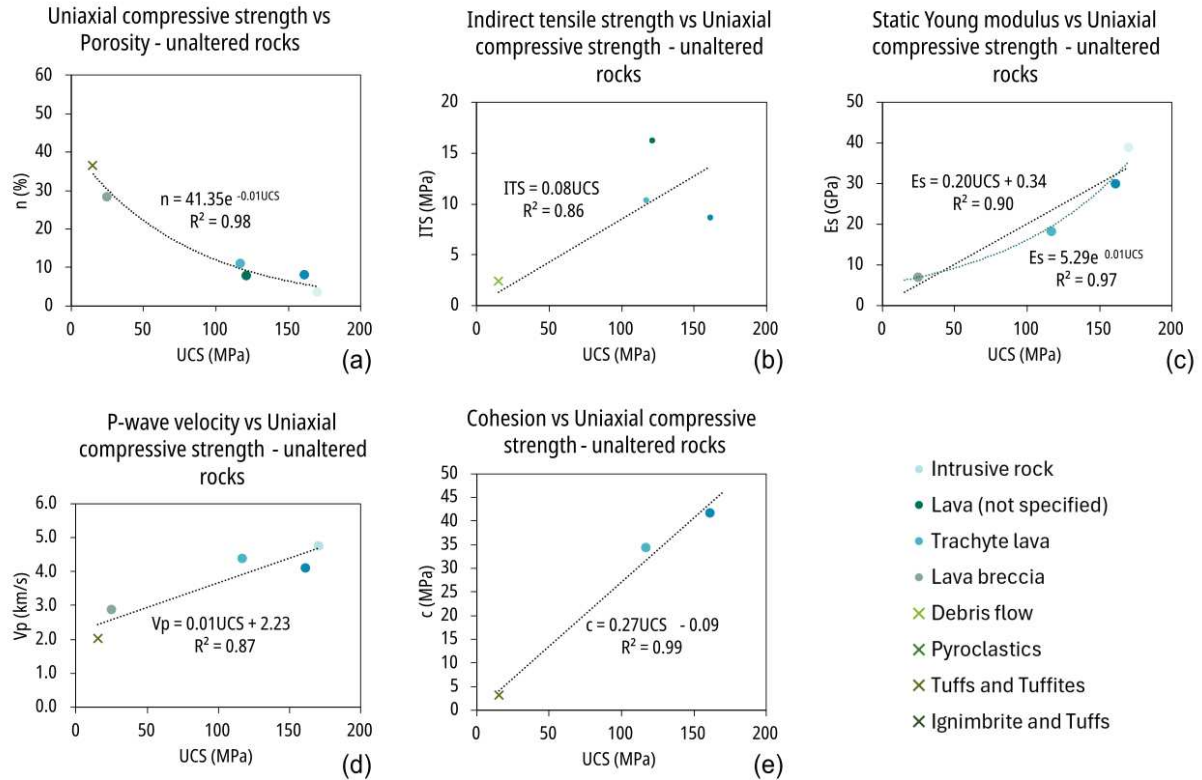


Fig. 2.17. Generalised correlation between mechanical and physical properties for several rock types, including intrusive rocks, lavas, and pyroclastic rocks. (a) unconfined compressive strength vs. porosity; (b) unconfined compressive strength vs. indirect tensile strength; (c) unconfined compressive strength vs. static Young's modulus; (d) unconfined compressive strength vs. P-wave velocity; (e) unconfined compressive strength vs. cohesion. Reproduced from Pereira et al. (2024a). Licensed under CC BY 4.0.

Compressive and tensile strength

Fig. 2.16a shows that UCS is eight to 18 times greater than the ITS, with differences more significant to lavas (trachyte and andesite) than for fragmental rocks.

Amongst dense rocks, intrusive rocks show the highest values for UCS (170 MPa), followed by andesites (161 MPa), which are more competent than trachytes (117 MPa) for the UCS (Pereira et al., 2024a). Andesitic lavas reviewed by Pereira et al. (2024a) are stronger than andesites of Vólcan de Colima (36 MPa; Heap and Violay, 2021). Contrary to what has been obtained before (e.g., González de Vallejo and Ferrer, 2011), trachytes have a slightly higher tensile strength (10 MPa) than andesites (9 MPa). Other authors established wide ranges of UCS (25 to 200 MPa) and ITS (12 to 40 MPa) for unaltered basalts (e.g., Pereira et al., 2021 and references therein), which cover the average values compiled by Heap and Violay (2021) for basalts from Mt. Etna (UCS = 77 MPa).

The group “lavas (not specified)” derived from Frolova et al. (2014) and Kennedy et al. (2020) refers to effusive lavas of different compositions, including basalts, basaltic andesites, andesites, dacites, or lavas whose nature is not specified. This group displays high competence, with UCS (121 MPa) and ITS (16 MPa) values in the same order of the strength reported for remaining lavas (trachytic and andesitic) (Pereira et al., 2024a).

Lava breccia is a transitional unit in terms of strength (UCS = 25 MPa), close in competence to the weak tuffs and tuffites (UCS = 15 MPa and ITS = 2 MPa) (Pereira et al., 2024a).

Elastic properties

Dynamic Young's modulus (Fig.2.16b) and Poisson's coefficient (Fig.2.16c) are 1.1 to 1.8 times and 1.7 to 1.8 times higher than values of the static homologous, respectively (Fig. 2.16b and Fig. 2.16c). Intrusive rocks are stiffer ($E_d = 44$ GPa and $E_s = 39$ GPa) but have significant discrepancies in the dynamic and static Poisson's ratio ($\nu_d = 0.31$ and $\nu_s = 0.18$) (Pereira et al., 2024a). Similar to $\sigma_{c, UCS}$, andesites ($E_d = 39$ GPa and $E_s = 30$ GPa) are stiffer than trachytes ($E_d = 32$ GPa and $E_s = 18$ GPa) but display similar ν (0.31–0.32). The ν average values calculated by Pereira et al. (2024a) are within the range of 0.19–0.38 reported for lava rocks worldwide (González de Vallejo and Ferrer, 2011).

Similar to strength, lava breccias are less stiff ($E_s = 7$ GPa and $E_d = 5$ GPa) than the remaining lavas, with proximate values to tuffs and tuffites ($E_d = 8$ GPa). The higher E_s than E_d for lava breccias results from the exceptional results of Schaefer et al. (2023). Conversely, the average dynamic Poisson's ratio of lava breccias ($\nu_d = 0.30$) is in the same order of magnitude as the remaining lavas, while pyroclastic materials have greater ν_d (0.39). These values (Pereira et al., 2024a) suggest that variations of ν are less evident amongst different volcanic rocks, especially lavas.

Shear strength

Villeneuve and Heap (2021) compiled several results on andesites, trachyandesites, basalts, dacites and one tuff, most of them affected by hydrothermal alteration. Results show variability in the c of fresh lavas (7–47 MPa), while ϕ has lower variation (40–57°), typically with lower c leading to higher ϕ . Villeneuve and Heap (2021) also provide empirical regressions of the shear parameters as a function of porosity based on the compiled data.

Pereira et al. (2024a) obtained average values within the specified c range for fresh lavas. The reviewed data confirm that lavas are more cohesive (andesites with 42 MPa; trachytes with 34 MPa) than lava breccias (9 MPa) and fragmental rocks (3 MPa).

The review by Pereira et al. (2024a) indicates that, in addition to microstructural factors such as porosity and porosity type, higher alkali and silica contents in lavas tend to weaken the rocks. However, this conclusion requires further support from additional experimental data.

2.2.7. Mechanical properties in the scope of the doctoral research

Like physical properties, the mechanical behaviour of the interlayered volcanic materials that compose the central volcanoes of the Azores is variable and, therefore, unpredictable. Moreover, limited studies on the mechanical properties of Azorean materials (Chapter 3.1.1) were conducted through a geotechnical lens.

The current state-of-the-art shows that thresholds of rock deformation, such as crack initiation and damage stresses, are poorly constrained for lava rocks. Their assessment is important for understanding the mechanical behaviour of volcanic materials, especially in tectonically and hydrothermally active regions like the Azores. Furthermore, shear strength parameters (c and ϕ) and the effects of saturation are currently overlooked for Azorean lava rocks, presenting an important scope for research.

The literature also shows that pre-existing defects, including vesicles and phenocrysts, influence the strength and stiffness of volcanic rocks. Yet, their role has not been systematically studied in Azorean lavas, either using conventional or advanced techniques.

Similar to physical properties, the impact of hydrothermal alteration on mechanical properties remains elusive and could benefit from an in-depth review of the existing data.

Understanding the mechanical performance of volcanic rocks, whether for stability analysis, geothermal exploitation, or hazard assessment, begins with intact rock testing and an in-depth characterisation of the rock to assess its microstructure. This work intends to combine these approaches to better constrain the mechanical behaviour of Azorean lava rocks, with broader relevance for volcanic terrains worldwide.

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“Mas a vida açoriana não data espiritualmente da colonização das ilhas: antes se projecta num passado telúrico que os geólogos reduzirão a tempo, se quiserem... Como homens, estamos soldados historicamente ao povo de onde viemos e enraizados pelo habitat a uns montes de lava que soltam da própria entranha uma substância que nos penetra. A geografia, para nós, vale outro tanto como a história, e não é de balde que as nossas recordações escritas inserem uns cinquenta por cento de relatos de sismos e enchentes. Como as sereias temos uma dupla natureza: somos de carne e pedra. Os nossos ossos mergulham no mar.”

Vitorino Nemésio in the definition of Açorianidade, 1932 (in Portuguese¹)

In: Teotónio de Almeida *A Questão da literatura açoriana. Recolha de intervenções e revisitação*, Angra do Heroísmo, Secretaria Regional de Educação e cultura, 1983, pp. 32-34

The Azores archipelago, set adrift in the middle of the Atlantic Ocean, is a living geological laboratory. However, the geology of the Azores does more than shape its islands or generate their many natural hazards—it shapes the people themselves, as Vitorino Nemésio once suggested. *Like mermaids, Azoreans carry a dual nature: made of both flesh and stone. They belong as much to the sea, where their bones dive, as to the living and burning land, fused to the lava mounts that release a core essence flowing through the Azorean people.*

Volcanic rocks, especially lavas, are woven into the very fabric of Azorean life. They crack and tremble in earthquakes, collapse in rockfalls, and wear away under wind and sea. They erupt from volcanoes and are altered deep within the Earth. They shape the landscapes of all nine islands, rise as monuments and homes, and define the Azorean character while enthralling those who come from afar.

The geographical and geological context of the Azores is unlike any other. It not only defines the people—it gives rise to singular rocks that are both witness and agent of the islands' phenomena, and their most vital geological resource.

¹ Translation to English non-official and made by me.

Chapter

Materials and Methods



Materials and methods

3.1. Materials

This chapter outlines the geological and volcano-tectonic context of the Azores, followed by a description of the sampling strategy and classification criteria. Lava flows from São Miguel Island, in particular from Sete Cidades and Fogo (Água de Pau) volcanoes, were sampled to cover the compositional and textural diversity of Azorean lavas.

3.1.1. Geological and geotechnical framework

3.1.1.1. The Azores

The Azores is a volcanic archipelago composed of nine volcanic islands aligned along a WNW-ESE direction and located in the central-north Atlantic Ocean in an anomalously shallow bathymetry zone (Fig. 3.1). The contact between Eurasia (Eu), Nubia (Nu), and North America (NA) lithospheric plates, the Azores Triple Junction (ATJ) (Searle, 1980; Miranda et al., 2014; Miranda et al., 2015), is responsible for the seismic and volcanic activity of the region. The Mid-Atlantic Ridge (MAR) corresponds to the boundary between NA/Eu and NA/Nu. The Eu/Nu plate boundary definition is less consensual. The boundary is considered a diffuse deformation region sheared by a dextral transtensive stress regime (Marques et al., 2013; Madeira et al., 2015) that is represented by the sigmoidal-shaped Azores–Gibraltar Fracture Zone, which includes the Terceira Rift (TR) and Gloria Fault (GF) (Marques et al., 2013; Miranda et al., 2014). It is assumed that the triple junction shifted from the precursor East Azores Fault Zone (EAFZ), which is currently seismically inactive, to the TR, with most of the seismicity located in the northeast (from FATJ – former ATJ – to ATJ in Fig. 3.1). The spreading rates also vary between MAR (23 mm/year to 19 mm/year in the northern and southern MAR, respectively; Miranda et al., 2014) and hyper-slow TR ($\sim 4.6 \pm 0.3$ mm/year; Marques et al., 2013), creating geodynamic complexity that leads to dextral and sinistral strike-slip, normal, oblique, and a few reverse events (Madeira et al., 2015 and references therein).

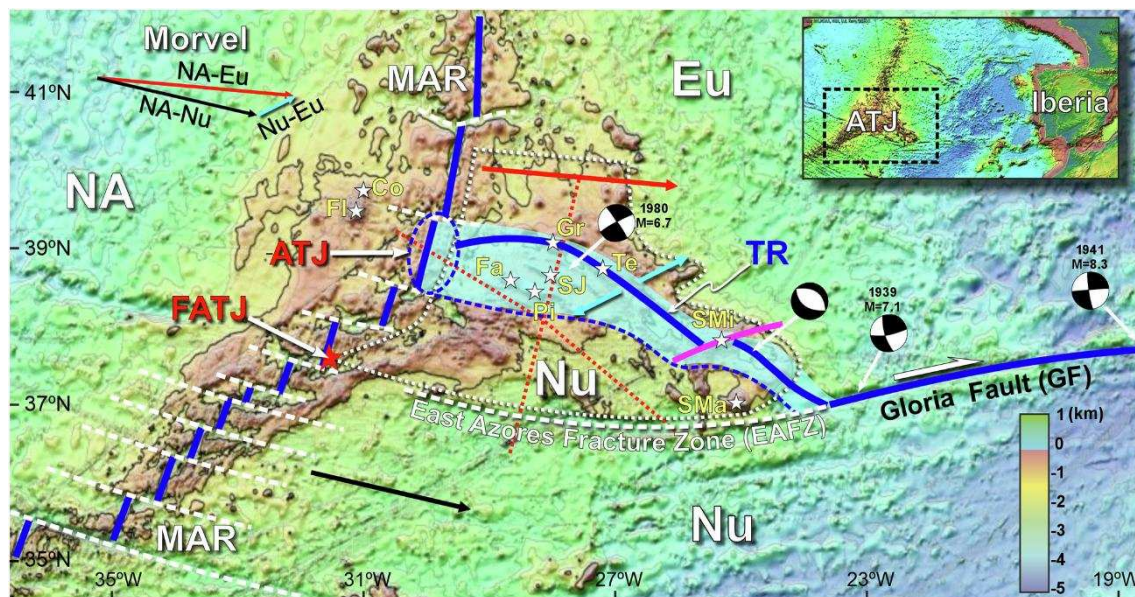


Fig. 3.1. Bathymetric map of the current Azores Triple Junction (ATJ, dashed blue ellipse) including the main topographic and tectonic features. The Terceira Rift (TR) and the diffuse Nubia-Eurasia plate boundary (light shaded blue), the Gloria Fault (GF), and the Mid-Atlantic Ridge (MAR) separate the North American (NA), Nubia (Nu), and Eurasian (Eu) tectonic plates. FATJ is a former ATJ (red stars). The dotted white line marks the boundary of the East Azores Rise and the EAFZ is the East Azores Fracture Zone. The Azores comprise nine islands (white stars), from W to E: Corvo (Co), Flores (Fl), Faial (Fa), Graciosa (Gr), Pico (Pi), São Jorge (SJ), Terceira (Te), São Miguel (SMi), and Santa Maria (SMa). Figure reproduced from Marques et al. (2025). Licensed under CC BY-NC-ND 4.0.

The formation of the submarine plateau marks the beginning of magmatism in the Azores (Luis and Miranda, 2008), whereas subaerial eruptions started with a first shield volcano in Santa Maria that emerged approximately 6.0 Ma ago and that was active until ~5.3 Ma (Marques et al., 2020). Magmas in the Azores erupted from both fissure zones and central volcanoes during overlapping periods and belong to the alkaline series, with Si_2O ranging between 41 and 68 wt.% and $\text{Na}_2\text{O}+\text{K}_2\text{O}$ between 1.7 and 13.5 wt.% (White, 1979; Zanon, 2015a). Primitive melts were generated by 1-5% partial melting of garnet-bearing peridotite. Magma evolution has resulted in distinct geochemical and compositional signatures, characterised by different incompatible elements and Sr-Nd-Pb isotopic signatures between and within the islands (Zanon, 2015a and references therein; Zanon et al., 2024). Ocean island basalts from the Azores and tholeiitic basalts from the Azorean Plateau have higher large ion lithophile elements (LILE) and isotopic ratios of Sr-Pb than typical tholeiitic basalts (MORB-N; White et al., 1979). Within the archipelago, the magma is enriched in incompatible elements from the MAR to the east following the thickening of the lithosphere that dictates the melting dynamics of the eastern Azores Plateau (Beier et al., 2018). Variable geochemical signatures indicate a heterogeneous mantle source that is variably enriched and remains far from fully understood (White et al., 1979; Zanon, 2015). While the genesis of the least evolved rocks is more controversial, the origin of the evolved

rocks is more consensual, suggesting an extensive fractional crystallisation in more sub-superficial reservoirs as part of the evolutionary magmatic process (White et al., 1979). Generally, mafic rocks correspond to basalts to hawaiites (sodic variety of trachybasalt), intermediate compositions are represented by mugearites (sodic variety of basaltic trachyandesite) and benmoreites (sodic variety of trachyandesite) and evolved materials correspond to trachytes.

The Azores are characterised by seismic activity along its tectonic structures, with occasional events exceeding magnitude five (Pacheco et al., 2013), including several historical destructive earthquakes. Regarding historic volcanism, 27 subaerial and submarine eruptions with distinct lava volumes have occurred in the archipelago. Mafic lava flows are more abundant and emitted by central volcanoes and fissure zones. Evolved magmas are emitted during explosive eruptions from the summit of Azorean stratovolcanoes (Zanon, 2015a).

3.1.1.2. São Miguel Island

São Miguel Island, in the eastern group of the archipelago (Fig. 3.1), is the largest island of the Azores. It has an east–west elongated shape due to the coexistence of various volcanoes, including three currently quiescent polygenetic stratovolcanoes – Sete Cidades, Fogo or Água de Pau, and Furnas – separated by the Picos and Congro fissural systems (Moore, 1990; Moore, 1991a). The eastern part of the island corresponds to the older and extinct Povoação-Nordeste system, which is now significantly eroded (Fig. 3.2). Central volcanoes have produced coeval basaltic and trachytic products, whereas effusive eruptions are predominant in fissure zones, with only occasional trachytic eruptions. Two historic explosive eruptions were reported in São Miguel – Fogo 1563 and Furnas 1630. The last eruption on land occurred in the Picos fissural system (1652) (Gaspar et al., 2015). Six major earthquakes have occurred during historical times, making São Miguel one of the most seismically active islands in the archipelago (Silva et al., 2015). Two recent unrest episodes were recorded in 2003–2006 (Trotta, 2009; Silva et al., 2012) and 2011–2012 (Okada et al., 2015) in the central part of the island, strongly related to the existing hydrothermal system.

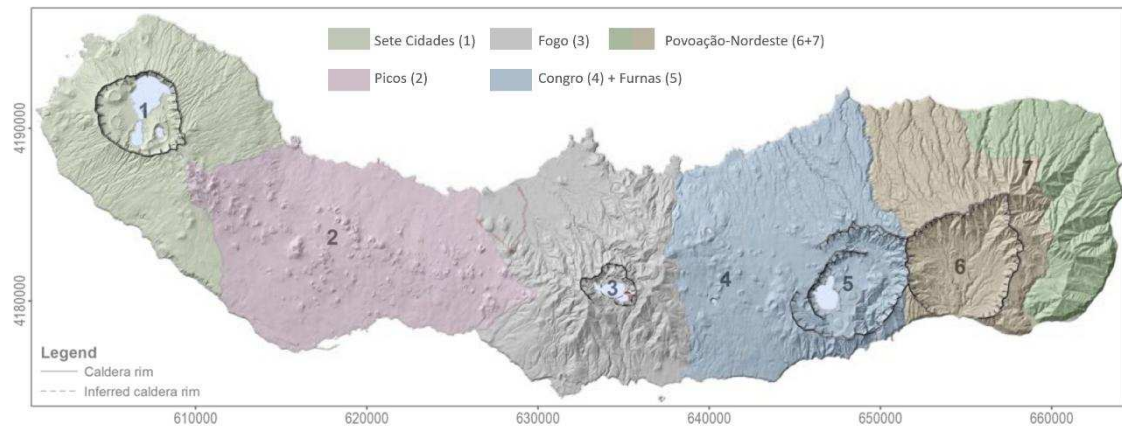


Fig. 3.2. Volcanic complexes of São Miguel Island (adapted from Nunes, 2004 and Carmo et al., 2015). 1. Sete Cidades Volcano; 2. Picos fissural volcanic system; 3. Fogo Volcano; 4. Congro fissural volcanic system; 5. Furnas Volcano; 6 + 7. Povoação-Nordeste volcanic system.

The main tectonic structures of the island are the result of a regional transtensional regime and an active TR. Most faults are oriented NW-SE- to WNW-ESE, dipping 60-90° to NE or SW, and N-S- to NNW-SSE trending faults are less common (Carmo et al., 2015). Central volcanoes occur along the intersection of the main fault system, whereas monogenetic cones and lineaments align with the rift zones according to the N-S- to NNW-SSE fault systems. The main faults are extensional structures that are materialised by scraps and define several grabens on the island (Carmo et al., 2015).

The mafic rocks produced in São Miguel Island are mainly basalts with MgO contents > 5 wt.% with variable porphyritic degrees, ranging from aphyric to highly porphyritic (Zanon, 2015a; Larrea et al., 2018). Phenocrysts are typically olivine, clinopyroxene, and minor plagioclase, with olivine appearing as megaphenocrysts in some alkali basalts. The plagioclase phenocrysts increase in number from alkali basalts to hawaiites. Microphenocrysts are typically olivine, clinopyroxene, and plagioclase in a microcrystalline to cryptocrystalline groundmass (Zanon, 2015a). Oxides, apatite, and rutile are typical accessory phases. The common textures are intergranular, intersertal, or seriate, with olivine often showing hourglass zoning and clinopyroxene a skeletal appearance. Plagioclase is typically euhedral tabular or acicular, commonly with disequilibrium features that produce sieve texture, embayments, and corrosion rims (Zanon, 2015a).

Intermediate rocks (mugearites and benmoreites) are less frequent. Common textures are intersertal to pilotaxitic or hyalophitic (Zanon, 2015a), with the mugearites being more porphyritic than the benmoreites (Larrea et al., 2018). The mineralogy of intermediate rocks includes olivine and clinopyroxene, similar to mafic rocks, but with higher amounts of feldspar (up to 30 %) and magnetite (Larrea et al., 2018).

The evolved rocks are trachytes, often vesicular, aphyric, and sub-aphyric pumices, or less porphyritic lavas with trachytic and pilotaxitic textures. Phenocrysts are alkali-feldspar (generally sanidine or anorthoclase, often zoned) and minor sodic plagioclase, biotite, amphibole, opaque minerals (titanomagnetite and ilmenite), aegirine-augite clinopyroxene, and rare anhedral olivine (McGraw, 1976; Zanon, 2015a). Accessory phases typically include quartz, apatite, and zircon (Zanon, 2015a; Larrea et al., 2018)

São Miguel rocks describe a well-defined geochemical trend along the TAS diagram without an evident compositional gap (Larrea et al., 2018), although the subordinate volume of intermediate rocks compared to basalts and trachytes was attributed before to an apparent Daly Gap and bimodal composition (McGraw, 1976; White et al., 1979; Jeffrey et al., 2016; Queiroz et al., 2015). São Miguel Island displays the largest incompatible element and radiogenic isotopic variability within the Azores archipelago, suggesting a less-enriched source in the west (Sete Cidades Volcano) and an enriched and highly radiogenic ancient eastern source (Nordeste Volcano). Haase and Beier (2003) suggested different source compositions, magma ascent, and limited magma mixing between the Fogo and Sete Cidade volcanoes. Melt inclusion studies indicate that after being formed in the asthenosphere, the magma beneath São Miguel first stalled at the Moho, followed by dyke propagation and new magma ponding in the base of the crust, only ascending to the surface through the deep active faults (Zanon et al., 2023, 2024). Storage levels at 29 and 8 km depths have been reported in fissural zones of São Miguel (Zanon, 2015b). However, shallower crustal depths (3–4 km depth) have been proposed for central volcanoes using thermodynamic modelling (Jeffrey et al., 2016 and references therein).

The target volcanoes in this study are the Sete Cidades and Fogo volcanoes, as they produced a full geochemical range of lavas at São Miguel (and other islands).

3.1.1.3. Sete Cidades Volcano

Sete Cidades is a stratovolcano with approximately 210,000 years old covering 110 km² on São Miguel's western end (Fig. 3.2; Queiroz et al., 2015). The volcano, rising ~845 m above sea level (asl), has a 5 km diameter caldera in its summit now hosting the Sete Cidades Lagoon (Moore, 1990; Queiroz et al., 2015). The main fracture system has a NW-SE trend, and the Mosteiros Graben is the most important structure (Carmo et al., 2015). The erupted products range from basalts to trachytes (Storey, 1985; Beier et al., 2006; Larrea et al., 2018) and were formed along three major phases of volcanism, materialised by several volcanic structures (Fig. 3.3; Moore, 1990): (1) a dominantly alkali basaltic, pre-caldera, shield-building phase; (2) a trachytic caldera-forming phase with paroxysmal eruptions;

and (3) a mainly trachytic, effusive, and post-caldera phase associated with small basaltic flank eruptions. Volcano-stratigraphy is described in Queiroz (1997), Queiroz et al. (2008), and Queiroz et al. (2015) and is divided generically into the Inferior Group (~210-36 ka), comprising undifferentiated deposits, and the Superior Group. Thick trachytic lavas followed by altered pyroclastic deposits were found in the Inferior Group (< 36 ka), with a top unit composed of vesicular 'aã lava flows. The Superior Group results from different activity phases and comprises six formations, including pumice and scoria fallout, pyroclastic density current deposits, and minor lava flows (Queiroz et al., 2008). Accompanying the explosive activity in the caldera with at least 17 trachytic events, 12 basaltic eruptions have occurred in the flanks of Sete Cidades or near the coast during the last 5 ka (Queiroz et al., 2015 and references therein).

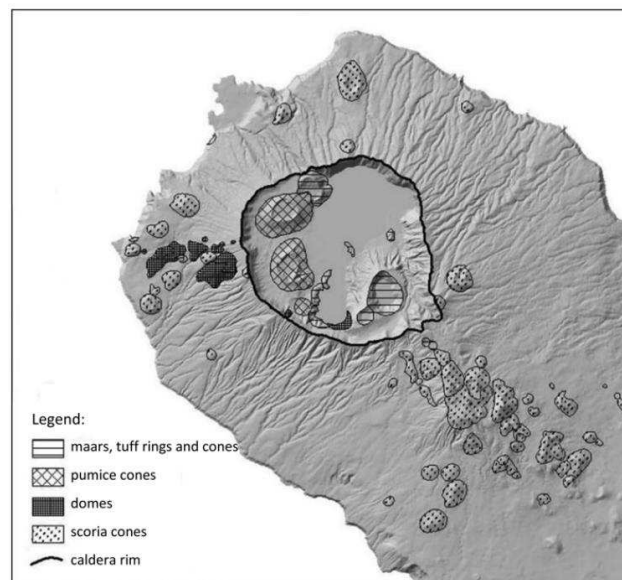


Fig. 3.3. Main volcanic structures of the Sete Cidades Volcano. Reproduced from Queiroz et al. (2008) with permission. Licensed obtained by the author of the thesis.

3.1.1.4. Fogo Volcano

Occupying 150 km² at the centre of the island and rising 947 m asl, Fogo (or Água de Pau) is a ~200,000-year stratovolcano that features a 3.2 km diameter crater at its summit, now hosting the Fogo Lake (Wallenstein et al., 2015; Fig. 3.2). Local structures have a NW–SE to NNW–SSE trend, with the Ribeira Grande Graben being the most prominent tectonic feature (Carmo et al., 2015). Fogo has its morphological expression in the Água de Pau Massif and is more complex than Furnas and Sete Cidades volcanoes, displaying several volcanic structures and a complex volcano-stratigraphy (Fig. 3.4.; Wallenstein et al., 2015). Generically, two major units – Lower Group (> 40 ka) and Upper Group (< 40 ka) – are divided regarding the formation of the Outer Caldera. The Lower Group (Muecke et al.,

1974; McGraw, 1976) comprises subsurface geology and is observed at the surface along trachytic lava flows and domes (Wallenstein, 1999). Drillhole samples contain 78 % lavas, including alkali basalts, hawaiites, mugearites, and trachytes, with the remaining materials (22 %) corresponding to pyroclastic deposits, mostly of trachytic compositions (McGraw, 1976). Subsurface pillow lavas (submarine basalts; ~280 ka) have also been identified (Muecke et al., 1974; Franco, 2016). Lower Group volcanoclastic deposits include tephra, and thick ignimbrites interbedded with trachytic lava flows (Wallenstein et al., 2015). The history of the last 40 ka (Upper Group) occurred in the Summit Caldera and along the flanks of Fogo Volcano. The volcano-stratigraphy of the Upper Group is detailed in Wallenstein (1999) and Wallenstein et al. (2015) and separated into the northern and southern flank groups, both characterised by bimodal volcanism expressed by basaltic flank and trachytic explosive eruptions.

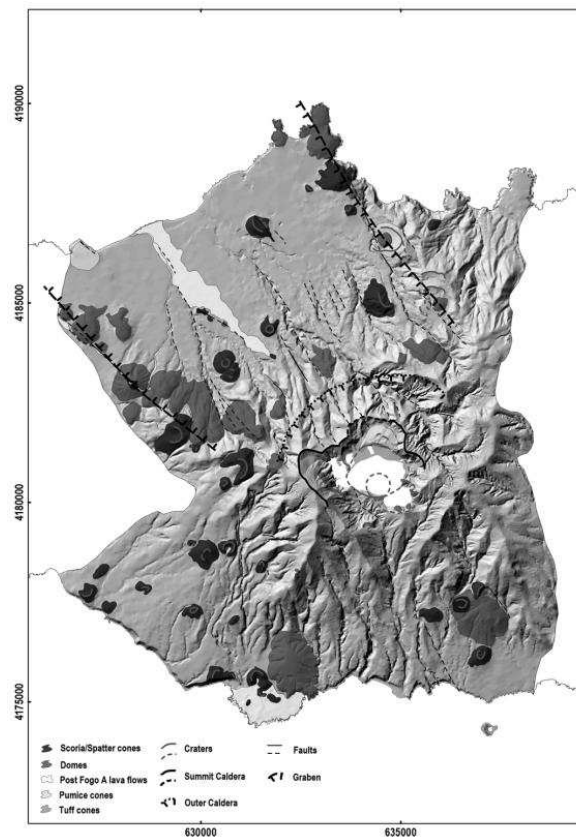


Fig. 3.4. Main volcanic structures of the Fogo Volcano. Reproduced from Wallenstein et al. (2015) with permission. Licensed obtained by the author of the thesis.

Fogo Volcano often associates with seismicity and had two recent unrest episodes. Most earthquakes below 5 km depth are considered to be primarily of hydrothermal origin, given the extensional hydrofracturing of the upper brittle rocks. In contrast, the origin of seismic

events above 5 km depth is less conclusive despite the presence of a compressive stress field (Silva et al., 2012).

The hydrothermal activity combined with the favourable tectonic structure created a high-temperature geothermal field on the northern flank of Fogo, which is currently explored by two power plants with a combined capacity of 23 MW (Franco and Ponte, 2019). The discovery of steam-productive zones and temperatures exceeding 200 °C at depth took place during the TG4 drilling near Ribeira Grande town (Muecke et al., 1974), intercepting the Lower Group unit (see above). New exploratory wells were established during 1978 and 1981 (Henneberger and Nunes, 1990). Maximum reservoir temperatures up to 230 to 245 °C at depths between 800 and 1300 m were measured in later studies (Carvalho et al., 2006; Rangel, 2014; Franco, 2016).

3.1.1.5. Volcanic formations of the Azores through a geotechnical perspective

Azorean islands are composed of volcanic materials with varying composition, structure, and welding, resulting from different styles of volcanic activity. Consequently, the physical and mechanical properties of rocks can be considered as a result of the eruptive style combined with post-eruptive processes. The main Azorean geological formations have been divided according to their geotechnical properties, differentiating hard volcanic rocks, such as lava flows and welded ignimbrites, from softer rocks, such as pumice and non-welded pyroclastic deposits (Table 3.1; Forjaz et al., 2001; Malheiro et al., 2018).

Table 3.1. Geotechnical classification of Azorean geological formations (reproduced from Forjaz et al., 2001). *s.l.* – *sensu latu*

Group	Subgroup	Description
Hard (I)	I a	Trachytic (s.l.) lava flows (including <i>coulées</i> and domes)
	I b	Basaltic (s.l.) lava flows
	I c	Welded ignimbrites
	I d	Surtseyan tuffs (hyaloclastites)
Intermediate (II)	II a	Non-welded ignimbrite and <i>lahars</i>
	II b	Slope alluvium and beach sand/gravel deposits
Soft (III)	III a	Pumice and other trachyte (s.l.) pyroclastic deposits
	III b	Basaltic (s.l.) pyroclasts (scoria)

Following the recommendations of Eurocode 8 (NP-EN 1998-1, 2010) in defining stratigraphic profiles and the formations of Table 3.1, five typical volcano-stratigraphic profiles (Fig. 3.5) have been established for the Azores (Malheiro and Nunes, 2007). These profiles consider the material geology, volcanological constraints (e.g., lava caves, grain size of debris, layering, welding), and geotechnical properties (ultrasonic wave propagation and the value of standard penetration tests – SPT) (Malheiro and Nunes, 2007). All profiles,

except for II (Fig. 3.5), are hard (geotechnical formation I, Table 3.1) and mostly correspond to depth and surface lava flows of variable thickness (Malheiro and Nunes, 2007).

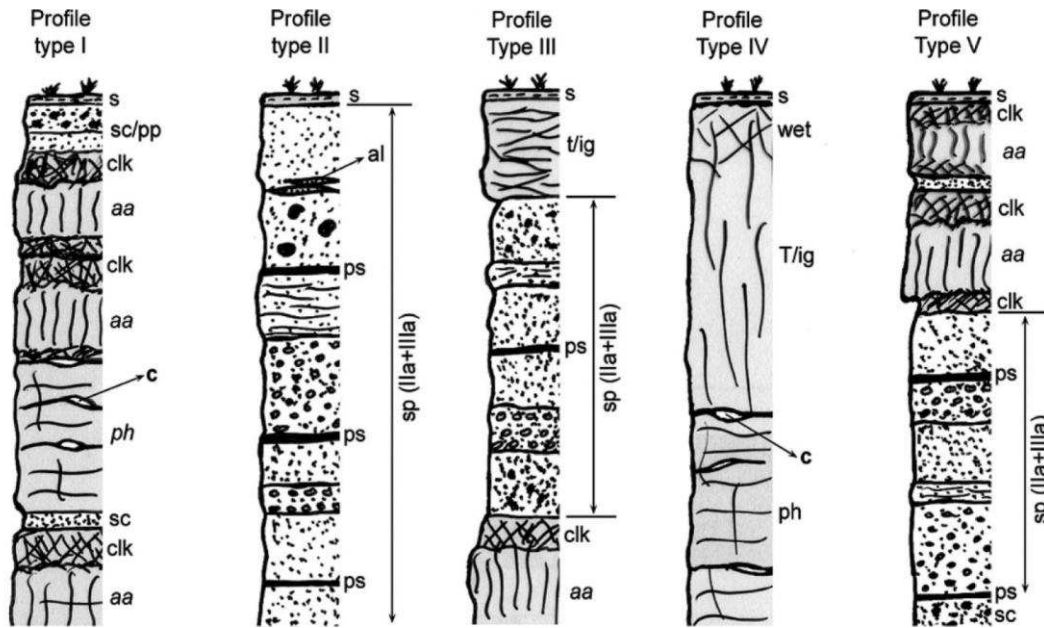


Fig. 3.5. Volcano-stratigraphic profiles for the Azores Islands (reproduced from Malheiro and Nunes, 2007). s: top soil; sc/pp: scoria or pumice deposits; clk: clinker; aa: basaltic (s.l.) a'ā lava flow; ph: basaltic (s.l.) pahoehoe lava flow; c: lava cave or void; sc: scoria deposit; al: alluvium/colluvium deposit; ps: paleosol; sp: Plinian sequence; t: surtseyan tuff; ig: welded ignimbrite; wet: weathering horizon; T: trachyte (s.l.) lava flow.

Because the selected geotechnical properties considered in the profiles are limited, other geomechanical studies have been conducted. For instance, Motta and Nunes (2003) determined the dry density of several lavas from S. Jorge Island, showing that massive/compact basalts ($2.887\text{--}2.702\text{ g/cm}^3$) are denser than vesicular basalts ($2.252\text{--}2.482\text{ g/cm}^3$) and trachytes ($1.619\text{--}2.425\text{ g/cm}^3$). The same lithotypes, but collected in São Miguel, were further characterised by Malheiro et al. (2018) and Amaral et al. (2018). Compact basalts (*sensu lato*) with n_{eff} between 5.6 and 16.8 % displayed an UCS ranging from 16.5 to 249 MPa and P-wave velocity between 1650 and 6273 m/s. Vesicular basalts ($\rho = 1.710\text{--}2.580\text{ g/cm}^3$; $n_{eff} = 12.2\text{--}26.1\%$) had lower average strength (10.7–105 MPa) and V_p (1843–5370 m/s) compared to massive basalts. Trachytes ($\rho = 2.080\text{--}2.540\text{ g/cm}^3$; $n_{eff} = 4.3\text{--}21.5\%$) have an UCS of 40–204 MPa, which is higher on average than that of massive basalt.

Despite being hard units, lava flows in São Miguel are exposed to extreme meteorological events (Malheiro, 2006; Silva et al., 2024), which, combined with a significant earthquake hazard and recent volcanic unrest episodes on the island, might favour landslides and rockfalls (Fernández et al., 2025). Such hazards are also enhanced by prominent coastal erosion and weathering, the steepness of cliffs, and increasing human occupation and

activity, posing a risk to local populations and infrastructure (Malheiro, 2006). Other factors to consider are the common presence of volcanic cavities in lava flows, which pose a geotechnical problem (Malheiro, 2006; Miranda et al., 2018), as well as the hydrothermal alteration in the active volcano-hydrothermal systems of the island.

3.1.2. Sampling campaign and sample organisation

Sampling focused on outcrops produced by Fogo and Sete Cidades volcanoes (Fig. 3.6), prioritising locations with easy access and large enough blocks suitable for specimen preparation. All samples were collected at the surface. Although intermediate lavas (mugearites and benmoreites) are minor when compared to alkali basalts and trachytes in both volcanoes, a full geochemical range of lavas were selected for this study, as confirmed by chemical analysis.

Mafic basalts were exclusively sampled from Sete Cidades, while intermediate, including trachytes, were collected from Fogo Volcano outcrops. In total, 113 blocks with varying textures and compositions were collected, each with a maximum dimension of 20 × 20 × 20 cm.

An additional ten smaller blocks (BP37, BP38, BAf14, BAf16, BAf18, BF3, BF13, BF15, T29, and T31) were gathered from the same sites for preliminary testing during specimen preparation. These representative samples are often referred to as “preliminary samples” throughout the thesis. From the 113 blocks, 11 were used not only to produce cylindrical and disc specimens, but also cubes of 28-31 mm size (BP25; BP8; BP13; BP23; BAf11; BF35; BF6; BF12; BF33; T13; T13).

Block references consist of a letter code indicating the sampling location followed by a sequential number (e.g., BP1). The collected materials were further subcategorised using a macroscopic description classification based on the general appearance (massive/coherent/compact or vesicular – see Section 2.1, Part A and Pappalardo et al., 2017), fractures and pores, dominant mineralogy, degree of weathering, and evidence of hydrothermal alteration (e.g., veins). In the present work, the terms *subcategories* and *subfacies* and *subgroups* are used interchangeably to describe these groupings.

Basalts were sampled from coastal outcrops at Mosteiros (BP – porphyritic olivine basalts) and Sto. António (BAf – less porphyritic basalts with plagioclase) parishes, corresponding to lava flows produced during flank eruptions of the Sete Cidades in the Pleistocene, following the caldera collapse (10–30 ka; Moore, 1991b).

BAf basalts were subdivided by the porosity degree of the hand sample: BAf.A corresponds to low-to-medium porosity lava rocks that maintain the massive appearance, with voids inexistent or ranging from micro- to millimetric diameters. BAf.B is a medium-porosity massive lava with higher number of pores of similar size to BAf.A and with a weathering grade of WG_{I-II} (adapted from Anon, 1995). BAf facies can contain closed fissures along the specimen. BAf14, BAf18, and BAf11 are part of BAf.A, whereas BAf16 was excluded from mechanical test specimen preparation due to extensive fracturing, which prevented successful core drilling.

Basalts (s.l.) from Fogo Volcano were sampled from an 'aã lava flow near Ribeirinha parish (BF), dated to ~5 ka B.P. (Moore, 1991b). These lavas contain plagioclase phenocrysts and rarely olivine, and most of them have a vesicular appearance (high porosity) characterised by millimetric to centimetric vesicles, of spherical to irregular shape (Fig. 3.6). BF.AI, BF.AII, and BF.AIII belong to this sample description and are differentiated based on the porphyritic degree and weathering grade (WG; Anon, 1995). BF.AII has larger and higher amounts of plagioclase phenocrysts, whereas BF.AI has a more homogenous appearance, with a lesser amount of plagioclase phenocrysts. BF.AIII differs from the remaining groups because it displays moderate weathering due to surface exposure, ranging from WG_{II} to WG_{III}. Typically, the oxidised products, possibly clays, fill the centimetric pores. BF.B and BF.C are distinguished from the previous subcategories because they correspond to massive, medium-porosity lavas, with pores spanning from micro- to millimetric in size. Moreover, BF.B is fresh and has olivine, clinopyroxene, and minor plagioclase phenocrysts. Some pores in BF.B specimens can reach centimetric sizes. On the other hand, BF.C may occasionally show slight weathering and some closed fissures (WG_{I-II}). From the samples used in the preliminary tests and cubes, BF15 and BF35 belong to BF.AI, BF13, BF6, and BF12 to BF.AII, BF33 to BF.AIII, and BF3 to BF.C.

Trachyte samples (T) were collected from a probable trachytic dome formed by Fogo Volcano during the Pleistocene (~85 ka B.P.; Moore, 1991b), located in the Vale das Lombadas. These rocks show a trachytic texture (aligned alkali feldspar phenocrysts). Subcategorisation was based on macroscopic porosity and relative density (Fig. 3.6). T.AI and T.AII are both coherent, low-porosity samples with a trachytic texture, lacking evident pores, and presenting scarce closed fissures and veins. T.AII is less dense in the hand sample than T.AI often show slight alteration. T.AIII is moderately altered and has a medium porosity, with micro- to millimetric pores. The veined structures are likely the result of metasomatic processes. T29, T31, T13, and T9 are representative of both T.AI and T.AII subgroups.

Core drilling of the block was performed at the Laboratório Regional de Engenharia Civil (LREC, Ponta Delgada), and specimen cutting was carried out at the Faculdade de Ciências da Universidade de Lisboa (FCUL), and the Instituto de Investigação para a Vulcanologia e Avaliação de Riscos (IVAR), Universidade dos Açores, Ponta Delgada.

An induced hydrothermal alteration was attempted in the representative samples (BP37, BP38, BAF14, BAF16, BAF18, BF3, BF13, BF15, T29, and T31) and some other test specimens by inserting them in soil for four months in a fumarolic ground in Caldeiras da Ribeira Grande (north flank of Fogo Volcano). To complement this set of samples, hydrothermally altered volcanic rocks were selected from drill cuttings obtained during the 2009 drilling of the RG5 geothermal observation well (Fig. 3.7). The cuttings were provided by EDA Renováveis S.A. in the ambit of the project HEATSTORE - Geothermica Era Net.

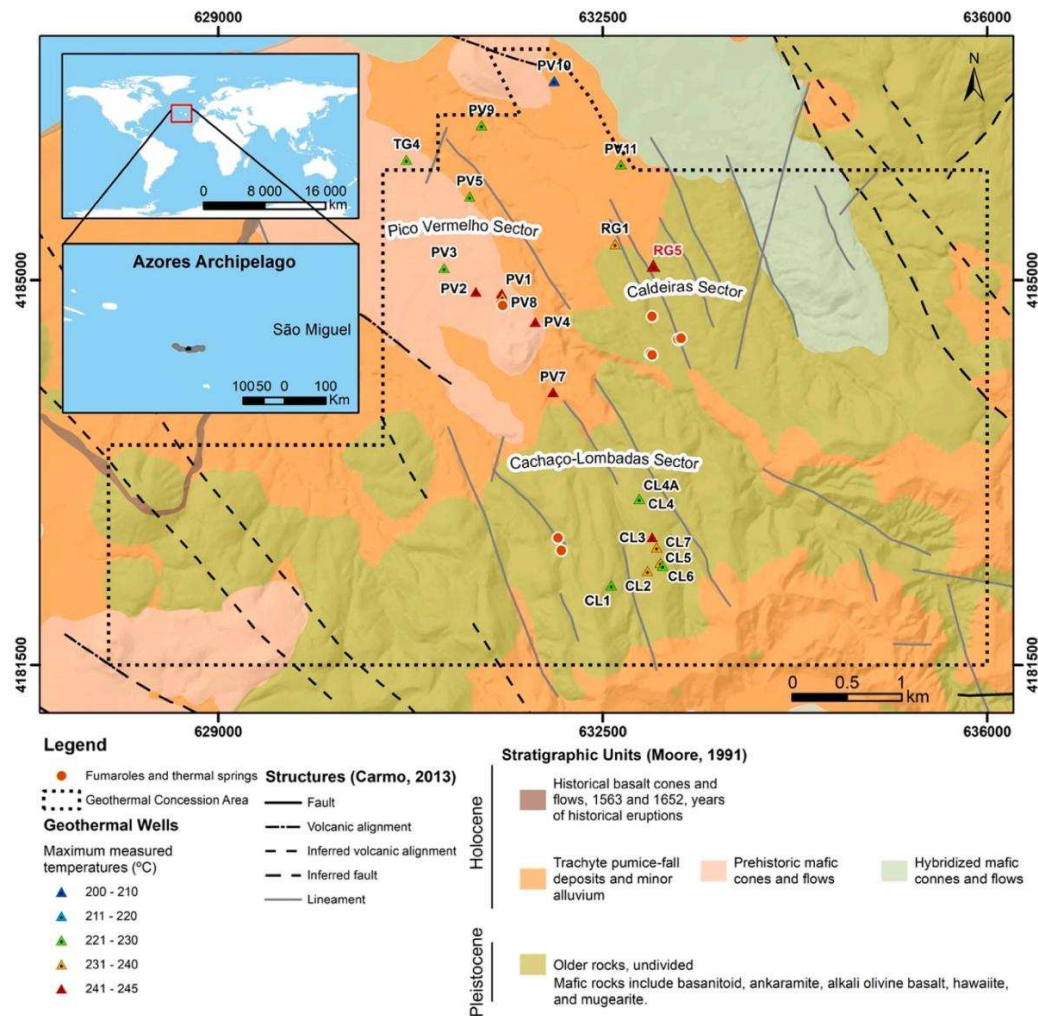


Fig. 3.7. Location of RG5 geothermal well by Pereira et al. (2022), including the geological map of the Ribeira Grande geothermal field (based on Moore 1991b and Carmo, 2013) with the existing exploration wells and respective maximum measured temperatures and main fumarolic emissions. Licensed under CC BY-NY-ND 4.0.

Located in the northeastern most part of the Ribeira Grande geothermal field, within the Caldeiras sector, RG5 well lies approximately 1.4 km from the nearest production well and ~0.7 km from the Caldeiras da Ribeira Grande fumarolic field (Fig. 3.7). RG5 reaches a depth of 1343 m, with a maximum recorded temperature of 241 °C, which is indicative of a high-temperature geothermal reservoir (Rangel, 2014; Franco, 2016; Franco et al., 2018).

Cuttings selected for this study (Table 3.2) were chosen based on prior X-ray diffraction and petrographic analyses conducted by Pereira et al. (2022), as well as their suitability for dry density and microstructural characterisation using a pycnometer and X-ray microtomography, respectively.

Table 3.2 Selected cuttings from RG5 well for the pycnometer test and X-ray microtomography analysis based on Pereira et al. (2022) results. X indicates the performed analysis.

Selected cuttings	Depth (m)	Number (N)	Pycnometer	μCT
Lithic tuff	15	7	X	X
Trachyte	25	2	X	
Trachyte	41-43	4	X	X
Altered lithic tuff	79	5	X	
Trachyte in smectite zone	153-155	4	X	X
Lithic tuff in the chlorite zone (illite + smectite)	195	5	X	
Lithic tuff in the chlorite zone (illite + smectite)	199	3	X	X
Intermediate lava	237	5	X	
Intermediate lava	269-261	7	X	X
Tuff breccia – cap rock	305	7	X	X
Lava breccia	377-379	6	X	
Lava from the geothermal reservoir	407-411	9	X	X
Lava from the geothermal reservoir	610	3	X	
Altered rock	847	1	X	

3.2. Methods

This chapter focuses on the research methodologies employed to characterise the lava rock samples at both macroscopic and microscopic scales, with particular emphasis on microstructural analysis in two- and three-dimensions (2D and 3D). Physical and mechanical properties were assessed using standardised tests and conducted at different scales. The research approach combined conventional laboratory techniques with advanced methods, including digital rock physics, to achieve a comprehensive characterisation of lava rocks with varying compositions and textures. The methods are also briefly described in each Chapter of results and discussion.

3.2.1. Macroscopic description

Macroscopic characterisation of the collected blocks and prepared specimens was carried out to define distinct subfacies (Fig. 3.6) and to support the interpretation of dynamic and mechanical test results. Hand samples used in the preliminary tests (BP37, BP38, BAF14, BAF16, BAF18, BF3, BF13, BF15, T29, and T31) were examined for texture, macroscopic mineralogy, and other features (e.g., xenoliths, veins), following the European standard EN 12407:2019 and classified using the field-based QAPF diagram (Streckeisen, 1980).

All disc and cylindrical specimens were measured and described according to the criteria outlined in Fig. 3.8, which include rock texture, mineralogy identifiable at the naked eye, colour index (based on tonality; Le Maitre et al., 2002), degree of weathering (or alteration for trachytes), fracturing, porous structure, and specimen shape. The hand sample description ensured the compliance with length-to-diameter (L/D) ratio requirements, but it also helped identify potential defects (e.g., fractures, edge irregularities) that could influence mechanical test results or V_p measurements. Specimen descriptions are provided in Appendix 3.1, which served as reference data for the results presented in Chapters 4, 5, and 6.

A. Texture and mineral composition
• A1. Holocrystalline, porphyritic, olivine and clinopyroxene are the main phenocrysts • A2. Holocrystalline, porphyritic, clinopyroxene is the main phenocryst • A3. Holocrystalline, porphyritic, plagioclase is the main phenocryst • A4. Holocrystalline, porphyritic, alkali-feldspar is the main phenocryst (rare biotite/ amphibole) • A5. Massive (coherent/compact; low porosity) • A6. Vesicular (high porosity, significant number of pores) • A7. Massive (coherent/compact, medium porosity)
B. Colour
• B1. Melanocratic, grey • B2. Melanocratic, brownish grey • B3. Melanocratic, dark grey • B4. Mesoleucocratic, whitish grey • B5. Mesoleucocratic, grey
C. Weathering Degree (WG*)
• C1. No alteration or oxidation (WG_I) • C2. Inexistence of weathering along the rock matrix, but in the fractures and around them, where a rock discolouration occurs (WG_{II}) • C3. Rock matrix weathered, with discolouration and/or oxidation but rock remains intact (WG_{III}) • *in trachytes is probably alteration and not weathering
D. Fracturing (F)
• D1. No fissures along the specimen • D2. Closed fissure crossing the specimen • D3. Wedge-shaped closed fissures • D4. More that one closed fissure in the specimen, randomly oriented • D5. Vein crossing the specimen • D6. Wedge-shaped vein • D7. More that one vein in the specimen, randomly oriented • D8. Wedge-shaped fracture surface close to the specimen edge • D9. Open fissure in the edge of the specimen
E. Structure and vesicularity
• E1. Rounded pores, isolated • E2. Rounded pores in higher volume fraction • E3. Elongated to coalescent pores • E4. Elongated pores, isolated • E5. Pores mainly vertically oriented to loading axis • E6. Pores mainly horizontally oriented to loading axis • E7. Pores mainly diagonally oriented to loading axis • E8. Pores randomly oriented • E9. Pore in the edge • E10. Vug with diameter > 3 cm (cavity) • E11. Few isolated pores • E12. Xenoliths • E13. Evident flux structures (trachytic texture; metasomatic)
F. Notes
• F1. Small rugosities around the specimen due to coring/ thinning • F2. Small rugosities in the specimen surface due to sawing (minimised with a dedicated rock polishing abrasive) • F3. Small deviation of the tops due to sawing • F4. Small deviation in the vertical axis

Fig. 3.8. Description parameters used for disc and cylindrical specimens before mechanical tests. The application of this description to the specimens is presented in Appendix 3.1.

3.2.2. Petrography, microstructural, and chemical assessment

3.2.2.1. Optical microscopy

Optical microscopy was used to characterise the mineralogy and texture of the ten lava samples selected for preliminary analysis (BP37, BP38, BAF14, BAF16, BAF18, BF3, BF13, BF15, T29, and T31). Polished thin-sections (50 × 25 mm, 30 µm thick) were prepared at FCUL and Universidade de Trás-os Montes e Alto Douro (UTAD). Petrographic analysis was conducted using a Nikon® ECLIPSE LV100POL microscope, with microphotographs captured using a Leica® DM7500 polarising microscope equipped with an ICC50HD camera.

Descriptions followed guidelines from MacKenzie et al. (1982), Le Maitre et al. (2002), and EN 12407:2019, with classification based on the IUGS QAPF diagram (Streckeisen, 1980). Modal mineralogy and total porosity were estimated by point counting using a Nikon ECLIPSE E200 and PetrogLite® software. However, due to the fine-grained groundmass and large phenocrysts, this method proved to be limited for accurate classification, prompting the use of whole-rock geochemical data (Section 3.2.3) to support rock-type identification.

3.2.2.2. Scanning electron microscopy

Scanning electron microscopy (SEM) provides high-resolution imaging essential for analysing rock texture, mineral microstructures, and porosity, supporting geological interpretation.

Fracturing and porosity in ten polished thin-sections (BP37, BP38, BAF14, BAF16, BAF18, BF3, BF13, BF15, T29, and T31) were examined using stitched backscattered electron (BSE) images acquired on a Hitachi® T4000 Plus benchtop SEM (at IVAR), at 15 kV and 100× magnification. Image mosaics, assembled with ZigZag Viewer® software, produced pixel sizes between 2.74 and 2.86 µm. In the BSE micrographs, porosity appears as black regions due to density contrast. Elemental mapping via energy-dispersive X-ray spectroscopy (EDS) was used to complement optical petrography.

Porosity quantification was performed using PerGeos® software (Section 3.2.6.2). However, due to the limitations of 2D imaging, it was not possible to distinguish between open and isolated pores, which would require 3D datasets. Mineral identification via SEM remained limited and served only as supplementary data to the optical thin-section analysis.

Additionally, SEM analysis (secondary and mixed modes) was used to examine the surface morphology of the ten preliminary samples subjected to induced alteration in the field.

3.2.2.3. X-Ray microtomography

Recent advances in rock microstructural analysis include X-ray microtomography (μ CT), which enables 3D high-resolution visualisation and quantification of grain and pore morphology, size distributions, and the architecture of vein and fracture networks, with minimal samples preparation (Landis and Keane, 2010; Pappalardo et al., 2018). The direct visualisation of the 3D internal microstructure of rocks provides insights into the processes underlying their formation. In volcanic rocks, μ CT data gives information on vesiculation, degassing, and crystallisation, contributing to a better understanding of eruption dynamics (Baker et al., 2012).

μ CT involves mounting specimens on a rotary stage and illuminating them with X-rays emitted from a source. As the beam passes through the sample, a detector captures 2D radiographs based on the linear attenuation of the X-rays, which depends on the density and composition of the rock. Attenuation scales linearly with density and follows a power-law relationship with atomic number (Baker et al., 2012). As a result, denser materials appear brighter (white), while pores appear darker (black), with component visibility depending on sufficient greyscale contrast. To reduce artefacts, such as beam hardening, and enhance image quality, appropriate source filters may be applied.

This study employed X-ray μ CT, using a ZEISS® Xradia Versa-410 μ CT scanner at the Istituto Nazionale di Geofisica e Vulcanologia – Osservatorio Vesuviano (INGV-OV, Italy) under varying conditions depending on sample geometry (Table 3.3) and producing 2401 to 4001 projections.

3D reconstructions were generated from a complete series of 2D radiographic projections. In the present work, image reconstruction was performed using a filtered back-projection algorithm implemented in ZEISS® XRM Reconstructor software. The resulting 3D pixels, or voxels, represent a trade-off between adequate resolution to capture pore space and maintaining sample representativeness while also ensuring reasonable scan times (Table 3.3).

Subsequent data analysis, including image processing and simulations using digital rock physics techniques, is detailed in Section 3.2.6.2.

Table 3.3. Conditions for image acquisition by the X-ray microtomography.

Sample		Size (diameter x height) (mm)	Source filter	Source Voltage (kV)	Current (μ A)	Source distance (mm)	Detector Distance (mm)	Pixel Size (μ m)	Optical Magnification	Exposure time (s)
Prism	BP37	11.5x15.9	LE6	100	100	-33	120	14.68	0.4	1.2
	BP38	11.8x15.9	LE6	100	100	-33	120	14.68	0.4	1.2
	BAf14	11.9x17.9	LE6	100	100	-33	120	14.68	0.4	1.2
	BAf16	16.0x20.6	HE2	120	83	-33	120	14.68	0.4	1.0
	BAf18	12.9x17.5	LE6	100	100	-33	120	14.68	0.4	1.2
	BF3	11.8x17.1	LE6	100	100	-33	120	14.68	0.4	1.1
	BF13	11.5x17.5	LE6	100	100	-33	120	14.68	0.4	0.8
	BF15	11.9x15.8	LE6	100	100	-33	120	14.68	0.4	0.9
	T29	11.6x16.2	LE6	100	100	-33	120	14.68	0.4	0.7
	T31	11.8x17.8	LE6	100	100	-33	120	14.68	0.4	0.8
	BP37_alt	9.1x18.2	Air	100	100	-33	120	14.68	0.4	1.0
	BAf18_alt	10.5x19.1	Air	120	83	-33	120	14.68	0.4	0.9
	BF3_alt	10.5x14.5	Air	120	83	-33	120	14.68	0.4	0.7
	BF13_alt	11.2x16.1	Air	100	100	-33	120	14.68	0.4	0.9
	T31_alt	8.7X16.1	Air	100	100	-33	120	14.68	0.4	0.7
Cylinder	BAf14	7.7x14.7	Air	120	83	-85	300	15.02	0.4	3.50
	BF3	7.6x14.3	Air	120	100	-85	300	15.02	0.4	3.30
	BF13	7.7x14.3	Air	120	83	-85	300	15.02	0.4	3.00
	T31	7.7x14.9	Air	120	100	-85	300	15.02	0.4	2.75
	BF35 (X, O, Δ)	7.7x14.9 13.2x7.75	Air	90	111	-85	300	15.02	0.4	5-5.5
Cuttings (prism/cylinder)	Trachyte	~4-8	Air	80	87	-27	33	4.04	4	0.8
	Trachyte sm	~4-8	Air	80	87	-27	33	4.04	4	1.0
	Intermediate lava	~4-8	Air	80	87	-27	33	4.04	4	0.9
	Lava reservoir	~4-8	Air	80	87	-27	33	4.04	4	1.1
	Lithic tuff	~4-8	Air	80	87	-27	33	4.04	4	0.8
	Altered lithic tuff	~4-8	Air	80	87	-27	33	4.04	4	0.7
	Lithic tuff ill/sm	~4-8	Air	80	87	-27	33	4.04	4	0.7

3.2.3. Chemical analysis

The petrographic classification was supplemented with whole-rock geochemical analysis to ensure accurate characterisation of the lavas. Representative samples (BP37, BP38, BAF18, BF3, BF13, BF15, T29, and T31) were analysed before and after exposure to a diffuse degassing environment (Section 3.1.2). A minimum of 15 g from each sample was sent to Activation Laboratories (Actlabs® Ltd., Canada), where they were powdered. Major elements were analysed via lithium metaborate/tetraborate fusion and fused in an induction furnace. The molten bead was digested in a 5 % nitric acid solution containing an internal standard and mixed continuously until completely dissolved. The solution was analysed by inductively coupled plasma (ICP) optical emission spectrometry and mass spectrometry. For each group of 10 samples, calibration was performed using 14 prepared US Geological Survey and Canada Centre for Mineral and Energy Technology certified reference materials (specified in Appendix 3.2). Sulfur content is determined through total digestion, where the samples are digested with four acids (hydrofluoric and a mixture of nitric and perchloric acids) and heated in several ramping and holding cycles to ensure dryness. The samples are then brought back into solution before ICP analysis. In-lab standards/certified reference materials are used for quality control (Appendix 3.2). The Loss on Ignition (LOI) was determined using the gravimetric method, where the percentage of volatile components in a sample are quantified by heating it and measuring the weight loss. The detection limit for the major oxides and LOI was 0.01 %, except for MnO (0.005 %) and TiO₂ (0.001 %). The detection limit for S was 0.001 %.

The results include concentrations of major, minor, and trace elements. Geochemical data were processed using the GCDKit 6.1 package (R® version 4.1.3) to generate classification diagrams. Major element compositions were plotted on a TAS diagram (Le Bas et al., 1986), with trachytes further classified using the Al₂O₃–FeO^T binary plot (Macdonald, 1974).

Alteration was assessed using total sulfur content (S), LOI, Na₂O, the binary diagram of CaO+K₂O+Na₂O (felsic minerals) and Fe₂O₃^T+MnO+MgO (mafic minerals), and chemical weathering indices, including the Chemical Index of Alteration (CIA; Nesbitt and Young, 1982; McLennan, 1993; Fedo et al., 1995 – Eq. 3.1) and the Chemical Index of Weathering (CIW; Harnois, 1988 – Eq. 3.2). Data was also plotted in the FMW ternary diagram, where F and M are the felsic and mafic source, respectively, and W is the degree of weathering (Ohta and Arai, 2007) using GCDkit.

$$CIA = \frac{Al_2O_3}{Al_2O_3 + CaO^* + Na_2O + K_2O} \times 100 \quad (3.1)$$

$$CaO' = CaO - 10/3 \times P_2O_5$$

$$CaO' > Na_2O, \text{ then } CaO^* = Na_2O$$

$$CaO' < Na_2O, \text{ then } CaO^* = CaO'$$

$$CIW = \frac{Al_2O_3}{Al_2O_3 + CaO^* + Na_2O} \times 100 \quad (3.2)$$

where CaO^* is the amount of CaO incorporated in the silicate fraction of the rocks, corrected using CaO for apatite ($Ca'O$). Concentrations are in molecular proportion.

3.2.4 Physical properties determination

3.2.4.1. Buoyancy method

The saturation and buoyancy technique, also referred to as solely the buoyancy method or the vacuum saturation method, is commonly used in rock mechanics. The method is standardised by the ISRM, ASTM, and European standards for natural stone (EN). This non-destructive gravimetric technique is based on Archimedes' principle and involves liquid saturation. It offers flexibility in accommodating various specimen sizes and shapes and requires only standard laboratory equipment.

In this study, specimens of different dimensions and geometries were tested. To ensure consistency with the larger cylindrical specimens, irregular lumps weighing at least 50 g, typically $\sim 4 \times 4 \times 3$ cm in size to be approximately ten times larger than the maximum crystal size, were analysed. A minimum of ten fragments per subfacies were tested, as recommended by ISRM (2007). Additionally, at least two cubic specimens per sample, each with sides of approximately 15 mm, were tested using the saturation and buoyancy method.

Porosity and density calculations are based on three mass measurements of each rock sample: dry mass (M1), submerged mass (M2), and saturated mass (M3). Cylindrical specimens were oven-dried at 105 °C for a minimum of 24 h, while smaller samples (e.g., cubes) were dried at 65 °C for at least 48 h, following standard procedures for rock mechanics and natural stone, respectively. All samples were cooled in a desiccator containing silica gel prior to testing.

To ensure saturation, samples were immersed in distilled water and placed under vacuum (800 Pa) in a sealed chamber for 24 h. During the initial hour, periodic agitation of the

chamber facilitated the removal of air from pore spaces. After saturation, M2 was measured by suspending a basket, previously tared, in water and weighing the immersed specimens. M3 was recorded following M2 after lightly wiping the samples with a damp cloth to remove surface water.

These measurements were used to calculate n_{eff} (Eq. 3.3) and both dry (ρ_{dry} ; Eq. 3.4) and saturated (ρ_{sat} ; Eq. 3.5) density. n_{eff} reflects the volume of interconnected voids (pores and cracks) and is a key parameter for understanding fluid transport and predicting rock mechanical properties. However, in highly porous rocks, the buoyancy method may underestimate n_{eff} , as water may not fully occupy large, interconnected voids due to gravitational drainage (Cueto, 2020).

$$n_{eff}(\%) = \frac{V_{voids}}{V} \times 100 = \frac{M3 - M1}{M3 - M2} \times 100 \quad (3.3)$$

$$\rho_{dry}(kg/m^3) = \frac{M1}{M3 - M2} \quad (3.4)$$

$$\rho_{sat}(kg/m^3) = \frac{M3}{M3 - M2} \quad (3.5)$$

Oven-dried regular prismatic specimens ($\sim 11.5 \text{ mm} \times 16\text{--}20 \text{ mm}$; three per sample) were tested using two buoyancy-based methods – the quick water immersion and paraffin immersion techniques (Crawford, 2013) – with an electronic densimeter (MD-2005) to determine the dry density ($\rho_{adp.ISRM}$) and effective porosity ($n_{eff_adp.ISRM}$). Both methods rely on Archimedes' principle. In the quick immersion method, specimens are rapidly submerged in distilled water to obtain the submerged mass (M2). Conversely, in the paraffin immersion method, specimens are coated with paraffin prior to weighing.

The densimeter directly calculates ρ , and n_{eff} was derived using Eq. 3.3. This complementary approach aimed to compare results with those obtained from irregular lumps tested using the standard vacuum saturation method.

For the selected cuttings from the RG5 geothermal well, dry density was determined using a 24.777 cm^3 pycnometer (INGV-OV) based on Archimedes' principle. Cuttings sized between 4 and 8 mm were oven-dried at 65°C for at least 48 h. After gradual cooling in the oven, their dry mass (M1) was measured. Each cutting was wrapped in a thin layer of parafilm for waterproofing, and the combined dry mass (cutting + parafilm; M4) was determined.

The parafilm-wrapped specimens were carefully placed in the pycnometer, which was filled to a predetermined level with distilled water. The total mass of the setup (M5) was recorded. A reference mass of the filled pycnometer without the sample (M6) was also obtained prior to testing. Pycnometric dry density (ρ_{dry_pyc}) was calculated using Eq. 3.6, representing the combined volume of the solid material and connected pore space.

$$\rho_{dry_pyc} (kg/m^3) = \frac{M1}{(M6 + M4) - M5} \quad (3.6)$$

In the present work, density is presented in g/cm³ and is calculated using the mass in g.

3.4.2.2. Mercury intrusion porosimetry

Mercury intrusion porosimetry (MIP) is another fluid saturation technique used to estimate pore mean size, size distribution, and connectivity in small specimens (Hall and Hoff, 2021). MIP forces mercury into a sample's pore network under increasing hydrostatic pressure using a porosimeter. Due to the high superficial tension and non-wetting nature of mercury in most natural rocks ($\theta > 90^\circ$), it rises through interconnected pores under the applied pressure. The volume of intruded mercury is constrained by the maximum pressure applied (Anovitz and Cole, 2015). Intrusion pressure (P , in psi) is inversely proportional to pore radius (r) and depends on the contact angle ($\theta > 90^\circ$), as described in Eq. 2.3.

Analyses were conducted using a Micromeritics AutoPore IV 9520 porosimeter from the , Instituto de Geociencias (IGEO) from Universidad Complutense de Madrid, capable of pressures up to 414 MPa, covering a pore radius range of ~ 0.0015 to $180 \mu m$. Penetrometers designed for solids with a five cm³ sample volume, maximum measurable volume of 0.366 cm³ and a total stem volume of 0.392 cm³ were used. Prismatic specimens previously scanned via μCT ($\sim 11.5 mm \times 16/20 mm$) were oven-dried at $70^\circ C$ until constant mass prior to testing.

As pressure increases, mercury progressively fills larger to smaller pores, with the intrusion and subsequent extrusion volumes recorded at each pressure step. These data generate intrusion and extrusion curves, which provide insights into the structure of the pore network, including pore size distribution and connectivity (Webb, 2001). Intrusion curves typically show a roughly sigmoidal shape, reflecting the pore size distribution and connectivity (Hall and Hoff, 2021).

MIP provides quantitative measurements of connected porosity (n_{eff_Hg}), mean pore radius (r), and pore size distribution (PSD). Data from MIP does not provide a complete description of the pore geometry of the samples, but it establishes a characteristic length scale for the pore system (Hall and Hoff, 2021).

3.2.4.3. Capillary absorption tests

Capillary absorption through spontaneous imbibition was assessed on cubic samples (28–31 mm per side), which were also used for ultrasonic wave velocity measurements (Section 3.2.4.4). The specimens represented a range of volcanic lithologies, from alkali basalts to trachytes, including intermediate vesicular lavas (BP8, BP13, BP23, BP25, BAf11, BF35, BF6, BF12, BF33, T9, T13). For each sample, two to three specimens were tested.

Samples were oven-dried for at least 48 h at 65 °C, cooled in a desiccator, and then weighed. Capillary absorption was determined along three orthogonal directions (X, O, Δ), following the NP-EN 1925:2000 standard. The dry specimens were positioned on supports and immersed to a depth of 3 ± 1 mm in a tank that could be covered to minimise water evaporation. Mass measurements were taken at standard-specified intervals, depending on the porosity of the samples. Medium-to-high porosity specimens (e.g., BP25, BF series) were measured at 1, 4, 10, 15, 30, 60, 480, and 1440 minutes, while denser, low-porosity, massive samples were measured at 1, 3, 15, 30, 60, 180, 480, 1440, 2880, and 4320 minutes. Prior to each weighing, surface water droplets were removed from the immersed face using a damp cloth.

Water absorption (Y) was calculated based on the mass gain at each time step. Most samples displayed nonlinear absorption behaviour. The capillary water absorption coefficient (C ; $g/m^2 \cdot s^{0.5}$) was determined using the product of a (maximum absorbed water per exposed surface area) and b (inverse square root of time), as specified in Annex A of NP-EN 1995:2000 (Eq. 3.7). Capillary-connected porosity (n_{cc}) was also calculated using Eq. 3.8 (Cueto et al., 2024).

$$Y(i) (g/m^2) = a \times b\sqrt{t(i)} \quad (3.7)$$

$$n_{cc}(\%) = \frac{(Mf - Mi)}{V \times \rho_l} \times 100 \quad (3.8)$$

where i corresponds to each time step, V is the volume (mm^3); Mi (g) is the initial mass and Mf (g) the final mass, and ρ_l is the liquid density of water at 25 °C ($0.997 g/cm^3$).

The standard coefficient C (C_{EN}) is limited in fully characterising the capillary uptake process, which prompted the application of the Sharp Front model (Philip, 1957; Ioannou et al., 2008, 2009; Hall and Hoff, 2021) to the more porous samples. SF model (see also Section 2.1.2.2, Part C) enabled the extraction of the initial absorption coefficient (C_e), intermediate anomalous absorption coefficient (C_a), and the later absorption coefficient (C_m). C_e and C_m correspond to the slopes of the linear portions of the water absorption curve along time ($t^{1/2}$), while C_a corresponds to the difference between the two coefficients.

3.2.4.4. Ultrasonic wave propagation tests

P-wave velocity (V_p) was measured on oven-dried cylindrical specimens (24 h at 105 °C), which were later subjected to uniaxial and triaxial mechanical tests. Measurements were conducted using a PROCEQ® Pundit Lab device equipped with 49.7 mm diameter transducers, operating at a frequency of 54 ± 5 kHz. Ultrasonic signals were acquired at 500 V with a receiver gain of 500×. The testing followed the first method recommended by the ISRM (2007), wherein the transducers are placed at the opposing ends of the cylinder (direct pulse transmission technique). This method assumes that the rock specimens are of sufficient size relative to the wavelength of the ultrasonic pulse, which in turn exceeds the average grain size of the rock (ISRM, 2007).

To further investigate the heterogeneity of the lava samples, additional ultrasonic tests were performed on the same cubic specimens tested for capillary absorption. Both longitudinal (V_p) and transverse (V_s) wave travel times were measured along three orthogonal directions (X, O, Δ) using the through-transmission method. A Panametrics® 5072 ultrasonic pulse was used to generate the signals, operating at 2 kHz with energy levels ranging from 20 μ J to 50 μ J, adjusted according to signal attenuation. Signal acquisition was carried out using a Tektronix® TDS 210 oscilloscope. The arrival time of the signal was measured visually in the oscilloscope, and the velocities were calculated by dividing the spacing between the transducers by the arrival time.

The types of transducers and operating frequencies differed between V_p and V_s measurements. V_p measurements used a Physical Acoustics R6-alpha sensor with a frequency range of 35–100 kHz, while V_s measurements used the SH10 sensor from the same manufacturer, with an operating frequency range of 100–200 kHz.

Several dynamic elastic properties were derived on V_p and V_s data following ASTM D2845-08 (2008), including dynamic Young's modulus (E_d ; Eq. 3.9), dynamic Poisson's ratio (ν_d ; Eq. 3.10), shear modulus (G ; Eq. 3.11), and bulk modulus (K ; Eq. 3.12).

$$E_d(Pa) = [\rho V_s^2 (3V_p^2 - 4V_s^2)] / (V_p^2 - V_s^2) \quad (3.9)$$

$$\nu_d = (V_p^2 - 2V_s^2) / [2(V_p^2 - V_s^2)] \quad (3.10)$$

$$G(Pa) = \rho V_s^2 \quad (3.11)$$

$$K(Pa) = \rho(3V_p^2 - 4V_s^2)/3 \quad (3.12)$$

where V_p and V_s are in m/s, and ρ in kg/m³. The dynamic moduli are often presented in GPa.

3.2.5. Mechanical tests

3.2.5.1. Brazilian test

The indirect tensile strength (σ_t or ITS) was determined through the Brazilian test following the guidelines of ISRM (2007). Testing was performed using a UTR-450-point load apparatus at FCUL, equipped with two steel loading jaws customised to match the diameter of the disc-shaped specimens. The specimens used were discs with diameters ranging from 45 to 51 mm and a diameter-to-thickness ratio averaging 2, as specified in ASTM D3967-23 (2023). Defects (e.g., edge fractures, phenocrysts) are documented in Appendix 3.1, as such irregularities may cause local stress concentrations that promote premature failure. Specimen surfaces were prepared to ensure flatness and parallelism, as recommended by the ISRM (2007).

Most tests (for 230 specimens) were conducted under dry conditions using oven-dried (at least 24 h, 105 °C) lavas. Each specimen was wrapped along its thickness with an adhesive paper strip prior to testing. To evaluate the effect of fluid saturation on the tensile behaviour of the lavas, an additional 46 specimens were tested after being saturated under vacuum.

The test procedure followed the ISRM (2007) standard. Each specimen was placed between the steel loading jaws, which were centred in the loading press. The compressive load was applied at a constant rate of approximately 0.2 kN/s to ensure specimen failure within 1–10 minutes, with a preferred failure time between 1 and 3 minutes (ASTM D3967-23, 2023). The maximum compressive load at failure was recorded and converted to tensile strength using Eq. 3.13.

$$\sigma_t(MPa) = \frac{2\pi P}{Dt} \quad 3.13$$

where P is the peak load (N), D is the diameter (mm) and t is the thickness (mm) of discs.

3.2.5.2. Uniaxial/unconfined compressive strength tests

The unconfined compressive strength ($\sigma_{c,UCS}$; UCS) was determined via uniaxial compression testing conducted at GEOLAB, Instituto Superior Técnico (IST). Cylindrical specimens with a 45–51 mm diameter and an L/D of 2 (ASTM D7012-23, 2023) were used. The specimen diameters met the ISRM (2007) criterion of being at least ten times greater than the maximum grain size in the rock. The specimen ends were prepared to be flat and parallel (ISRM, 2007), and all specimens were previously described (Appendix 3.1). Tests were carried out under dry conditions, and each oven-dried specimen (24 h; 105 °C) was centred in the loading press prior to testing.

A servo-controlled press (FORM + TEST D-88499) with a maximum capacity of 1000 kN was used. The test procedure followed the ISRM (2007) guidelines, using a constant loading rate of 0.5 MPa/s and a peak sensitivity setting of 95 % to ensure specimen failure within 5–10 minutes of loading. At the beginning of each test, three loading–unloading cycles were performed to stabilise the sample response. To ensure these cycles remained within the elastic regime, preliminary compression tests were carried out on specimens of each rock type and texture to define an appropriate stress cut-off.

Strain measurements were recorded using Tokyo Measuring Instruments Lab strain gauges (PFL-30-11-5LJC-F; gauge length: 30 mm; sensitivity: 2.09 ± 1 %; resistance: 118.5 ± 0.5 Ω). Four gauges were glued 90° apart to simultaneously capture axial and lateral strain. When only axial strain was assessed, two gauges were affixed 180° apart on the specimen lateral surface.

The peak stress (σ_p) was automatically recorded upon sample failure. Prior input of the specimen surface area enabled automated strength ($\sigma_{c,UCS}$; in MPa) calculation. Axial and lateral strain values (Eq. 2.9 and Eq. 2.10) were normalised to the original specimen dimensions and expressed as percentages. When feasible, the volumetric strain was also determined (Eq. 2.8). The volumetric strain curve reversal (slope shifts to negative) allows for the determination of the damage threshold stress (σ_{cd}), which marks the beginning of the unstable crack growth (Fig. 2.13). The crack initiation stress (σ_{ci}) was identified using the Lateral Strain Response Method (LSRM), which detects deviations in the lateral strain response relative to a linear reference baseline (Nicksiar and Martin, 2012). In one sample, where the measurement of $\mathcal{E}l$ was not possible, the σ_{ci} was determined by selecting the point

where the stress-axial strain curve clearly departed from linearity, following the approach of Basu and Mishra (2014).

Stress-strain data were used to derive various Young's moduli and Poisson's ratios (ISRM, 2007; ASTM D7012-23, 2023). Tangent modulus (E_{tg}) was determined at 50 % of the peak stress; average modulus (E_{avg}) was defined as the slope of the linear portion of the stress-strain curve; and secant modulus (E_{sec}) was calculated from the origin to a selected point between 35 % and 50 % of the peak stress.

3.2.5.3. Triaxial/confined compressive strength tests

Triaxial compression tests were conducted using a Hoek cell mounted on the FORM + TEST D-88499 servo-controlled press at GEOLAB, with a peak load sensitivity of 6 kN. Cylindrical specimens, 42 mm in diameter and with an L/D of 2, were prepared according to ASTM D7012-23 (2023). The specimen diameter exceeded ten times the maximum grain size, complying with ISRM (2007) recommendations. All samples were oven-dried at 105 °C for 24 h and tested under dry conditions.

The test procedure followed ISRM (2007) Protocol I for individual triaxial tests. Both axial stress (σ_1) and confining pressure ($\sigma_2 = \sigma_3 = P_{conf}$) were increased simultaneously until the hydrostatic pressure reached the target P_{conf} . Thereafter, axial loading continued at a constant rate of 0.1 MPa/s while maintaining a fixed P_{conf} . Tests were with no pore fluid pressure applied ($P_{eff} = P_{conf}$). The loading rate was selected to induce failure within 5 to 15 minutes, as recommended by the ISRM (2007).

Different confining pressures were selected for the triaxial test to mimic the depth of the subsurface geology of the target central volcanoes and Ribeira Grande geothermal field (Fig. 3.9). The pressure at depth was estimated assuming hydrostatic and lithostatic pressures are equivalent ($\sigma_H = \sigma_v$), following previous works (e.g., Heap et al., 2015; Heap and Violay, 2021). Lithostatic pressure (in MPa) was calculated as the product of dry density, gravitational acceleration ($g = 9.81 \text{ m/s}^2$), and depth (z , in m). Assuming an average bulk density of 2.5 g/cm^3 for lavas in general, the resulting lithostatic gradient is approximately 25 MPa/km. Depth estimates were based on the elevation of the Cachaços-Lombadas geothermal sector (~500 m), located near the summit of the volcano. Confining pressures were applied as follows: 10, 20, and 30 MPa for BP and BAf; 10 and 30 MPa for BF.D; 5, 10, 15, 20, and 30 MPa for vesicular BF samples; and 5, 10, and 15 MPa for T samples. Lower

confining pressures were selected for vesicular BF specimens to ensure the integrity of the rubber jacket and the validity of the tests.

Different strain gauge (SG) configurations were employed in the triaxial tests. For massive samples, one horizontal SG (30 mm; $2.02 \pm 0.1\%$ sensitivity; $119.5 \Omega \pm 0.2\%$ resistance) and two vertical SG positioned 180° apart (20 mm; $2.01 \pm 0.25\%$ sensitivity; $119.5 \Omega \pm 0.2\%$ resistance) were used. In vesicular samples, four SG (Kyowa KFGS-10.120-C1-11; 10 mm; $2.12 \pm 1\%$ sensitivity; $120.2 \Omega \pm 0.2\%$ resistance) were affixed at 90° apart.

To avoid damaging the rubber jacket because of vesicular specimens, a linear variable differential transformer (LVDT) was also used to monitor displacement and record the axial strain continuously. The LVDT measured mechanical displacement of the setup via magnetic induction, while SG measured strain through changes in electrical resistance due to deformation of the specimen itself. As a result, strain measurements obtained from LVDT and SG are not directly comparable.

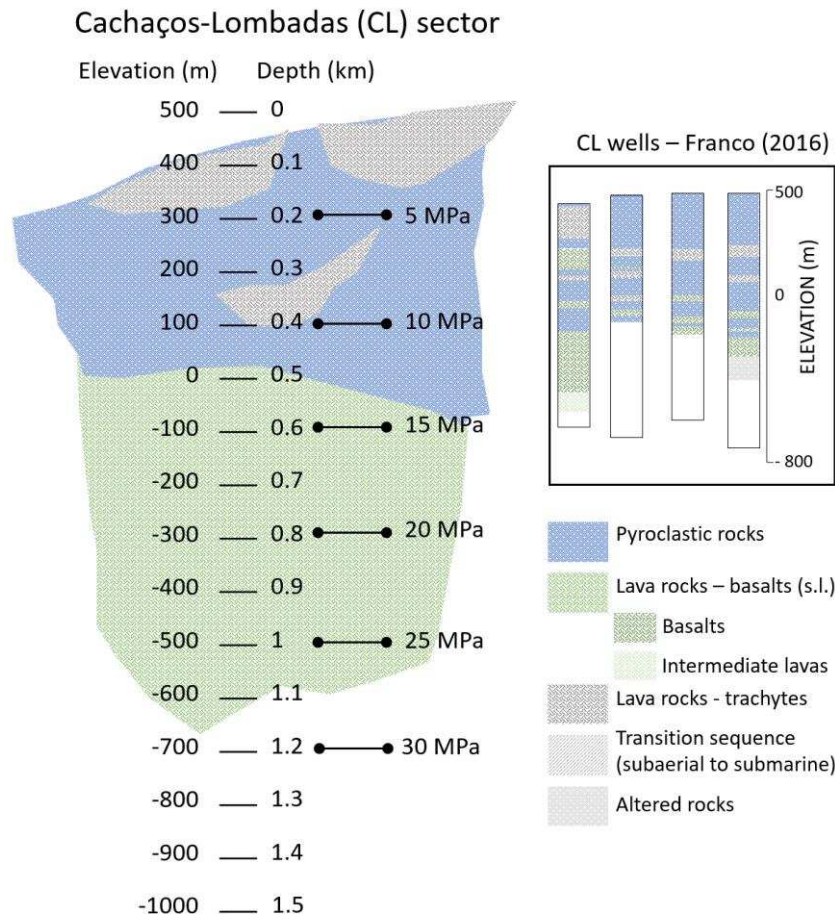


Fig. 3.9. Confining pressures (MPa) selected for the triaxial test considering the depth and subsurface geology of Cachaços-Lombadas sector of Ribeira Grande geothermal field (GeothermEx, 2008; Franco, 2016).

The compressive strength (σ_c) is automatically calculated using the surface area of the specimen. In this work, strain is converted to percentage. E , ν , σ_{cd} , and σ_{ci} were not calculated for triaxial data since SG were affected by the confinement during the triaxial test. Instead, the data was used to derive the fitting parameters for Mohr-Coulomb and Hoek-Brown in a dedicated software (Section 3.2.6.3).

3.2.5.4. Time-resolved mechanical tests

In addition to the standard uniaxial and Brazilian tests on larger specimens, smaller samples were tested for mechanical strength. Cylindrical specimens with diameters ranging from 7.5 to 7.7 mm and L/D of approximately 1.9–2 (Table 3.3) were used for UCS tests. Disc-shaped specimens, 13.2 mm in diameter and approximately 8 mm thick, were tested using the Brazilian method. All samples were drilled from larger cubes and oven-dried for at least 24 h at 65 °C.

Mechanical testing was performed using a Deben *in situ* load cell stage (CT5000H250; 5210 N capacity) integrated with the ZEISS® equipment at INGV-OV. A constant displacement rate of 0.03 mm/min was applied. For UCS specimens, pre-and post-test 3D scans were acquired using 801 projections over a 180° rotation (plus fan angle), with scan times ranging from 2.75 to 5.5 s per projection at 90–120 kV and 10 W (Table 3.3). Imaging was conducted at 0.4× optical magnification, yielding a voxel resolution of ~15 µm. During Brazilian tests, real-time 2D imaging at 90 kV and 10 W enabled direct observation of fracture propagation at failure.

3.2.6. Data collection and analysis

3.2.6.1. Data collection

The bibliography information was obtained from several online databases, including Google Scholar, Elicit, Web of Science, and ResearchGate. The main keywords used for the search were “volcanic rocks”, “mechanical properties”, “physical properties”, “rock mechanics”, “rock deformation”, and “hydrothermal alteration”. The collected data were used to develop a database that served as the groundwork for the review presented in Pereira et al. (2024a) and in Chapter 7, where a total of 32 studies from the last 15 years were considered.

3.2.6.2. Digital rock physics

Digital rock physics refers to the integration of high-resolution X-ray microtomography, pore-scale image analysis, and advanced numerical simulations to characterise the properties of rocks (Schepp et al., 2020). In recent years, rock digital physics has gained prominence as a complementary tool to laboratory testing, offering a better understanding of the physical processes governing rock transport and mechanical behaviour (e.g., Bultreys et al., 2016). However, discrepancies between laboratory measurements (e.g., porosity) and image-based estimates persist, mainly due to the limited dynamic range of μ CT imaging (Hall and Hoff, 2021). As reviewed by Baker et al. (2012), digital rock physics applied to igneous rocks enables detailed imaging and quantification of textural and morphological features, such as vesicles and crystals.

Image analysis: Filtering, segmentation, and quantification of size and shape features

PerGeos® software (version 2020.1), provided by INGV-OV, was employed to analyse 3D and 2D scanned images acquired through μ CT and SEM, respectively. Given the specimen size and available computational capacity, no volume of interest (VOI) was selected, as the full volume adequately represented sample heterogeneity. While non-local means filtering was occasionally applied, most raw images were of sufficient quality to be used directly without further processing.

Segmentation of the pore space and main phenocrysts was conducted using both thresholding and morphological operations. Pore space segmentation was conducted by manually thresholding the grey-level histogram. When fractures were present, they were segmented independently from the rest of the pore network. Due to the similar X-ray attenuation between phenocrysts and groundmass, traditional thresholding methods were insufficient for accurate segmentation. As a result, a machine learning-based, texture-supervised classification was implemented, using manually segmented phenocrysts as ground truth. The quantification of the number of pores (porosity) and phenocrysts to microphenocrysts (porphyritic degree) considered their volume fraction in a segmented mask, also created using thresholding and morphological operations. Regarding porosity, besides total porosity (n_T or $n_{T-\mu CT}$), effective porosity ($n_{eff-\mu CT}$) was quantified using a dedicated module to determine the connectivity along the elongated axis of the samples (z-axis). Isolated porosity ($n_{isol-\mu CT}$) corresponds to the difference between the $n_{T-\mu CT}$ and $n_{eff-\mu CT}$. When the pore space demonstrated connectivity, tortuosity of the pore space (centroid path tortuosity; T) was computed on PerGeos® based on the path formed by the centroids on each plan along the z-axis of the 3D image and the path length through the centroids, dividing it by the number of planes along the z-axis.

Table 3.4. Selected label analysis parameters and their description according to the user's guide of PerGeos® software (PerGeos, 2021). Table reproduced after the Glossary of Pereira et al. (2025a).

Parameter	Description
Anisotropy	One minus the ratio of the smallest to the largest eigenvalue of the covariance matrix, measuring the deviation of a region from a sphere
Area	Area of the object or of the object boundary
Breadth	Largest distance, in a plane orthogonal to the maximum Feret diameter, between two parallel lines touching the object but not intersecting it.
Circularity	Proximity of the boundary of a particle to a perfect circle (Eq. 3.14)
$Circularity = \frac{4\pi Area}{CroftonPerimeter^2} \quad (3.14)$	
Crofton perimeter	Average of four <i>VarDiameter</i> measures, which are the product of <i>intercept(i)</i> with the distance between interception points. This measure is preferred for measuring object perimeters.
Eccentricity	Deviation of a conic section (circle, ellipse, etc.) from a circular shape, reaching the value zero for a true circle.
Elongation	Ratio between the largest eigenvalue of the covariance matrix, with elongate objects having values close to zero.
Equivalent diameter	Diameter of the circle of same area (2D; Eq. 3.15) or of the sphere of same volume (3D; Eq. 3.16). The equivalent radius is half of the equivalent diameter.
$EqD = \sqrt{\frac{4 Area}{\pi}} \quad (3.15)$	
$EqD = \sqrt[3]{\frac{6 Volume}{\pi}} \quad (3.16)$	
Feret diameter	Length of the Bounding Boxes distributed along the designated directions, describing how “wide” an object is in a given direction.
Feret shape	Ratio between b/a , where a is the minimal Feret diameter and b is the Feret diameter closest to the normal of the minimal Feret diameter.
Length	Maximum of the Feret diameters.
Roundness	Deviation of the surface of a particle from a true circle (Eq. 3.17).
$Roundness = 4 \left(\frac{Area}{\pi Length^2} \right) \quad (3.17)$	
Shape factor	Describes the shape of an object in 2D (Eq. 3.18) or 3D (Eq. 3.19), excluding the effect of its dimensions.
$SF_{2D} = \frac{CroftonPerimeter^2}{4\pi Area} \quad (3.18)$	
$SF_{3D} = \frac{Area^3}{36\pi Volume^2} \quad (3.19)$	
Sphericity	Proximity of a particle to a sphere (Eq. 3.20).
$Sphericity = \frac{\pi^{\frac{1}{3}} (6Volume)^{\frac{2}{3}}}{Area} \quad (3.20)$	
Thickness	Largest distance, in a plane orthogonal to the maximum Feret diameter, that touches an object by its end points.
Width	Minimum of the Feret diameters.
Length phi	Angle ϕ of the maximum of the Feret Diameters, in degrees [0, +90].

The size and geometry parameters of pores and crystals were quantified using the label analysis module of PerGeos®, which can be personalised in terms of parameters to be quantified. Table 3.4 parameters were quantified and defined according to the user's guide PerGeos® (PerGeos, 2021).

A filter analysis was performed to exclude objects with less than two voxels/pixels in volume or area, as such small features are associated with high uncertainty (Hughes et al., 2017; Pappalardo et al., 2018). During data processing, it was observed that these small objects led to erroneous sphericity measurements and were, therefore, removed from subsequent analyses.

Computed permeability

Permeability (k) in rocks can be assessed through various laboratory techniques or estimated using theoretical models (Lavallée and Kendrick, 2021, and references therein). Laboratory-based permeameters are commonly used, yielding values between 10^{-15} and 10^{-11} m² for volcanic rocks. However, challenges in specimen preparation and measurement have encouraged the use of computational methods based on 3D connected pore network, employing physical principles such as the Navier–Stokes equation and specified boundary conditions. Despite these advances, accurately capturing the full complexity of pore networks, especially nanoscale feature, remains difficult (Hall and Hoff, 2021).

In this work, k was calculated using μ CT data and the Absolute Permeability Lattice Boltzmann module in PerGeos® software. After segmenting the connected pore space, the module simulated single-phase fluid flow by solving the Navier-Stokes equation and applying Darcy's law (Eq. 2.7). Permeability was derived as the product of fluid viscosity and the ratio of steady-state superficial velocity to the mean pressure gradient (Baker et al., 2012; PerGeos® user's guide, 2021). This analysis was applied to regular specimens and cuttings (Table 3.3), for which effective porosity was resolved at the given voxel resolution.

Pore network models

Pore network models (PNM) were generated using PerGeos® software for specimens with a resolved connected pore space. The PNM algorithm transforms the segmented pore space into a simplified representation composed of pores—idealised as spheres with equivalent volumes to the original pore—and throats—cylindrical connections characterised by specific lengths and diameters—forming a network.

These models enable visualisation and analysis of pore connectivity and geometry. Parameters such as pore and throat size distributions (based on equivalent radius), cumulative pore volume, and channel length were quantified. The coordination number (CN), which indicates the number of throats connected to each pore, was computed to assess the connectivity of the network.

3.2.6.3. Computation of the failure criteria

Laboratory triaxial data were used as input in RSData software (v1.007; Rocscience®) to derive both the Mohr-Coulomb (MC; Section 2.2.4.4, Part C) and Hoek-Brown (HB; Section 2.2.4.4, Part C) failure criteria. For the MC calibration, the Levenberg-Marquardt curve-fitting algorithm was employed, using vertical error summation and absolute residuals. The HB criterion was calibrated using the modified Cuckoo algorithm with basic error summation and absolute residuals. ITS or σ_t data were included in the HB analysis.

Upscaling to rock mass conditions was performed using the HB criterion, assuming a GSI of 55, characteristic of a fractured and heterogeneous rock mass, and a disturbance factor (D) of 0. A slope height (H_{slope}) of 500 m was considered, corresponding to the elevation of the Cachaços-Lombadas sector in the Ribeira Grande geothermal field. The dry unit weight (γ) was calculated from ρ_{dry} obtained via ISRM (2007).

Rock mass internal friction angle (ϕ_{rm} ; Eq. 3.21) and cohesion (c_{rm} ; Eq. 3.22) were determined based on the maximum confining stress (σ'_{3max} ; Eq. 3.23 and Eq. 3.24), which depends on the global rock mass strength (σ_{rm} ; Eq. 3.25). The elastic modulus of the rock mass (E_{rm}) was estimated using the generalised Hoek and Diederichs (2006) equation (Eq. 2.12).

$$\phi'_{rm} = \sin^{-1} \left[\frac{6am_b(s + m_b\sigma'_{3n})^{a-1}}{2(1+a)(2+a) + 6am_b(s + m_b\sigma'_{3n})^{a-1}} \right] \quad (3.21)$$

$$c'_{rm} = \frac{\sigma_{ci_HB}[(1+2a)s + (1-a)m_b\sigma'_{3n}](s + m_b\sigma'_{3n})^{a-1}}{(1+a)(2+a)\sqrt{1 + (6am_b(s + m_b\sigma'_{3n})^{a-1})/((1+a)(2+a))}} \quad (3.22)$$

$$\sigma_{3n} = \frac{\sigma'_{3max}}{\sigma_{ci_HB}} \quad (3.23)$$

$$\sigma'_{3max} = 0.72\sigma'_{crm} \left(\frac{\sigma'_{crm}}{\gamma H} \right)^{-0.91} \quad (3.24)$$

$$\sigma_{rm} = \sigma_{ci_HB} \frac{(m_b + 4s - a(m_b - 8s))/(m_b/4 + s)^{a-1}}{2(1+a)(2+a)} \quad (3.25)$$

3.2.6.4 Statistical analysis

Descriptive statistics

Descriptive statistics was used to summarise the characteristics of the obtained dataset. The analysis was conducted using Microsoft® Excel's data analysis toolpak to characterise parameters such as strength, open porosity, dry density, and features describing the shape and size of vesicles and crystals. The statistical outputs included mean (avg), median, maximum (max), minimum (min), range, count (N), standard deviation (std.dev), variance (var), and sum. Among these, the mean and range were more often used to report results from the physical and mechanical laboratory tests.

Multivariate statistical analysis

Principal Component Analysis (PCA; Pearson, 1901) is a multivariate method that enables the identification of subsets of variables that are highly correlated with each other and weakly associated with variables in other subsets. In this way, it makes it possible to divide the variables of interest into distinct subgroups, allowing to:

1. Identify the relevant dimensions that structure the relation between the variables and understand this structure
2. Reduce the information by defining new variables that correspond to the identified dimensions.

PCA is only applied when there is an adequate sample dimension and when there are multiple correlations between the input variables, which can be assessed using the Kaiser-Meyer-Olkin (KMO) statistics and Bartlett's test of sphericity. It is considered that the higher the value of KMO, the higher the number of correlations between the input variables, which favour the PCA (Reis, 2006). For Bartlett's test, when the level of significance is below the p -value (e.g., 0.05), then the correlation matrix is not an identity matrix (Reis, 2006).

As described by Jolliffe (2002), PCA transforms a dataset into a new system structured by uncorrelated variables called principal components (PCs), each formed by a linear combination of the initial variables. These components are calculated in order by the amount of variance they explain in the data.

PCA is based on the eigenvectors and eigenvalues of the covariance matrix (Reis, 2006). The eigenvectors define the directions of maximum variance (the PCs), while the eigenvalues

indicate the proportion of variance in each component. The first principal component (PC1) captures the most variance in the original dataset, the second (PC2) captures the largest remaining variance, and so on. The final components contribute the least to explaining the total variance.

During the extraction phase of PCA, only a subset of components is retained based on specific criteria. Common methods include the Kaiser criterion, the percentage of total variance explained, and the Scree test (Cattell, 1966), which is typically visualised using a Scree plot. Communalities, representing the variance of each initial variable explained by the PCs, should generally be greater than 0.5.

The results are summarised in a component matrix, which shows the loadings of each initial variable on the PCs. In each component, variables with loadings of $|0.5|$ or higher are considered representative, although thresholds of $|0.3|$ or $|0.4|$ are also acceptable (e.g., Field, 2013). In other words, these high-loading variables are used to interpret and define the meaning of each PC.

Component rotation is optional but frequently applied in PCA to aid interpretation (Reis, 2006). Rotation clarifies the results by maximising the loading of each variable on a single component while minimising its influence on others. Rotations can be orthogonal (e.g., varimax), preserving the independence of components, or oblique, which allows components to be correlated.

A PCA scatter plot illustrates the relationship between the original variables and the principal components (Mason and Gunst, 1985). In this plot, variable loadings are represented by their direction and distance to the plot origin, which indicate the strength and influence of each variable on the components, helping to identify those that most significantly contribute to the data's variance, as well as outliers.

PCA analyses were performed in IBM® SPSS statistics 29.0 software. They were conducted in Chapter 4, based on the work of Pereira et al. (2024b) and Pereira et al. (2025a), and in Chapter 6. The goal was to reduce the number of variables characterising the pore system (2D and 3D), including those describing the connected and isolated porosity. The original dataset comprised the following variables (Table 3.4): length, width, breadth, thickness, Feret diameter, area, Crofton perimeter, equivalent diameter, Feret shape, shape factor, eccentricity, elongation, anisotropy, roundness, circularity, and sphericity. The analysis was performed using a varimax rotation (orthogonal) with Kaiser normalisation.

In Chapter 6, a PCA analysis was performed to investigate the correlation between the original variables (V_p , V_s , V_p/V_s , E_d , ν_d , G , K , C_{EN} , n_{cc} , C_m , C_e , C_a , UCS , ITS , V_p) and the established PCs, using a Varimax rotation with Kaiser normalisation.

Regression analysis

Regression analysis is a statistical method that was employed in this research to estimate the relationships between a dependent variable and one or more independent variables. The main goal was to obtain empirical equations for variable prediction in the same or similar rock materials.

Simple and multiple regression analyses of geotechnical properties were conducted using Microsoft® Excel and IBM® SPSS softwares. Model significance was evaluated through analysis of variance (ANOVA; Herzog et al., 2019), using the p -value and F -test at a 95% confidence level. Pearson's correlation coefficient was applied to assess linear relationships, while Spearman's rank correlation was used to explore potential non-linear associations between variables (Benesty et al., 2009).

The performance of the empirical models was evaluated using several statistical metrics: coefficient of determination (R^2), root mean square error (RMSE; Eq. 3.26), mean absolute percentage error (MAPE; Eq. 3.27), and variance accounted for (VAF; Eq. 3.28).

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (y - y')^2} \quad (3.26)$$

$$MAPE = \left[\frac{1}{N} \sum_{i=1}^N \left| \frac{y - y'}{y} \right| \right] \times 100 \quad (3.27)$$

$$VAF = \left[1 - \frac{var(y - y')}{var(y)} \right] \times 100 \quad (3.28)$$

where N is the number of data points, var is the variance, and y and y' correspond to the measured and estimated values, respectively.

3.3. Overview

Fig. 3.10 summarises the materials and corresponding methods used in the subsequent results and discussion chapters (Chapter 4 to Chapter 8).

Table 3.5. presents the various standards and procedures used for each test, software used for the several analysis and respective objectives.

	MATERIALS	LABORATORY	METHODS	ANALYSIS	
FRESH AZOREAN LAVA ROCKS	Ch.4	Thin sections Irregular lumps Prisms (~11.5 mm×16/20 mm) Cylinders (~7.7 mm diameter; L/D~2)	Petrography + SEM-BSE Whole-rock chemistry + buoyancy method (ISRM, 2007) μCT + MIP + buoyancy method Uniaxial test w/ μCT	Classification (TAS) Image analysis + models Descriptive statistics Multivariate analysis	
	Ch.5	Irregular lumps Discs Cylinders	Buoyancy method (ISRM, 2007) Brazilian test (ISRM, 2007) Uniaxial test + triaxial test (ISRM, 2007) + direct pulse transmission (ISRM, 2007)	Descriptive statistics Regression analysis Failure criteria computation	
	Ch.6	Cubes (~28 - 31 mm) + Prisms (~10×20 mm) Cylinders (~7.7 mm diameter; L/D~2) Discs (13.2 mm diameter; L/D~0.5)	Buoyancy method (ISRM, 2007) + capillary absorption (NP EN 1925:2000) + direct pulse transmission + MIP Uniaxial test w/ μCT Brazilian test w/ μCT	Descriptive statistics Multivariate analysis Image analysis + models	
	HYDROTHERMALLY ALTERED ROCKS	Ch.7	Worldwide altered volcanic rocks Data compiled by Pereira et al. (2024a)		Data collection Descriptive statistics
		Ch.8	Prisms (~10×18 mm) Cuttings	Whole-rock chemistry + μCT Pycnometer + μCT	Image analysis Descriptive statistics Classification (TAS) + CIA, CIW, LOI, and major elements

Fig. 3.10. Summary of the materials and methods used in Chapters 4, 5, 6, 7, and 8, which represent the results (and their discussion) of the thesis.

Table 3.5. Summary of the conducted analyses and respective methods. Used guidelines/standards and software.

Analysis	Method	Thesis Section	Guidelines/ Standards	Software for data treatment	Objective
Macroscopic description	Hand sample observation	3.2.1.	EN 12407:2019; field-based IUGS QAPF diagram Proposed description in Fig. 3.8.	-	Macroscopic classification and sample grouping Defect recognition
Petrographic analysis	Optical microscopy and point counting	3.2.2.1.	EN 12407:2019; IUGS QAPF diagram	PetrogLite®	Petrographic classification
2D imaging	SEM-BSE and image analysis	3.2.2.2	No standard	PerGeos®	Full BSE image of the thin-sections
3D imaging and time-resolved tests	µCT and image analysis	3.2.2.3	No standard; see conditions in	ZEISS® XRM	Define the 3D internal
		3.2.5.4	Table 3.3	Reconstructor PerGeos®	microstructure of samples, UCS and ITS
Whole-rock analysis	ICP – fusion for major oxides and gravimetric method for LOI	3.2.3	Actlabs procedure. 14 reference materials for calibration and detection limits between 0.01–0.001 %	-	Obtain geochemical data
Geochemical data analysis	TAS diagram Ternary plots - FMW Binary plots - Al ₂ O ₃ –FeOT; CaO+K ₂ O+Na ₂ O- Fe ₂ O ₃ ^T +MnO+MgO Variation: S; LOI; Na ₂ O Alteration index: CIW; CIA	3.2.3	See Section 3.2.3. for the authors that proposed the diagrams and chemical weathering indices	Microsoft® Excel R® GCDKit	Classify the rocks geochemically and identify signs of alteration
Density and open porosity	Saturation and buoyancy techniques	3.2.4.1	ISRM (2007) or an adaptation for smaller prismatic specimens	Microsoft® Excel	Determine n_{eff} and ρ for several specimens and irregular lumps
Dry density	Pycnometer method	3.2.4.1	No standard	Microsoft® Excel	Determine ρ for cuttings
Micropore characterisation	MIP	3.4.2.2	Procedure from IGEO	Microsoft® Excel	Define r , PSD, n_{eff_Hg} , and cumulative mercury intrusion and pore size distribution curves

Table 3.5. (continued).

Capillary water absorption	Determination of water absorption coefficient by capillary	3.2.4.3.	NP-EN 1925:2000 SF model	Microsoft® Excel	Obtain the water absorption curves and determination of C
Ultrasonic wave velocity	Direct pulse transmission technique	3.2.4.4	First methods of ISRM (2007) or an adaptation for cubic samples ASTM D2845-08 (2008)	Microsoft® Excel	Determine V_p , V_s , and ultrasonic elastic constants
ITS or σ_t	Brazilian test	3.2.5.1	ISRM (2007) ASTM D3967-23 (2023)	Microsoft® Excel	Determine the ITS
UCS or σ_{c_UCS} and deformability	Uniaxial test Stress-strain curves-based methods	3.2.5.2	ISRM (2007) ASTM D7012-23 (2023) LSRM and volumetric strain	Microsoft® Excel	Determine UCS and elastic properties Determine the crack thresholds
Strength in triaxial compression	Triaxial individual test (type I)	3.2.5.3	ISRM (2007) ASTM D7012-23 (2023)	Microsoft® Excel	Determine σ_c for distinct confining pressures
Digital rock analysis	Image analysis and modelling	3.2.6.2	-	PerGeos® Microsoft® Excel	Determine of porosities, k , PNM, parameters in Table 3.4., Determine shear strength
Failure criteria analysis	HB and MC criteria using triaxial data	3.2.6.3.	-	Rocscience® RSDData	parameters for the intact rock and strength and deformability for a rock mass Define the relation between variables and reduce the dataset
Statistical analysis	PCA Regression analysis	3.2.6.4	-	Microsoft® Excel IBM® SPSS	Define new empirical equations and evaluate the performance of the empirical models

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Fresh Azorean Lava Rocks

Chapter

Characterisation of the physical
and mechanical properties
of Azorean lava rocks with distinct
microstructure through a multi-
-method approach

Characterisation of the physical and mechanical properties of Azorean lava rocks with distinct microstructure through a multi-method approach

This chapter is based on the publication by Pereira et al. (2025a)¹. An adaptation of the paper was pursued, with excerpts integrated throughout this chapter and properly cited, following Universidade dos Açores rules and also aligning with the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0).

4.1. Preliminary notes

The diverse origins of volcanic rocks result in complex and variable microstructures (Rust and Cashman, 2011; Sparks et al., 2019), which lead to their unpredictable deformation features (e.g., Pappalardo and Mineo, 2017). Rock properties such as permeability and mechanical strength are controlled by porosity, as well as the size, shape, and orientation of voids (Heap et al., 2014b, 2018c, 2022; Pappalardo et al., 2017, 2025; Vairé et al., 2024), crystal content (Heap et al., 2016; Zorn et al., 2018), and alteration processes (Jamtveit et al., 2011; Vieira et al., 2021; Liu et al., 2023). However, the complex interactions among pores, microcracks, and crystals, as well as their implications for rock deformation and long-term durability (Heap et al., 2014a; Zhu et al., 2016; Heap et al., 2020ab; Török and Přikryl, 2010), remain insufficiently understood. Additional microstructural characterisation may provide valuable insights into these mechanisms, with potential to improve geomechanical classifications (Bieniawski, 1989; González de Vallejo and Ferrer, 2011; Miranda et al., 2015) and predictive models of intact rock (e.g., Bubeck et al., 2017; Griffiths et al., 2017) and rock mass failure (e.g., Reinoso et al., 2019).

To investigate the microstructure of volcanic rocks, various analytical techniques have been applied, including digital rock physics, which integrates X-ray microtomography (μ CT), 3D image analysis, and advanced numerical modelling (Higgins, 2000, 2006; Baker et al., 2012; Cnudde and Boone, 2013). In volcanic rocks, 3D imaging enables detailed interpretation of

¹ Pereira, M.L., Pappalardo, L., Buono, G., Cueto, N., Vázquez-Calvo, C., Fort, R., Costa e Silva, M., Fernandes, I., Zanon, V., and Amaral, P., 2025a, A multi-method approach in the physical and mechanical assessment of lava rocks with distinct microstructure: *Engineering Geology*, v. 346, 107907, <https://doi.org/10.1016/j.enggeo.2025.107907>. Licensed under CC BY4.0.

lava emplacement dynamics and flow direction (Walker, 1987; Song et al., 2001; Jamtveit et al., 2011; Polacci et al., 2018; Heap et al., 2020b; Liu et al., 2023). μ CT has also been extended into four dimensions by capturing temporal changes in rock structure under varying conditions (Noiriel and Renard, 2022), making it suitable for investigating deformation during mechanical loading (McBeck et al., 2020) and fluid flow in porous media (Noiriel and Renard, 2022). Combining μ CT with traditional 2D imaging techniques (e.g., Heap et al., 2014b; Zhu et al., 2016) and laboratory testing (Heap and Violay, 2021; Lavallée and Kendrick, 2021) improves the characterisation of volcanic rocks.

On São Miguel Island, lava rocks are considered “hard” geotechnical units (Table 3.1; Fig. 3.5), though they remain susceptible to seismic, volcanic, and meteorological hazards (Malheiro, 2006; Malheiro and Nunes, 2007). Despite their widespread use in engineering applications, including building stone and aggregate, the data on the physical and mechanical properties of these materials remains limited (Loaiza et al., 2012; Moreira and Wallenstein, 2012), with their microstructure largely unexplored.

This chapter presents the first microstructural characterisation of lava rocks from São Miguel Island, focusing on representative samples from the stratigraphy and subsurface geology of the Fogo (Água de Pau) and Sete Cidades volcanic systems (see Section 3.1.2). A comprehensive, multi-scale approach was employed, integrating 2D petrographic analysis with 3D digital rock physics. Crystal and vesicle content, size, and shape were assessed using μ CT and thin-section imaging. Physical properties, including effective porosity (n_{eff}) and density (ρ), were quantified using ISRM suggested methods and mercury intrusion porosimetry (MIP). μ CT-based characterisation of pore geometry (e.g., size distribution, mean pore size, and sphericity) was coupled with permeability modelling and the development of pore network models. The mechanical behaviour of the rocks was evaluated through unconfined compressive strength (UCS) testing, with μ CT capturing the development of microcracks during loading.

4.2. Summary of materials and methods

Ten samples were selected for the preliminary multi-method analysis. The samples correspond to representative lava rocks obtained from five basaltic (BP37, BP38, BAF14, BAF16, BAF18), three intermediate (BF3, BF13, BF15) and two trachytic (T29, T31) blocks (Fig. 4.1). The intermediate terms are basalts *sensu lato* but show more plagioclase phenocrysts at hand sample than BP and BAF. The samples represent the subfacies BPA, BAF.A, BFA, BFB, and TAI/AII from Fig. 3.6.

The rocks are also referred to by their vesicular (BF13 and BF15), fractured (BAf16) and massive (remaining lavas) textures (Fig. 4.1). The term vesicular refers to textures of high porosity and evident pores, whereas massive lavas are compact/coherent low-porosity rocks without evident voids. The specimens were obtained for different sizes and configurations according to the laboratory test (Fig. 4.2).

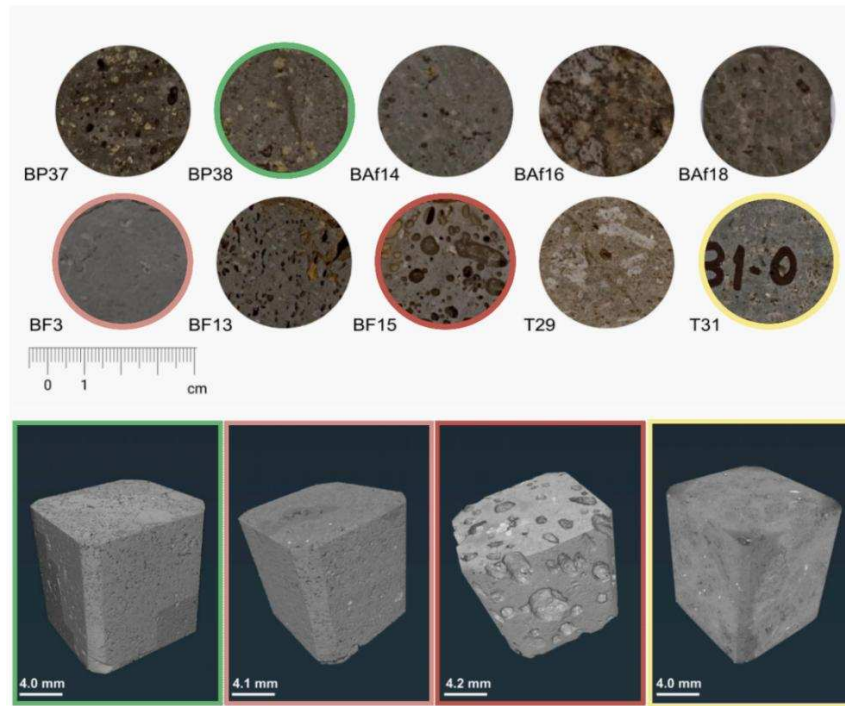


Fig. 4.1. Texture of the hand specimens per sample and 3D X-ray microtomography image of a low-porosity olivine basalt (BP38; green), low-porosity intermediate lava (BF3; pink), a vesicular/ high-porosity intermediate lava (BF15; red), and a trachyte (T31; yellow). Image reproduced and caption adapted from Pereira et al. (2025a), licensed under CC BY 4.0.



Fig. 4.2. Sample size and configurations. Image reproduced from Pereira et al. (2025a), licensed under CC BY 4.0.

4.2.1. Petrographic, geochemical and microstructural analysis

The petrographic analysis included the description of the ten samples as polished thin-sections and the point counting of the crystals ($Ph_{2D; PC}$) and voids (n_{T-PC}), using the equipment presented in Section 3.2.2.1. Microstructure was further investigated using a SEM to obtain high-resolution (2.74 to 2.86 μm) 2D scans (see Section 3.2.2.2). Whole-rock chemistry was conducted, and geochemical data was classified, as described in Section 3.2.3.

μCT equipment was employed to scan prisms of $\sim 11.5 \text{ mm} \times 16/20 \text{ mm}$ (Fig. 4.2) of all 10 samples in 3D. X-ray imaging conditions are presented in Table 3.3 for prisms BP37, BP38, BAF14, BAF16, BAF18, BF3, BF13, BF15, T29, T31. 1601 2D radiographs were acquired in absorption mode over a 360° rotation with 100 to 120 kV voltage, 10 W power, variable exposure time (0.7 to 1.2 s), $0.4\times$ optical magnification, using distinct source filters to minimise beam hardening. The resulting nominal voxel size ranged between 14.68 μm and 15.37 μm . The reconstruction of 3D images was performed as described in Section 3.2.2.3 and the obtained images are presented in Fig. 4.1.

Ten oven-dried prisms were analysed in a porosimeter to define connected porosity (n_{eff_Hg}), mean porous radius (r) and pore size distribution (PSD) for a pore radius range of approximately 0.0015 to 180 μm . The equipment and procedure were presented in Section 3.4.2.2.

4.2.2. Physical properties

The ρ and n_{eff} were calculated for irregular lumps of the 10 samples, using the saturation and buoyancy technique described by the ISRM method in Section 3.2.4.1 (ISRM, 2007; ρ_{ISRM} ; n_{eff_ISRM}). The method was also applied utilising an electronic densimeter (Section 3.2.4.1; $\rho_{adp.ISRM}$; $n_{eff_adp.ISRM}$) in four prisms and one prism of each sample, using the quick water and paraffin immersion techniques (Crawford, 2013), respectively.

4.2.3. Mechanical properties

Time-resolved UCS tests combined with μCT imaging were performed on four $\sim 7.5 \text{ mm}$ diameter oven-dried cylinders (i.e., BAF14, BF3, BF13, and T31 samples; Fig. 4.2) with an L/D of ~ 1.9 . The tests were as described in Section 3.2.5.4. The σ_{c_UCS} corresponded to the peak stress achieved and the Young's modulus (E) was calculated using the stress-strain curves. Distinct elastic modulus (average - E_{avg} , tangent - E_{tg} , and secant- E_{sec}) were

determined following Section 3.2.5.2, as they are known to change significantly (Małkowski et al., 2018).

Pre- and post-deformation 3D scans were obtained, using 801 projections over a total angular scan of 180° (plus fan angle) to obtain 3D images with a nominal voxel size of 15 µm (see conditions in Table 3.3 for cylinders Baf14, BF3, BF13).

4.2.4. Data analysis and simulations

3D µCT and 2D SEM scanned images were analysed following the procedure described in “Image Analysis: Filtering, Segmentation, and Quantification of Size and Shape Features” of Section 3.2.6.2. Given the difficult segmentation of the phenocrysts, machine learning-based texture-supervised classification was applied. Regarding the segmented objects, those with less than two pixels/voxels in area/volume were excluded as mentioned in Section 3.2.6.2.

Total porosity ($n_{T-\mu CT}$ for prism scans; $n_{T-2D;IA}$ for thin-section images), effective porosity ($n_{eff-\mu CT}$), isolated porosity ($n_{isol-\mu CT}$), tortuosity of the void space (centroid path tortuosity; T), porphyritic degree ($Ph_{\mu CT}$ for prism scans; $Ph_{2D;IA}$ for thin-section images), and geometric parameters of pores and crystals were quantified using dedicated modules from PerGeos®. The absolute permeability (k) was simulated for a single-phase fluid flow, as described in Section 3.2.6.2. (Computed permeability).

The label analysis allowed to calculate numerous 3D and 2D parameters (length, width, breadth, thickness, Feret diameter, area, Crofton perimeter, equivalent diameter, Feret shape, shape factor, eccentricity, elongation, anisotropy, roundness, circularity, and sphericity) that describe the shape and size of the pores and crystals (see Table 3.4; PerGeos, 2011). To reduce the number of variables describing the shape and size of the pores, a principal component analysis (PCA) was conducted (see Section 3.2.6.4., “Multivariate Statistics”). Those parameters were also applied in the characterisation of the crystals.

Pore network models (PNM; Section 3.2.6.2) were obtained for vesicular (BF13 and BF15) and fractured (BAf16) prismatic specimens to model the internal and connected pore structure, composed by a network of pores (spheres) and throats (lines).

4.3. Results and discussion

The analysis strategy adopted by Pereira et al. (2025a) involved various multi-scale techniques to examine the full range of pores and phenocrysts. The applied methods have

been widely used individually before, but their integration remains underexplored. The selected strategy, combining 2D and 3D imaging with laboratory techniques and image analysis, effectively characterises heterogeneous materials like lava rocks. As Schepp et al. (2020) emphasise, the resolution plan and varying sample dimensions yield complementary but not coincident results.

4.3.1. Petrographic and geochemical characterisation

Results on the petrography and whole-rock chemistry of the 10 samples are reproduced from Pereira et al. (2025a). IUGS classification using the mineral content (Streckeisen, 1980; Le Maitre et al., 2002) classifies BP and BAf (Sete Cidades Volcano) and BF (Fogo Volcano) as basalts, and T29 and T31 as trachytes. Whole-rock chemistry further classifies the samples into *alkali-basalts* (BAf and BP; BAf18 is a trachybasalt), *basaltic trachyandesites* or mugearites (BF3 and BF15), *trachyandesite* or benmoreite (BF13), and comenditic *trachytes* (T; Cox et al., 1979; De la Roche et al., 1980; Le Bas et al., 1986). Onwards, mugearites are referred to as basaltic trachyandesites, while benmoreites as trachyandesites. Both are also referred to as intermediate lavas. The FMW classification (Ohta and Arai, 2007) indicates that basalts are fresh, while trachytes are slightly altered.

All samples have holocrystalline with a porphyritic (Fig. 4.3a) to seriate texture (Fig. 4.3b), sometimes intergranular (Fig. 4.3c) and rarely glomeroporphyritic (Fig. 4.3d). The texture can be vesicular (BF15, BF13; Fig. 4.3f), fractured (BAf16; Fig. 4.3p), and massive (remaining samples; Fig. 4.3e)

Regarding the minerals in the samples, basalts (s.l.) comprise euhedral to anhedral phenocrysts often with zoning (Fig. 4.3g and Fig. 4.3h), signs of disequilibrium (reaction rim; Fig. 4.3i), embayments, rare skeletal shape, and a sieve texture of the plagioclase (Fig. 4.3j). The minerals correspond to olivine, clinopyroxene, and plagioclase phenocrysts, also present in the fine to medium-grained groundmass together with opaque minerals (titanomagnetite and ilmenite; Fig. 4.3k). Trachytes are composed of tabular to needle-like alkali-feldspar arranged sub-parallelly, forming a trachytic texture (Fig. 4.3r). Alkali-feldspar (Fig. 4.3t; Fig. 4.3s) occurs as phenocrysts or in the groundmass with biotite, opaque minerals, minor amphibole (Fig. 4.3u), quartz, apatite, and brown clinopyroxene/amphibole (T31; 4.3w).

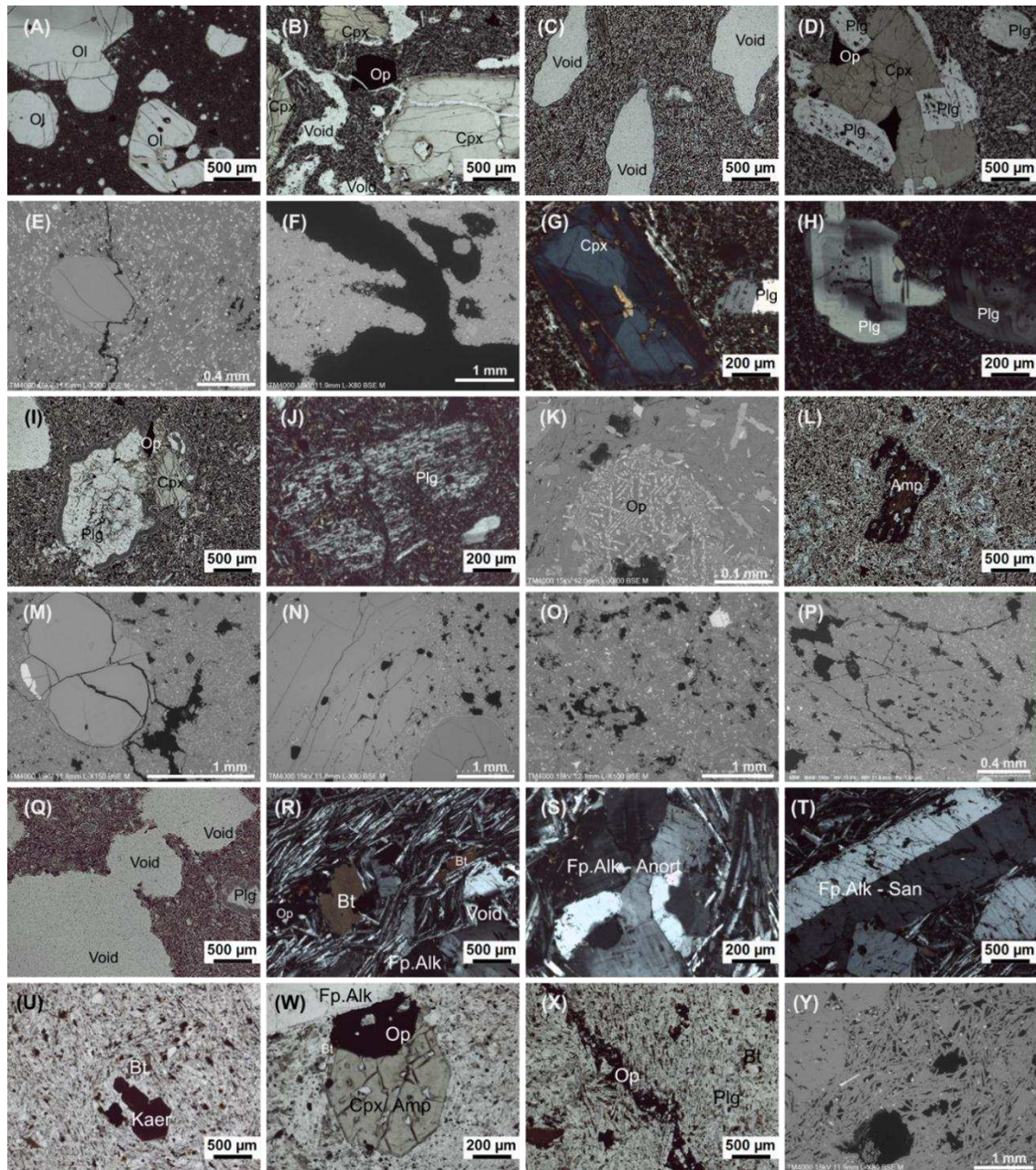


Fig. 4.3. Microphotographs (// - plane-polarised light; X – cross-polarised light) and electron microscope images in backscattered mode (SEM-BSE) of polished thin-sections. Ol – olivine; Cpx – clinopyroxene; Plg – plagioclase; Op – opaque mineral; Amp – amphibole; Bt – biotite; Fp. Alk- alkali-feldspar; Anor – anorthoclase; San – sanidine; Kaer- kaersutite. (A) Porphyritic texture with phenocrysts of olivine and clinopyroxene in a fine-grained groundmass (BP37; //); (B) seriate texture, intergranular with isolated and elongated pores (BF13; //); (C) seriate texture, intergranular with isolated and elongated pores (BF13; //); (D) clots of clinopyroxene, plagioclase and opaques – glomeroporphyritic texture (BAf14 //); (E) massive texture with a transgranular fracture with sawed contour (BAf18; SEM-BSE); (F) coalescence of elongated pores (BAf13; BSE); (G) hourglass zoning of clinopyroxene (BAf18; X); (H) zoning of plagioclase (BAf14; X); (I) clot of plagioclase (reaction rim), clinopyroxene and opaque in a vesicular specimen (BAf15; //); (J) disequilibrium of the plagioclase with intense sieve texture (BAf16; //); (K) opaque minerals along the reaction rim of plagioclase (BF3; SEM-BSE); (L) minor brown-amphibole with opaque minerals on its borders (BF3; //); (M) opening of the pre-existing fractures of olivine, connecting to pores in the groundmass (BAf16; SEM-BSE); (N) isolated small pores in the groundmass and phenocrysts (BP37; E; SEM-BSE); (O) irregular

and angular pores in the groundmass (BF3; SEM-BSE); (P) intracrystalline pores connected by transgranular cracks (BAf16; SEM-BSE); (Q) coalescence of pores (BF15; //); (R) trachytic texture and biotite crystal (T29; X); (S) anorthoclase and (T) sanidine twinning (T29; X); (U) kaersutite amphibole (T29; //); (W) alteration product with green colour (T31; //); (X) filling of fractures by opaque minerals (T29; //); (Y) pore space limited by the laths of feldspar (T29; SEM-BSE). Image and caption reproduced from Pereira et al. (2025a). Licensed under CC BY 4.0.

In terms of weathering and alteration, basalts are fresh, with minor oxidation in BAF and a brown amphibole in the intermediate rocks (BF; Fig. 4.3l). Trachytes show minor alteration of feldspar to sericite, biotite to chlorite, and the oxide infill of fractures (Fig. 4.3x). Regarding voids, compact rocks contain rare disperse transgranular to intragranular microcracks (Fig. 4.3e). BAF16 fractured basalt have cracks nucleating from intragranular microcracks and pores (Fig. 4.3m). Massive basalts have round (Fig. 4.3n) and coalescent pores in the groundmass. The pores are angular and limited by the feldspar laths in the basaltic trachyandesite (BF3; Fig. 4.3o) and in the trachytes (Fig. 4.3y). Intracrystalline pores are observed in sieved plagioclase (Fig. 4.3p). Vesicular specimens (BF13 and BF15) display irregular and elongated pores due to the coalescence and pore-linking fractures (Fig. 4.3f).

4.3.2. Physical properties data

The analysis strategy involved various multi-scale techniques that produce complementary but not directly coincident porosity and porphyritic degree (or phenocryst content) data (Table 4.1). Results are reproduced from Pereira et al. (2025a) and presented by rock type.

Thin-section analysis enabled the determination of the number of pores and crystals through 2D image analysis (IA) and point counting (PC). Dry density and effective porosity were determined for 50 prisms ($\rho_{adp.ISRM}$; $n_{eff.adp.ISRM}$) and 98 larger irregular lumps (ρ_{ISRM} ; $n_{eff.ISRM}$) based on saturation and buoyancy techniques of ISRM (2007). One prism per sample (* in Table 4.1) was further analysed for $n_{eff.Hg}$ using MIP (pore radius < 180 μm) and to determine several physical properties and phenocryst content in 3D using the μCT .

Table 4.1.(next page) Average values and number of specimens (N) tested under dry conditions and through distinct methods, reproduced from Pereira et al. (2025a; licensed under CC BY 4.0) and updated from Pereira et al. (2023a). *Corresponds to the porosity of the prisms analysed in the μCT and MIP ρ – dry density; n_T – total porosity; n_{eff} – effective/ open porosity; n_{isol} – isolated porosity; k – permeability; T – tortuosity; Ph – phenocrysts; H₂O – quick water immersion technique; Paraff. – paraffin immersion technique; Hg Por. – mercury porosimeter. The areal percentage of crystals and void space were assessed using point counting and image analysis (PerGeos®) of SEM-BSE images. Since two thin-sections for each sample of BP and BAF were analysed, quantifications refer to average values. Configurations of prismatic specimens tested in the μCT are in Table 3.3.

Table 4.1. Caption in the previous page.

Sample	Thin-section				Irregular lumps; ISRM (2007)		Prismatic specimens; ISRM (2007) and electronic densimeter			Prismatic specimen (*); μ CT and image analysis						Prismatic specimen (*); Hg Por.	
	Point counting (%)		Image analysis (%)		ρ_{ISRM} (g/cm ³)	$n_{\text{eff_ISRM}}$ (%)	$\rho_{\text{adp.ISRM}}$ (g/cm ³)		$n_{\text{eff_adp.ISRM}}$ (%)	$n_{\text{T},\mu\text{CT}}$ (%)	$n_{\text{eff},\mu\text{CT}}$ (%)	$n_{\text{isol},\mu\text{CT}}$ (%)	T	k (mD)	Ph μCT (%)	$n_{\text{eff_Hg}}$ (%)	
	Ph _{2D} ; PC	n _{T_2D} ; PC	Ph _{2D} ; IA	n _{T_2D} ; IA			H ₂ O (N=4)	Paraff. (N=1)	(N=3)								
Basalt to trachybasalt																	
BP37	13.75	4.05	12.96	5.96	2.840 N = 10	6.30	2.906	2.859	6.98; 5.37*	2.07	-	-	-	-	16.60	4.08	
BP38	9.75	8.80	11.84	8.82	2.840 N = 11	5.55	2.808	2.713	2.79; 2.84*	3.92	-	-	-	-	21.85	8.25	
BAf14	19.35	5.30	17.79	6.38	2.741 N = 11	3.57	2.796	2.647	3.26; 2.46*	0.97	-	-	-	-	16.74	4.17	
BAf16	15.05	12.35	14.14	12.42	2.438 N = 10	13.10	2.479	2.287	14.62; 13.79*	14.33	8.53	5.78	2.92	248.6	14.84	17.75	
BAf18	13.40	7.40	13.89	10.70 (4.97 ^a)	2.723 N = 7	5.50	2.808	2.719	6.72; 4.72*	2.20	-	-	-	-	15.43	4.48	
Basaltic trachyandesite to trachyandesite																	
BF3	23.49	8.27	15.60	8.64	2.596 N = 11	7.96	2.655	2.591	5.90; 4.24*	2.44	-	-	-	-	9.36	6.17	
BF13	14.63	24.65	18.03	25.76	2.243 N = 8	15.64	2.318	2.155	11.67; 9.66*	19.61	12.85	6.75	2.59	256.2	10.66	8.17	
BF15	12.31	29.93	12.70	29.05	2.190 N = 10	21.85	2.196	1.888	13.64*	25.13	19.41	5.71	1.60	13263.9	5.74	12.64	
Trachyte																	
T29	27.30	17.00	19.54	16.10	2.145 N = 10	13.97	2.200	2.166	8.45*	3.33	-	-	-	-	19.38	16.06	
T31	30.00	3.60	21.14	3.53	2.467 N = 10	4.35	2.463	2.444	5.09; 5.11*	1.29	-	-	-	-	10.23	6.22	

The saturation and buoyancy technique (Table 4.1) adapted to prisms showed that paraffin and the quick water immersion tests produce similar results for massive rocks. For vesicular and fractured samples, paraffin-immersed samples yield anomalous results that may be due to incomplete waterproofing.

4.3.2.1. Alkali-basalts (BP and BAf)

In μ CT images, BP samples show higher phenocryst content (16.60–21.85 %) compared to BAf samples (14.84–16.74 %). However, phenocryst abundance observed in thin-sections may be underestimated by 1–11% relative to 3D digital analyses, as isolated megacrysts may not be present in thin-sections.

Localised zones of higher porosity are observed in massive basalts, but micropores predominate in the groundmass (pore radius <15 μ m; Franzson et al., 2010). Due to the higher resolution of SEM-BSE imaging, the total 2D porosity ($n_{T,2D}$) is higher for BP (4.05–8.82 %) and massive BAf (5.30–10.70 %) than the values obtained via μ CT ($n_{T,\mu CT}$), varying between 2.07–3.92 and 0.97–2.20, respectively.

ρ measurements indicate that massive BP basalts vary between 2.8 and 2.9 g/cm³, whereas BAf samples range from 2.7 to 2.8 g/cm³. n_{eff} ranges from 3.5 to 7 %, showing agreement between $n_{eff,ISRM}$ and $n_{eff,adp.ISRM}$. In some instances (e.g., BP38), prism samples may lack an interconnected pore network, a feature better represented in irregular lumps. MIP data vary, yielding lower (e.g., BP37), higher (e.g., BP38, BAf14), or comparable (e.g., BAf18) $n_{eff,Hg}$ values relative to $n_{eff,adp.ISRM}$ measurements that fall within a 2–8 % range.

BAf16 differs markedly from other BAf samples due to its fractured nature, resulting in lower ρ (2.4–2.5 g/cm³) and higher $n_{eff,ISRM}$ and $n_{eff,adp.ISRM}$ (13.10% - 14.62%). The BAf16 specimen analysed via μ CT shows $n_{eff,\mu CT}$ = 8.53 %, $n_{eff,adp.ISRM}$ = 13.79 %, and $n_{eff,Hg}$ = 17.75 %, and is significantly more permeable (249 mD) than the other BAf samples.

4.3.2.2. Intermediate lava rocks (BF)

Intermediate lavas demonstrate a lower phenocryst content (9.36–10.66 %) compared to alkali-basalts, with trachyandesite (BF13) containing more phenocrysts than the basaltic trachyandesites (BF15 and BF3). Contrary to massive BP and BAf, thin-section analysis reveals up to 8 % more phenocrysts than are detected in 3D image analyses, either resulting from specimen variability or the nature of phenocrysts (mostly plagioclase for BF). As with previous observations, the higher resolution used in 2D imaging yields greater total porosity

($n_{T,2D}$) values than those derived from μ CT, although this discrepancy is reduced in vesicular samples, where pores exceeding 15 μ m in radius are more prevalent.

The massive BF3 sample displays a ρ of 2.6–2.7 g/cm³, with effective porosity values of $n_{eff_ISRM} = 7.96$ %, $n_{eff_adp.ISRM} = 5.90$ %, and $n_{eff_μCT} = 6.17$ %. In contrast, vesicular counterparts (BF15) are less dense (1.9–2.2 g/cm³), with higher porosity (n_{eff_ISRM} up to 21.85 %; $n_{eff_adp.ISRM}$ up to 13.64 %; $n_{eff_μCT}$ up to 12.64 %) and permeability ($k = 13\,634$ mD). The trachyandesite (BF13) has density and porosity values intermediate between those of BF3 and BF15.

For BF3, $n_{eff_adp.ISRM}$ is slightly lower than n_{eff_Hg} , whereas vesicular samples display the opposite trend. $n_{eff_μCT}$ in vesicular specimens exceeds those from other measurement methods, ranging between 12.85 % (BF13) and 19.41 % (BF15).

4.3.2.3. Trachytes (T)

Phenocryst content in trachytes were overestimated by point counting compared to results from both 2D SEM image analysis and 3D digital prism analysis. For instance, similar phenocryst contents were observed for sample T29 (~19 %) across both image-based methods, while an 11 % discrepancy was found in T31 ($Ph_{μCT}$ at 10.23 %; $Ph_{2D, 1A} = 21.14$ %). In contrast, total porosity estimates derived from point counting and 2D SEM imaging were consistent for both T29 (16.10–17 %) and T31 (3.53–3.60 %).

T29 displayed lower dry density (2.1–2.2 g/cm³) and higher n_{eff} ($n_{eff_ISRM} = 13.97$ %; $n_{eff_adp.ISRM} = 8.45$ %) compared to T31, which had a density of 2.5 g/cm³ and lower porosity values ($n_{eff_ISRM} = 4.35$ %; $n_{eff_adp.ISRM} = 5.09$ %). For both trachytic samples, $n_{eff_adp.ISRM}$ was lower than n_{eff_Hg} , with differences reaching approximately 8 %. The selected research strategy for microporous and low-porosity trachytes yielded greater $n_{eff_adp.ISRM}$ and n_{eff_Hg} than $n_{eff_μCT}$.

4.3.2.4. Overview and discussion

Results discussion and their integration is presented in the following paragraphs and Fig. 4.4 (a to h) Pereira et al. (2025a).

Estimating phenocryst content in volcanic rocks through point counting (Fig. 4.4a, Fig. 4.4b and Fig. 4.4h) may yield imprecise results due to the scale distinction between groundmass and phenocrysts. Although image analysis offers an alternative, accurately differentiating crystals from the groundmass remains challenging due to their similar grayscale values (Baker et al., 2012). To address this, texture-supervised classification was employed,

enabling more reliable quantification of phenocrysts (Fig. 4.4c). Nonetheless, some inaccuracies may persist, including underestimation due to the exclusion of microphenocrysts and overestimation caused by incorrect crystal extensions into the groundmass, as observed in sample BP38.

$n_{T_{2D};PC}$ and $n_{T_{2D};IA}$ determined on the same thin-sections of massive lavas agree (Fig. 4.4a; Fig. 4.4h), effectively capturing the prevalent micropores ($< 15 \mu\text{m}$ in radius). On the other hand, fractured BAF16 basalt has an $n_{T_{\mu CT}}$ 2.2 % higher than the $n_{T_{2D};IA}$ (Fig. 4.4b, Fig. 4.4c, and Fig. 4.4h), indicating that distributed fractures are well-predicted at the used 3D scan resolution.

Digital rock physics effectively characterises complex geomaterials, such as lavas, and has significance for aggregate and building stone selection, by detecting internal “defects”, such as microcracks (e.g., Pereira et al., 2023b), not visible at the naked eye and not determinable by 2D techniques.

The obtained results of n_{eff} are aligned with those determined for basalts, andesites, and trachytes (Motta and Nunes, 2003; Loaiza et al., 2012; Amaral et al., 2018; Malheiro et al., 2018; Pereira et al., 2024a and references therein; Fig. 4.4d–g). The wide range of n_{eff} in this research (4 to 22 %; Fig. 4.4g) confirms the complex internal pore structure of lava rocks, as previously noted (e.g., Kennedy et al., 2010; Heap et al., 2014b).

Texture varies within a lava flow (Couves et al., 2016; Becker et al., 2019), while vesicularity (or more generally, porosity) depends on the magma chemistry, volatile content, and cooling rate (e.g., Walker, 1987). n_{eff} , besides being a consequence of volcanological and later processes, is considered as key parameter in characterising any rock used as building stones (e.g., Pappalardo and Mineo, 2017), with a pore connectivity that can be an enhancer of fluid circulation within the rock (e.g., Bernabé et al., 2010) or lead to unpredictable crack pattern development and brittle deformation.

Microstructure images reveal that the architecture of the porous system, resulting from the formation and emplacement of the lava, is defined by the proportion of fractures and coalescence of the pores, leading to different textures and porosities. This work also supports that both texture and the number of pores influence n_{eff} , while the mineralogy plays a minor role.

Pore Space and Phenocrysts in Thin Section

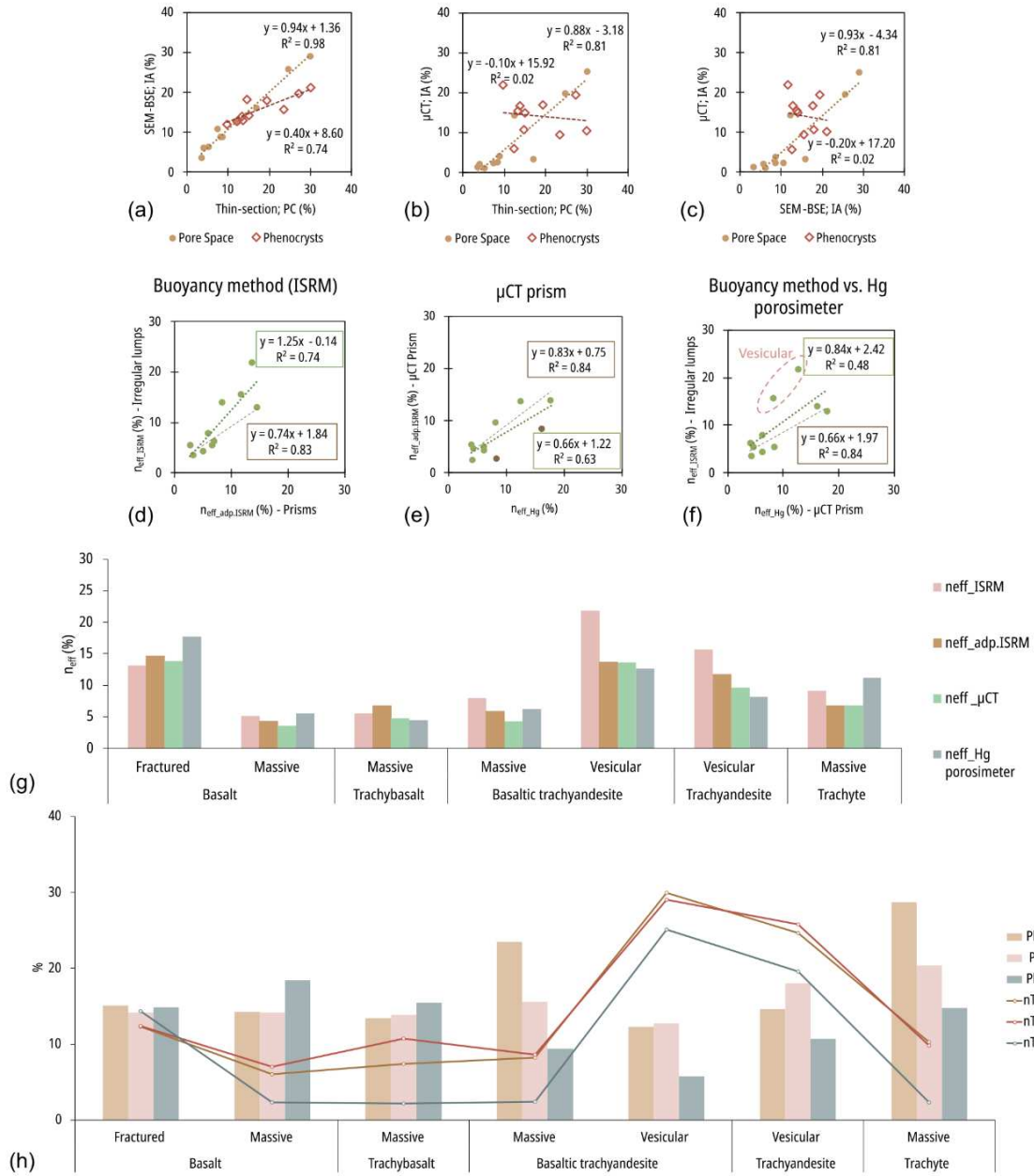


Fig. 4.4. Microstructure comparison quantifications in two dimensions and three dimensions. (a) porosity and phenocrysts content determined through image analysis of SEM-BSE images versus point counting; (b) porosity and phenocrysts content determined through image analysis of μ CT images versus point counting; (c) porosity and phenocrysts content determined through image analysis of μ CT images versus image analysis of SEM-BSE image; (d) open porosity determined through the buoyancy and saturation techniques for irregular lumps and prisms; (e) open porosity determined through the buoyancy and saturation techniques for the and mercury porosimeter for the μ CT prism; (f) open porosity determined through buoyancy and saturation techniques for irregular lumps and mercury porosimetry; (g) quantification of the total porosity (n_T) and phenocrysts (Ph) by point counting and image analysis of both SEM-BSE images of thin-sections and μ CT images. (h) connected porosity (n_{eff}) obtained by the buoyancy method for irregular lumps (ISRM) and prisms (adp. ISRM), by image analysis of μ CT images, and by mercury porosimeter. IA –

image analysis; PC – point counting; Hg – mercury; n_{eff} – effective porosity. Image and caption reproduced from the supplementary material from Pereira et al. (2025a), licensed under CC BY 4.0.

A scale effect is evident when comparing prismatic specimens and irregular lumps in rocks with $n_{eff} > 10\%$ (e.g., BF13, BF15, and T29; Fig. 4.4d–e). Prisms may be insufficiently sized to preserve pores and localised fractures that are present in the larger, irregular samples. The exclusion of high-porosity rocks ($n_{eff} > 10\%$) enhances the linear correlation among measurement techniques (Fig. 4.4d–e). Additionally, the different number of specimens (10 irregular lumps versus three prismatic samples per lithotype) contributes to data variability. In vesicular lavas, both n_{eff_ISRM} and $n_{eff_adp.ISRM}$ values are typically higher than n_{eff_Hg} , likely due to the combined effects of specimen scale and the inability of the MIP technique to fully capture macropores. On the other hand, the fractured basalt BAF16 exhibits higher n_{eff_Hg} values compared to other techniques, suggesting that mercury, under pressure, more effectively accesses microcracks than water.

ρ tends to decrease with increasing n_{eff} (Fig. 4.5a), consistent with prior findings (e.g., Pereira et al., 2021; see also Section 2.1.4 – Fig. 2.12). Porosity in vesicular specimens typically reduces density by around 0.2 g/cm^3 compared to massive equivalents, while fracturing may decrease density by up to 0.3 g/cm^3 . However, moderate to weak correlations suggest that other factors, including mineralogical composition, the proportion of feldspar minerals, and the presence of microcracks, also influence density. For instance, BP basalts are denser despite similar or greater porosity than BAF basalts, which have a higher plagioclase content, supporting the inverse relationship between feldspar abundance and density. The reported ρ values fall within the ranges previously observed for fresh trachytes and andesites (Pereira et al., 2024a; Section 2.1.4).

ρ measurements are consistent across samples of varying size and geometry (Fig. 4.5b), and both water and paraffin immersion techniques yield comparable results (Fig. 4.5c). Nevertheless, rapid water immersion is preferred due to its efficiency and the ability to reuse specimens. In contrast, paraffin is difficult to remove from pore networks and can lead to inaccurate results, particularly in vesicular or fractured samples.

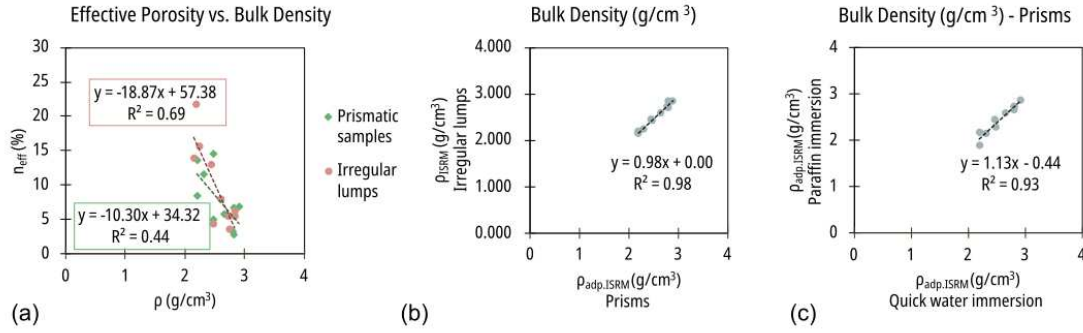


Fig. 4.5. Correlations of the physical properties. (a) open porosity versus dry density determined through the buoyancy and saturation method for irregular lumps and prisms; (b) correlation of apparent bulk densities for different size specimens – irregular lumps and prisms; (c) correlation of apparent bulk densities for prisms using paraffin immersion and the quick water immersion.; n_{eff} – effective porosity; ρ – dry density. Image and caption reproduced from Pereira et al. (2025a), licensed under CC BY 4.0.

4.3.3. Pore size distribution and pore network models

The results for the r and PSD are presented in Table 4.2 and Fig. 4.6, according to Pereira et al. (2025a). Regardless of lithology, pore size is primarily governed by the rock's microstructure. For massive specimens, r ranges between 0.01 and 0.14 μm , while higher values are observed in fractured samples (e.g., Baf16; 0.22 μm), porous trachytes (T29; 0.27 μm), and vesicular varieties (BF15; 0.22 μm). Micropores (pore radius < 15 μm ; Franzson et al., 2010) dominate the pore volume in massive samples, typically exceeding 80 %, whereas vesicular rocks contain a proportion of macropores > 22 %. An exception is the vesicular trachyandesite BF13, which has a lower r compared to other vesicular samples. Additionally, some rocks with a predominance of micropores (e.g., Baf16 and T29) show increased r values, assumed to be due to the presence of microfractures.

Pore size distribution and cumulative pore volume curves (Fig. 4.6) indicate that samples BP38 (Fig. 4.6b) and Baf14 (Fig. 4.6c) possess a single dominant pore population within the 0.01–0.1 μm range, similar to T29, which is characterised by a dominant pore size range of 0.1–1 μm (Fig. 4.6i). These specimens display an S-shaped cumulative pore volume curve, characteristic of unimodal and uniform distributions. In contrast, samples BP37 (Fig. 4.6a), Baf16 (Fig. 4.6d), Baf18 (Fig. 4.6e), BF13 (Fig. 4.6g), and BF15 (Fig. 4.6h) have a more pronounced stair-step profile in their cumulative curves, whereas BF3 (Fig. 4.6f) and T31 (Fig. 4.6j) present a smoother stair-step pattern. Both are indicative of polymodal pore distributions that evidence the heterogeneous nature of the pore networks of these lavas.

Table 4.2. Mean porous radius, r , and pore size interval obtained by mercury intrusion porosimetry (MIP) of lava rocks. 15 μm corresponds to the micropores to macropores threshold defined by Franzson et al. (2010). Adapted from Pereira et al. (2025a). Licensed under CC BY 4.0.

Sample		r (μm)	$< 15 \mu\text{m}$ (%)	$\geq 15 \mu\text{m}$ (%)	Pore size interval in μm (%)					
					<0.01	$0.01-0.1$	$0.1-1$	$1-10$	$10-100$	>100
Basalt to trachybasalt	BP37	0.14	79.6	19.6	0.0	14.6	12.8	51.2	18.5	2.3
	BP38	0.01	90.9	8.5	5.3	68.0	12.7	4.2	7.3	1.8
	BAf14	0.06	85.6	13.8	0.0	51.8	26.4	6.2	10.8	3.7
	BAf16	0.22	81.6	17.7	0.0	10.9	41.4	26.8	18.2	2.0
	BAF18	0.06	87.6	11.3	0.0	41.8	24.8	19.3	10.3	2.7
Basaltic trachyandesite to trachyandesite	BF3	0.10	94.5	5.0	0.0	21.4	61.7	9.3	6.3	0.9
	BF13	0.03	67.1	30.9	7.6	13.5	12.8	24.6	35.8	3.7
	BF15	0.22	77.8	22.2	0.0	16.7	10.1	40.9	31.0	0.9
Trachyte	T29	0.27	93.9	5.4	0.0	5.8	78.8	8.5	5.0	1.2
	T31	0.04	93.7	6.0	0.0	45.1	30.4	16.4	6.3	0.8

The results indicate that the rock composition does not govern pore size distribution, as comparable PSD curves are observed across both basaltic and trachytic samples. Vesicular specimens display a pronounced polymodal PSD, whereas massive and fractured samples do not conform strictly to a unimodal distribution. Based on the results from Table 4.2, it is also suggested that water intrusion is less efficient for specimens with a single pore family, such as BP38 and T29, which explains the lower n_{eff_ISRM} compared to n_{eff_Hg} .

The MIP technique is crucial for assessing micropores, providing a complete PSD under a 180 μm radius. However, due to this upper limit, full characterisation of macroporosity, particularly that associated with pores with radii $> 1 \text{ mm}$, coalesced pores, and fissures, is not achievable. To address this, a PNM (Fig. 4.7) was developed for the digital rock samples (nominal voxel size of $\sim 15 \mu\text{m}$) with connected porosity (Fig. 4.7a), including vesicular (BF13 and BF15) and fractured (BAf16) basalts. The models evidence that void space connectivity and, therefore, permeability are enhanced by vesicular and fractured textures, with fractures and pore-linking microcracks having the potential to act as conduits for fluids.

BAf16 (Fig. 4.7b) contains a higher density of low volume pores (Fig. 4.8a), predominantly with equivalent radii around 100 μm (Fig. 4.8b), which are interconnected by numerous throats with length $< 100 \mu\text{m}$ (Fig. 4.8a and Fig. 4.8b). BAF16 also displays a relatively uniform porosity distribution across slices (Fig. 4.7a).

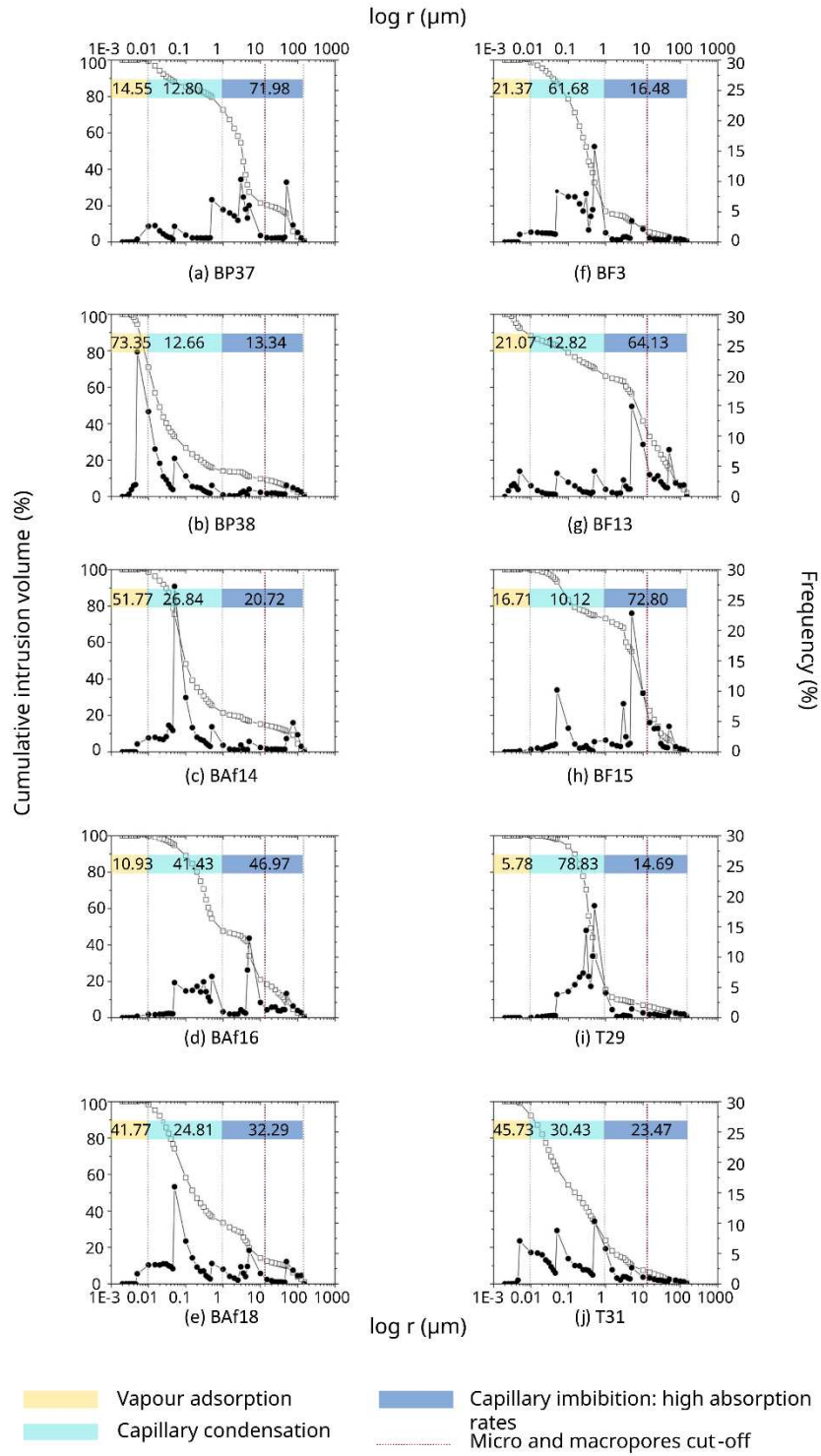


Fig. 4.6. Cumulative mercury intrusion (empty squares) and pore size distribution (solid circles) curves of the lava rocks. Alkali-basalts correspond to (a) BP37, (b) BP38, (c) BAf14, and (d) BAf16. Trachybasalt is (e) BAf18. Intermediate rocks include (f) BF3, (g) BF13, and (h) BF15. Trachytes are (i) T29 and (j) T31. Pore volume curves with a S-shaped trend [(b), (c), (i)] and stair-shaped trend [(a), (d), (e), (f), (g), (h), (j)]. Plots and caption reproduced from Pereira et al., (2025a). Licensed under CC BY 4.0.

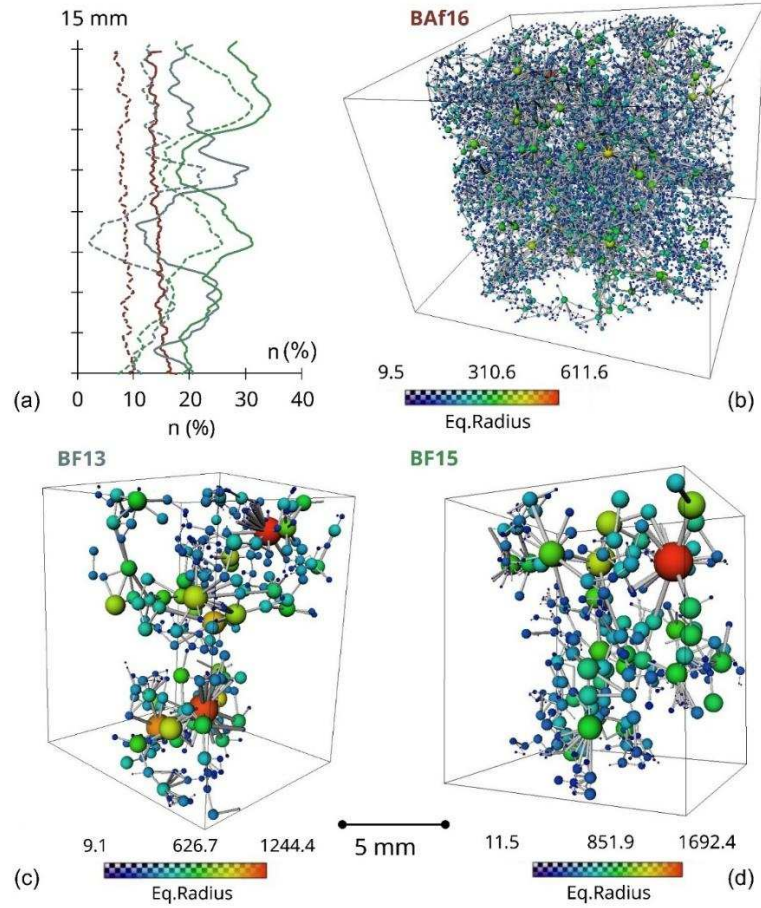


Fig. 4.7. Pore network models. (a) Porosity variation per slice – connected (dashed line) and total (full line) – and pore network model representations for samples (b) BAF16 – a fractured basalt containing smaller pores connected by a higher number of throats; and (c) BF13 and (d) BF15 that correspond to vesicular specimens with pores of larger size but lower number of throats than BAF16. Pores are represented as a function of their equivalent radius (coloured), and throats are channels, whose width depends on their length (greyish white cylinders). Figure and caption reproduced from Pereira et al., (2025a). Licensed under CC BY 4.0.

In contrast, BF13 (Fig. 4.7c) and BF15 (Fig. 4.7d) show more heterogeneous structures, with porosity peaks coinciding with larger pores (Fig. 4.7a). These vesicular samples contain fewer pores, but with significantly larger equivalent radii ($\sim 1000 \mu\text{m}$) and volumes ($> 1010 \mu\text{m}^3$), connected by fewer throats (Fig. 4.8a and Fig. 4.8b). Unlike BAF16, where maximum throat lengths intersect with larger pore sizes, in BF13 and BF15, such a relationship is not consistently observed.

The coordination number (CN), defined as the number of connections per pore (node), indicates that most pores are connected via one to three throats (Fig. 4.8c). $\text{CN} > 2$ are key contributors to effective porosity and permeability. Fig. 4.8 shows that the number of throats contributes more to CN than the size of the pores. On the other hand, higher n_{eff} (Table 4.1)

in vesicular specimens suggest that larger pores, even if combined with lower CN and shorter throats, contribute to higher pore connectivity.

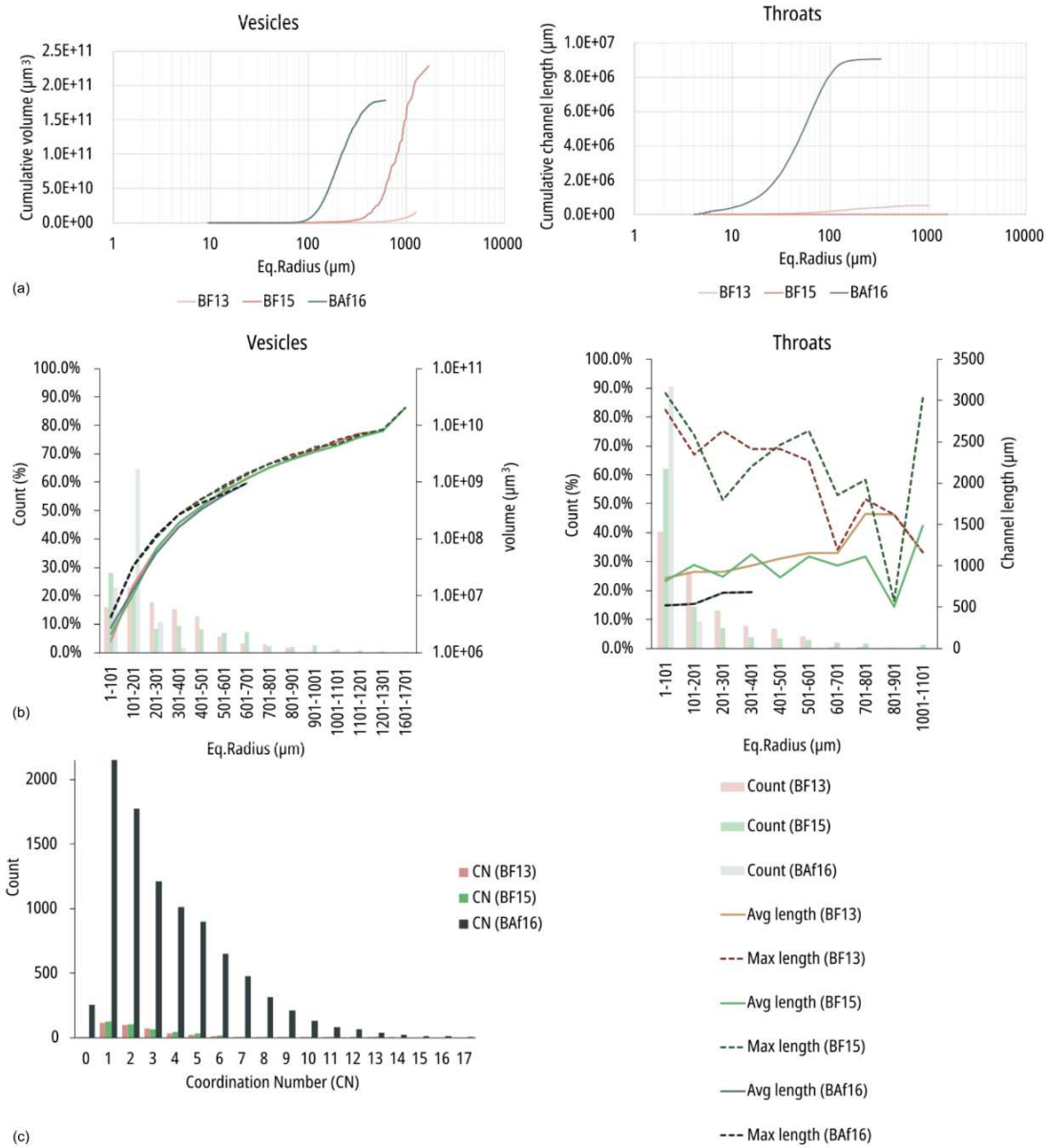


Fig. 4.8. Pore network model (PNM) data quantification for BAF16, BF13, and BF15. (a) distribution of the equivalent radius of pores/vesicles and throats with the cumulative volume or channel length; (b) counts of pores and throats per group of equivalent radii vs. volume of the pores and channel length of the throats; (c) coordination number (CN) of pores. Figure and caption reproduced from Pereira et al., (2025a). Licensed under CC BY4.0.

Based on Hölting's classification (Fig. 2.10; Hölting, 1989; Benavente et al., 2015), the presence of pore throat equivalent radii > 1 mm in vesicular samples (Fig. 4.8) suggests an intercrystalline porosity regime, where permeability is primarily governed by vesicle/pore size rather than total porosity, unlike in massive lava rocks.

Sorption processes in rocks under subaerial exposure conditions are described by their respective mechanism (Fort, 1996; Benavente, 2011), as presented in Section 2.1.2.2. Several intrinsic and extrinsic factors, including r , PSD, and relative humidity (RH), influence fluid sorption by pore systems, with fluids following various kinematic processes due to different mobilising forces (Cueto, 2020).

In the majority of samples (BP38, BAf14, BAf16, BAf18; BF3; T29; T31), dominant pore sizes fall within the 0.001 to 1 μm range (Table 4.2; Fig. 4.8), indicating that vapour adsorption and capillary condensation primarily govern fluid transport. Vapour absorption transport mechanism (individual molecule diffusion or surface flow) depends on the RH. Capillary condensation occurs for RH $\sim$ 75–85 %, pore size $\sim$ 0.1 μm , and the temperature of the porous medium is lower than the dew point of the air, combining diffusion and capillarity transport mechanisms.

Condensed fluids can hinder surface gas diffusion by blocking direct pathways (Cueto, 2020), but the elevated temperatures and pressures typical of volcano-hydrothermal systems facilitate gas migration via adsorption, especially along conduit walls (e.g., Jaupart and Allègre, 1991; Heap et al., 2018c). Increased RH and water condensation also decrease fracture toughness and crack growth resistance (Nara et al., 2012), potentially affecting time-dependent fracturing of rocks and rock masses, which relates to the increase of seismicity detected prior to volcanic eruption (Kilburn and Voight, 1998). Furthermore, capillary condensation can promote the leaching of host rocks and void infill by secondary minerals (Stimac et al., 2015) at depth. At the surface, given the prevalent pore size found in these massive lavas, salt crystallisation may contribute to the rock materials deterioration (Fig. 2.9).

Basaltic specimens BP37 and BAf16, along with vesicular trachyandesites BF13 and BF15, show primarily pore radii $> 1 \mu\text{m}$ (Table 4.2; Fig. 4.8) and, except for BP37, n_{eff} greater than 10 %. Capillary absorption refers to fluid movement driven by capillary forces arising from surface tension (Benavente, 2003; Hall and Hoff, 2021). Imbibition processes become active in pores larger than 0.1 μm (Winkler, 1997), but high-water absorption rates are achieved within a pore size range of 1 μm to 1 mm (Benavente et al., 2018). Accordingly, these studied samples are capable of absorbing water through capillarity, although pores exceeding 100 μm may additionally facilitate mechanical weakening and enhanced fluid migration within the rock matrix (Benavente et al., 2018). When pore radii $> 1 \text{ mm}$, such as observed for the vesicular specimens, fluid transport transitions to a hydrodynamic regime, with gravity becoming the dominant mechanism (Hall and Hoff, 2021).

The developed PNM (Fig. 4.7) suggest that permeability depends on the type of porosity, as well as its geometry, and tortuosity, supporting previous findings (Degruyter et al., 2010; Colombier et al., 2017b; Heap et al., 2018c; Buono et al., 2020; 2023; Vieira et al., 2021; Liu et al., 2023). Trachyandesites of the Azores ($n_{eff} = 18\%$; Loaiza et al., 2012) were described as having a mercury porosimeter permeability of 3 mD and an r of $0.25\ \mu\text{m}$, which is in line with the $r = 0.22\ \mu\text{m}$ obtained for the tested basaltic trachyandesite (Table 4.2). However, the obtained permeability largely surpasses the permeability established by Loaiza et al. (2012) and for other andesitic lavas (Fig. 2.11c; Pereira et al., 2024a).

At the scale of volcanic systems, brittle failure can rejuvenate permeability pathways and enhance the circulation of magmatic and hydrothermal fluids (e.g., Barreyre et al., 2022). Rapid fluid uptake by capillarity could also alter near-surface moisture distribution, potentially impacting volcanic flank stability (e.g., Baumann et al., 2019). On the surface, fractured and vesicular lavas are characterised by lower mechanical strength and higher susceptibility to degradation. Thus, they should be cautiously considered for use as construction materials, particularly given the volcanic and seismic hazards affecting São Miguel Island.

4.3.4. Characterisation of the size and shape of the pores and phenocrysts

Pereira et al. (2025a) applied a PCA to both 2D (thin-sections; SEM-BSE images) and 3D datasets (prisms and cylinders; μCT), each representing different observational scales. Despite these scale differences, the data are complementary, as trends in object size and shape are consistent across lithologies.

Three PCs (Fig. 4.9) explain 85 % of the total variance. PC1 groups size variables from both 2D (e.g., length, width, Feret diameter, equivalent diameter, area, and Crofton perimeter – see Table 3.4) and 3D (e.g., length, width, breadth, thickness, and equivalent diameter – see Table 3.4) measurements, along with shape descriptors derived from volumetric and surface properties (e.g., sphericity and shape factor). PC2 captures variables associated with deviations in shape, including 2D features (Feret shape, eccentricity, anisotropy, elongation, and shape factor), as well as volume and surface area in 3D. PC3 reflects additional 2D shape characteristics (circularity and roundness) and 3D shape deviation parameters, such as anisotropy and elongation.

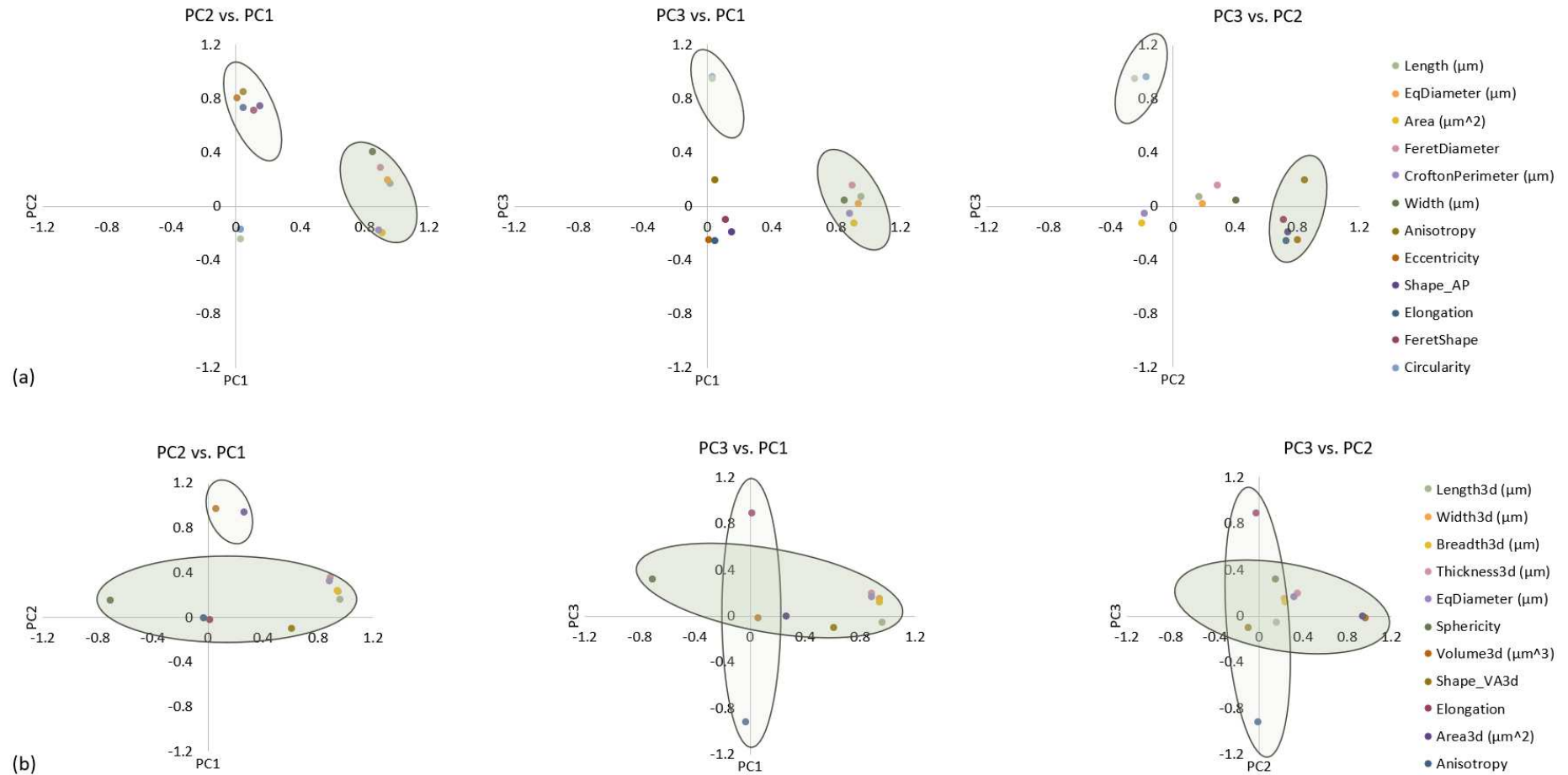


Fig. 4.9. Principal component analysis: biplots with the components of the rotated matrix for the three first principal component (PC1, PC2, PC3) (a) based on data from SEM-BSE images of thin-sections; (b) based on data from μ CT images of prisms and cylinders, considering both the connected and isolated porosity. Image updated from Pereira et al. (2025a). Licensed under CC BY 4.0.

For 3D characterisation of pore networks and phenocrysts, length, equivalent diameter, sphericity, and elongation were selected as representative parameters (Fig. 4.10a; Fig. 4.10b). In 2D, length, equivalent diameter, elongation, and circularity were used to describe the geometry of pores and phenocrysts (Fig. 4.10c; Fig. 4.10d).

Results regarding the size and shape of both pores and crystals (Pereira et al., 2025a) are presented and discussed below.

4.3.4.1. Alkali-basalts (BP and BAf)

In 3D, pores in basalts show average lengths below 212 μm and equivalent radii under 56 μm , with elongation and sphericity values of 0.42 and 0.84, respectively. Sample BAf16 has larger connected pores (length: 844 μm ; equivalent radius: 155 μm) of reduced sphericity (0.48), suggesting fracture-induced pore linking, while elongation remains consistent with other alkali-basalts. Ferromagnesian minerals, in 3D, span from 188–351 μm in equivalent radius, averaging 0.38 in elongation and 0.58 in sphericity, with lower sphericity linked to prismatic clinopyroxene (Fig. 4.3g). Plagioclase, present only in BAf basalts, reaches a maximum equivalent radius of 268 μm , with a mean sphericity and elongation of 0.47 and 0.39, respectively.

In 2D, basalt pores average 18–25 μm in length and under 8 μm in equivalent radius, with circularity > 0.81 and elongation < 0.28. BAf16 displays slightly higher elongation, while circularity remains relatively unchanged. Phenocrysts reach up to 1205 μm in length and 422 μm in equivalent radius, with elongation and circularity ranging from 0.28–0.41 and 0.25–0.41, respectively (Fig. 4.10d).

4.3.4.2. Intermediate lava rocks (BF)

Vesicular samples BF15 and BF13 present greater average 3D lengths (1106–1620 μm) and equivalent radii (309–396 μm) than basalts, attributed to vesicle connectivity and coalescence. These samples also show higher elongation (0.45–0.52) and reduced sphericity (0.59–0.65). In contrast, the BF3 basaltic trachyandesite and isolated pores within BF15 and BF13 display average 3D lengths around 150 μm , equivalent radii near 32 μm , elongation of 0.34, and sphericity of 0.81, values comparable to massive basalts. Ferromagnesian and plagioclase 3D elongation decreases from basalts to intermediate lavas, although plagioclase in the latter reaches larger sizes, averaging 994 μm in length. Although elongation remains stable across intermediate types, plagioclase sphericity is reduced to 0.39 in the trachyandesite (BF13).

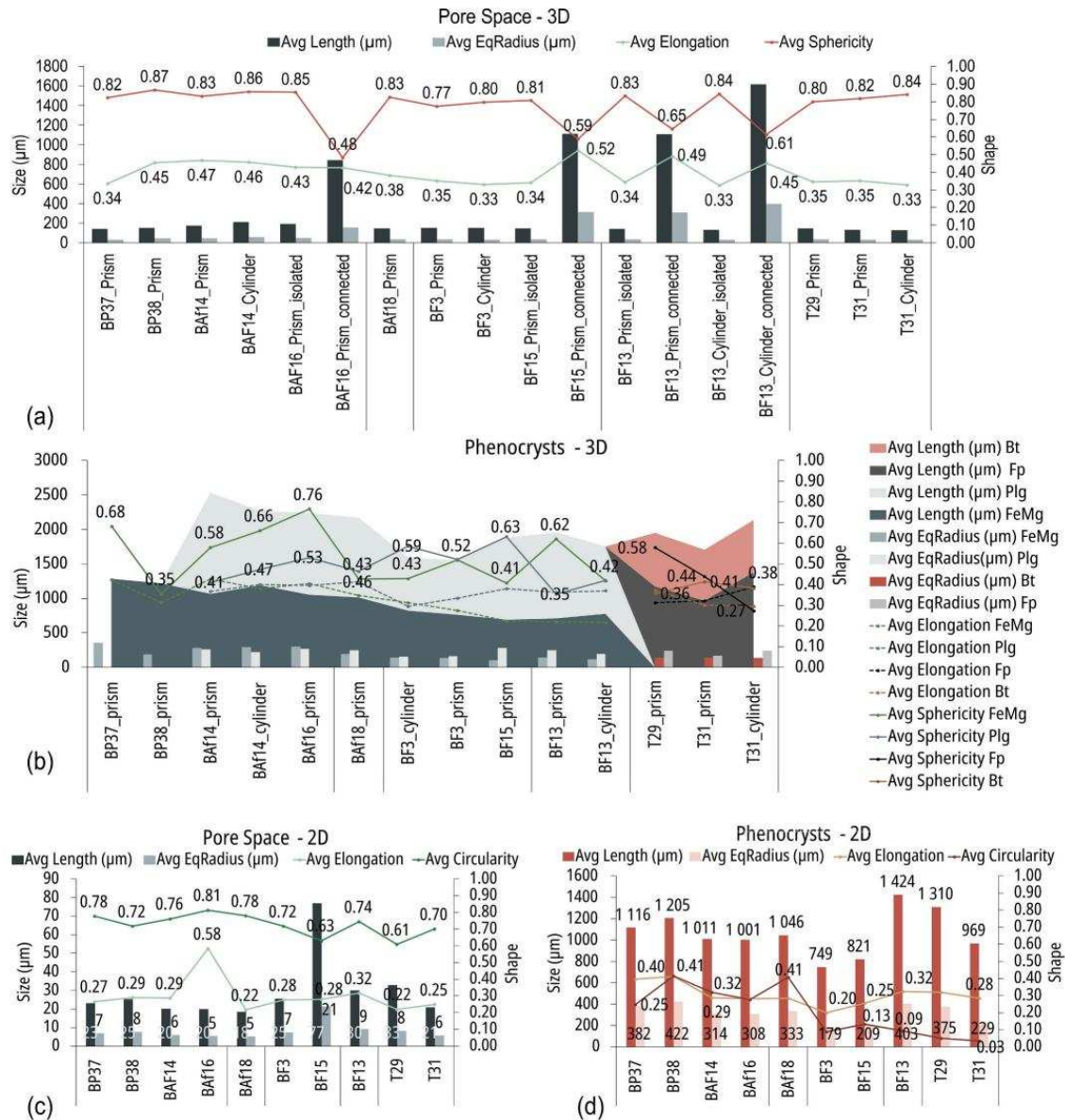


Fig. 4.10. Characterisation of the microstructure of volcanic rocks from Sete Cidades (BP37; BP38; BAf14; BAf16 – alkali-basalt; BAf18 - trachybasalt) and Fogo (BF3; BF15 – basaltic trachyandesite; BF13 – trachyandesite; T29; T31 - trachyte) volcanoes in three dimensions (a and b) and two dimensions (c and d). (a) average size and shape of pores in 3D; (b) average size and shape of phenocrysts in 3D; (c) average size and shape of pores in 2D; (d) average size and shape of phenocrysts in 2D. Avg – average; Bt – biotite, FeMg – ferromagnesian minerals; Plg – plagioclase; Fp – Alkali-feldspar. Figure and caption reproduced from Pereira et al., (2025a). Licensed under CC BY 4.0.

In 2D, vesicular rocks (BF15, BF13) confirm higher average lengths (30–77 μm), equivalent radii (9–21 μm), and lower circularity (~0.63) than alkali-basalts. The massive trachyandesite (BF3), however, aligns closely with basalts (~25 μm length, ~7 μm equivalent radius, ~0.72 circularity). Euhedral plagioclase (see Section 4.3.1) associates with reduced circularity, whereas 2D elongation decreases to a lesser extent (0.20–0.25).

BF13 also contains the largest phenocrysts observed, averaging a length of 1424 μm and an equivalent radius of 403 μm .

4.3.4.3. Trachytes (T)

Trachytes exhibit average 3D pore lengths of 125–144 μm , equivalent radii of 28–32 μm , an elongation of 0.34, and a sphericity of 0.82, consistent with other massive lithologies. Corresponding 2D values include lengths of 21–33 μm , equivalent radii of 6–8 μm , elongation around 0.23, and circularity near 0.65. In sample T29, the sub-parallel alignment of feldspar laths bordering pores slightly reduces vesicle circularity in 2D.

Phenocryst analysis shows that alkali-feldspars have larger 3D equivalent radii (169–242 μm) than biotite/amphibole (137–143 μm). From T29 to T31, alkali-feldspar elongation increases (0.31–0.39) as sphericity drops (0.27–0.58), a trend not observed for biotite/amphibole. In 2D, phenocrysts are, in average, more elongated and less circular than in other rock types, with lengths of 969–1310 μm , equivalent radii of 229–375 μm , circularity of 0.03–0.05, and elongation of 0.28–0.32.

4.3.4.4. Overview and discussion

μCT provides a direct visualisation and quantification of pores and crystals larger than 15 μm in radius, often with regular geometries, that are not accurately captured by conventional 2D methods. To complement μCT analysis, smaller objects (radius < 15 μm), typically spherical (e.g., Giachetti et al., 2011; Pappalardo et al., 2018), were analysed using SEM-BSE images at higher resolutions (~ 3 μm). Results show that the range of phenocryst size was consistent across both μCT and SEM-BSE data. However, μCT detected larger and more irregular pores, with average equivalent radii up to 396 μm , while SEM-BSE revealed smaller, more circular pores averaging up to 21 μm in equivalent radii. The analysed lavas highlight the diverse microstructural characteristics often found in volcanic rocks, comprising microcracks, microporosity, or both (Couves et al., 2016; Griffiths et al., 2017; Cant et al., 2018).

The size and shape of pores and crystals reflect emplacement and cooling dynamics, such as compaction and bubble coalescence (e.g., Couves et al., 2016). Vesicles, relics of gas bubbles in magma, undergo modifications due to post-emplacement processes (Shea et al., 2010; Zou et al., 2013), which alter their geometry. The mechanical behaviour of rocks can be influenced by these pores, which impact deformation, failure mode, and long-term

durability (Guéguen and Kachanov, 2011), and may ultimately contribute to the inherent heterogeneity of volcanic rock masses, thereby dictating their stability.

3D analysis demonstrates that pores larger than 15 μm have sphericity values around 0.80, with their size and shape more influenced by microstructural properties than by lithology. In vesicular lavas, coalescence and pore-linking fractures reduce pore sphericity and increase elongation. Samples with fractures (e.g., BAF16) have an average sphericity of the pores decreased, whereas elongation remains unchanged due to the prevalent micropores with low elongation. As a result, pore sphericity or other shape factors, such as aspect ratio, can be used to evaluate material suitability, as low sphericity is typically associated with decreased rock competence and higher deterioration potential (Qajar and Arns, 2022; Zhang and Shen, 2023). In fact, elongated or interconnected pores, such as the observed coalesced pores, are known to contribute to stress concentration at their tips and edges, promoting mechanical instability (Jaeger et al., 2007; Davis et al., 2017).

Micropores (pore radii < 15 μm) observed in 2D generally corroborate 3D observations for the pore system, though circularity shows less variation than sphericity. Fractures produce a more pronounced effect on reducing 2D elongation compared to their impact in 3D.

Textural components also influence phenocryst morphology: feldspar laths and prismatic pyroxenes lower sphericity and circularity, while increasing elongation. On the other hand, rounded, anhedral olivine tends to increase the sphericity of phenocrysts.

4.3.5. Mechanical properties and post-deformation physical properties

The UCS samples analysed via X-ray imaging include a porphyritic alkali-basalt (BAF14), a less porphyritic intermediate lava (BF3), a vesicular intermediate lava (BF13), and a trachyte (T31). Their physical and hydraulic characteristics before and after deformation are detailed in Table 4.3 (Pereira et al., 2025a). In massive specimens, n_{eff} is primarily governed by micropores smaller than 15 μm , leading to underestimated or null permeability prior to deformation.

Mineralogical composition has a more significant effect on strength than phenocryst abundance (Table 4.3). Among the massive lavas, trachytes exhibit a higher phenocryst content but lower strength, whereas the porphyritic basalt (BAF14) maintains high mechanical competence despite its porphyritic texture.

Table 4.3. Microstructure ($Ph_{\mu CT}$ – phenocrysts content) and physical and hydraulic properties ($n_{T-\mu CT}$ – total porosity obtained by the μCT , $n_{eff-\mu CT}$ – effective porosity obtained by the μCT , k – absolute permeability, and T – tortuosity) of the cylinders obtained from representative volcanic rocks from Sete Cidades and Fogo volcanoes amongst the previously studied as prismatic specimens by μCT (Fig. 4.2.). “-” represents null values for the chosen μCT resolution. Table adapted from Pereira et al. (2025a), licensed under CC BY 4.0.

	$n_{T-\mu CT}$ (%)		$n_{eff-\mu CT}$ (%)		$n_{isol-\mu CT}$ (%)		T		k (mD)		$Ph_{\mu CT}$ (%)
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	
BAf14	2.58	2.58	-	-	2.58	2.58	-	-	-	-	14.97
BF3	1.89	12.90	-	11.56	1.89	1.29	-	1.50	-	42.6	12.13
BF13	15.36	21.21 ^a	4.10	19.08	11.26	2.13	1.55	1.35 ^b	0.5	210.4 ^c	6.54
T31	0.67	11.34	-	10.17	0.67	1.04	-	1.36	-	23.0	20.89

* k was calculated along ZZ axis (height of the specimen)

^a from 21.21 % of the void space, 6.24 % are fractures

^b the tortuosity considering solely the fractures is increased to 2.16

^c fractures contribute with 8 mD to the total 210 mD permeability.

All samples demonstrate brittle failure, characterised by an abrupt post-peak stress drop (Fig. 4.11). BAF14 ($\sigma_{c_UCS} > 106.24$ MPa; Fig. 4.11a) did not fail during testing due to the 5210 N load limit of the testing apparatus. In contrast, the BF3 trachyandesite shows a lower σ_{c_UCS} of 80.98 MPa (Fig. 4.11b). It is hypothesised that increasing plagioclase content in intermediate lavas, responsible for a loss in density, may also contribute, to some extent, to strength and E reduction.

The obtained results further confirm that microstructure influence rock strength. Higher pore size and n_{eff} in the vesicular specimen (Table 4.3) correlate with reduced strength. For example, the vesicular trachyandesite (BF13; UCS = 21.84 MPa; Fig. 4.11c) displays a 3.7-fold decrease in strength relative to the massive BF3. Hence, n_{eff} may be considered a weakening factor. As established in prior studies (e.g., Bernabé et al., 2010; Heap and Violay, 2021), n_{eff} facilitates fluid flow, mixed-mode failure, and contributes to unpredictability in fracture mechanisms.

The T31 trachyte ($\sigma_{c_UCS} = 77.65$ MPa; Fig. 4.11d), composed predominantly of alkali-feldspar and amphibole/biotite, has lower mechanical competence and greater strain accumulation compared to the other massive rocks. Both BF3 and T31 exhibit a stress drop at approximately 40 MPa, followed by partial recovery of strength within the elastic regime.

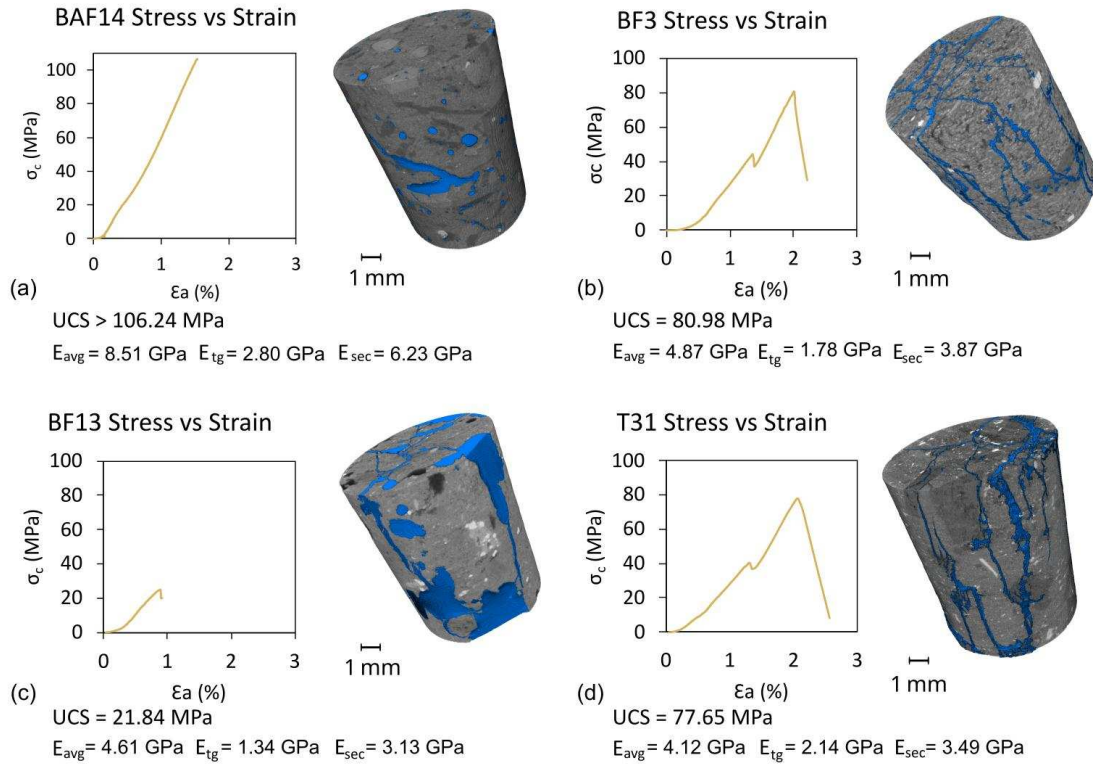


Fig. 4.11. Stress-strain curves, peak strength, and failure for (a) BAF14: massive basalt specimen with 7.72 mm diameter; (b) BF3: massive basaltic trachyandesite specimen with 7.64 mm diameter; (c) BF13: vesicular trachyandesite specimen with 7.67 mm diameter; and (d) T31: trachyte specimen with 7.69 mm diameter. Connected porosity is represented in blue. Figure adapted and caption reproduced from Pereira et al. (2025a). Licensed under CC BY 4.0.

In terms of stiffness, E_{avg} is consistently higher than E_{tg} , with E_{sec} falling between the two. A positive correlation is observed between stiffness and $\sigma_{c,UCS}$, where more competent rocks like BAF14 display higher moduli values, whereas BF13 shows the lowest stiffness.

Post-failure microstructural changes include increased porosity, tortuosity, and permeability (Table 4.3). Low-porosity samples, such as BF3 and T31, reach post-failure $n_T = 12.90\%$, $n_{eff} = 11.56\%$, $k = 43$ mD, $T = 1.50$ and $n_T = 11.34\%$, $n_{eff} = 10.17\%$, $k = 23$ mD, $T = 1.36$, respectively. In contrast, the vesicular trachyandesite (BF13) displays substantial post-deformation changes, reaching $n_T = 21.21\%$, $n_{eff} = 19.08\%$, $k = 210$ mD, and $T = 1.35$. In other words, failure increased n_{eff} and k by 5 and 420 times, respectively. The overall T of the vesicular specimen decreases, although higher values are observed when considering only the fractures and not the entire voids (Table 4.3).

Post-failure digital cores (Fig. 4.11) indicate that unconfined compression induces tensile splitting, with fractures following the wing crack model (see Heap et al., 2016). Data from

4D μ CT tests further reveal that fracture propagation benefits from pre-existing weaknesses, including pores, intragranular cracks, and phenocryst boundaries, as also noted by Tang et al. (2007), Villeneuve et al. (2012), Heap et al. (2014a), Coats et al. (2018), McBeck et al. (2019), Xu et al. (2020), and Heap et al. (2023).

In BF3, multiple and widespread fracturing occurs, with crack paths influenced by matrix porosity (Fig. 4.3o) and pores resulting from disequilibrium textures in feldspar. BF13 fracturing is dictated by elongated macropores, which are interconnected through radial cracks emanating from the pore edges. The crack pattern is characterised by pore-emanated fractures, indicating that coalescent pores with significant elongation are preferential features for earlier crack nucleation and propagation. This supports earlier studies showing that clustered, low-sphericity pores can divert crack paths and produce more complex fracture patterns under compression, increasing unpredictability in both intact rock and rock mass failure (e.g., Tang et al., 2000; Reinoso et al., 2019).

In the trachyte, tensile fractures tend to follow the boundaries of feldspar phenocrysts parallel to the loading axis. Within phenocrysts, the presence of intragranular pores and microcracks promotes the development of dense and irregular fracture networks. Regardless, 3D imaging reveals that in massive samples, fractures predominantly propagate through the matrix, using pre-existing microstructural defects, like small pores and crystal boundaries.

4.3.6. Implications and applications in volcanic systems and terrains

Basalts, trachyandesites, and trachytes are the primary lava rock types composing the volcanic structures and at the Ribeira Grande geothermal field on São Miguel Island (e.g., Moore, 1991a; 1991b; Pereira et al., 2022). These rocks are part of much of the island's slopes and are widely used as sources of natural stone and construction aggregate. Understanding their physical and mechanical properties helps in volcanic hazard assessments, slope stability analysis, and engineering applications, including rock selection for construction purposes.

The results confirm that mineral composition, namely the presence of ferromagnesian and feldspar minerals, and textural features influence dry density and failure mechanisms under unconfined conditions, consistent with earlier studies (Fereidooni and Sousa, 2022). UCS and E are key geomechanical parameters that warrant further attention in these lava rocks. These properties are used in geomechanical classification systems (e.g., Bieniawski, 1989;

see Section 2.2.2 Part A), failure criteria definition (e.g., Hoek and Brown, 1980; Section 2.2.4.4 Part C), *in situ* stress estimation (Hudson and Harrison, 2000), and assessments of deformability in fractured rock masses, including volcanic terrains (Hoek and Diederichs, 2006; Yoshinaka et al., 2008). Additionally, these parameters support models addressing the propagation, deflection, and arrest of hydrofractures at depth (e.g., Gudmundsson, 2011; Acocella, 2021; Section 2.1.3 Part B), as well as volcanic slope instability at the surface (e.g., Reid, 2004; van Wyk de Vries and Davies, 2015; Ball et al., 2018; Section 2.2.2, Part B).

Vesicular samples, characterised by pores that are often aligned with the direction of the lava flow (Vairé et al., 2024), are classified by the obtained mechanical data as low-strength rocks with an average E (Fig. 4.11; Deere and Miller, 1966), possessing interconnected pore networks and pores with an average low sphericity. These features may render such units structurally unstable at the rock mass scale. Although trachytes are massive in texture, their high alkali-feldspar content makes them susceptible to weathering, which affects their long-term durability and aesthetic value as dimension stone.

The studied lavas show variable properties across different scales, mostly driven by changes in porosity, mineralogy, and the nature of the microstructure (size and shape of the voids). Microcracks and pores, whether intragranular or intergranular, act as weakness features, facilitating crack propagation, lowering strength and stiffness, and increasing permeability. The observed fracture networks partially represent the larger-scale discontinuities responsible for fluid flow in fractured rock masses and volcanic edifices, where such features are pervasive (e.g., Heap et al., 2018c; 2020a). These structural features may dictate pore pressure distribution and facilitate hydrothermal alteration (Heap et al., 2018c; Rossetti et al., 2018; Pereira et al., 2024a), thereby increasing variability in lava rocks (Pereira et al., 2024a and references therein).

The applied research strategy, integrating both conventional and advanced imaging techniques across micro- to intact rock scales, provides high-resolution data essential for future research. The obtained data can be used to calibrate models predicting rock mass failure (e.g., Reinoso et al., 2019) and volcanic slope instability (e.g., Heap et al., 2020b; 2023). Nonetheless, extrapolating these findings to larger-scale volcanoes and geothermal reservoirs remains a nontrivial issue (Heap et al., 2020a; Vairé et al., 2024).

4.4. Conclusions

The following conclusions are reproduced after the work of Pereira et al. (2025a). Lava rocks from São Miguel Island are microstructurally characterised in detail, exploring the correlation of void space parameters with selected index properties. Evaluating volcanic rocks across micro- to intact rock scales is essential to deepen the current knowledge of the complex pore networks and how these influence mechanical behaviour. The main conclusions are as follows:

- The composition and texture of lava rocks from São Miguel are varied. Dense, low-porosity, and mechanically competent porphyritic basalts are coeval with intermediate and trachytic lavas, which are generally of lower strength and density. Vesicular textures and post-emplacement fracturing can further decrease strength and increase porosity.
- This chapter is the first study to assess the microstructure of São Miguel's lava rocks using a multi-method approach. The integration of laboratory and digital rock physics techniques has proven effective in capturing both macro- and microporosity and assessing the mechanical properties.
- Pores within these rocks are typically round, with an average sphericity of ~ 0.80 , although they may become angular when constrained by feldspar microlites. Phenocrysts are typically elongated. Depending on the orientation to the loading axis, the boundaries of phenocrysts, intracrystalline cracks and micropores, favour crack propagation.
- Pore sphericity and circularity analyses effectively indicate pore coalescence and the presence of fractures, features that correlate with increased connectivity and reduced rock competence. These characteristics are well resolved at the voxel size used in μ CT imaging.
- The quantitative shape and size metrics can be used to predict and clarify brittle deformation in volcanic materials.
- Thin-section petrography provides a preliminary assessment of mineralogy and texture. However, 3D imaging techniques, such as μ CT, improve microstructural characterisation.
- Suggested ISRM (2007) methods are cost-effective and widely accessible in rock mechanics, facilitating inter-laboratory data comparison. This work demonstrates that density assessments can be adapted for the small specimens used in MIP and

μ CT techniques. However, scale-dependent representation of fractures may induce variability in data across specimen sizes.

- Time-resolved compression tests using μ CT provide a direct visualisation of microcrack propagation and ultimate convergence leading to failure. μ CT is confirmed as a robust tool for capturing the mechanical and physical behaviour of lava rocks.
- Digital rock physics effectively quantifies porosity and generates pore network models that visually complement microstructural data derived from MIP.
- All tested rocks exhibit brittle behaviour, failing through tensile splitting under unconfined compression. Variations in the cracking pattern are linked to pre-existing features such as primary and coalesced pores, clustered voids, phenocryst boundaries, and intragranular microcracks, which serve as stress concentrators and early failure zones.
- Vesicular textures associate with reduced strength and stiffness of the rocks, which have implications for both rock mass stability and the long-term performance of lava rocks as construction materials.
- The cores of lava flows are typically massive, of low-porosity, and dominated by micropores. While generally medium- to high-strength, these units may be susceptible to long-term degradation.
- In vesicular lava rocks, permeability is governed by pore size, with interconnected pores > 1 mm in radius facilitating fluid flow, presumably to be performed by gravitational mechanisms. In contrast, massive lavas with $n_{eff} < 10$ % are assumed to have a permeability primarily controlled by their porosity.

The merged data provide a foundation for future research into the geomechanical behaviour of intact volcanic rocks, as well as the influence of pore orientation on the physical and mechanical properties of lavas.

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Fresh Azorean Lava Rocks

Chapter

Engineering properties of Azorean lava rocks: Insights from a laboratory campaign

Engineering properties of Azorean lava rocks: Insights from a laboratory campaign

This chapter is reproduced from the publication “Engineering properties of lava rocks and empirical correlations for geotechnical applications: Insights from laboratory testing”. The paper was submitted on Rock Mechanics and Rock Engineering and is currently under review.

5.1. Preliminary note

Intact rock properties are determined through laboratory tests, which constitute the first step in any engineering project (Hudson and Harrison, 2000; Hoek and Brown, 2019; see Chapter 2.2.1. Part A). Intact rock studies allow for direct determination of the mechanical deformation of rocks towards failure (González de Vallejo and Ferrer, 2011; Xie et al., 2025), which can only be inferred from time-averaged field observations. Deformation is often combined with the assessment of other physical and dynamic properties, such as effective porosity (n_{eff}) and P-wave velocity (V_p). The unconfined compressive strength (UCS or $\sigma_{c,UCS}$) and Young’s modulus (E) describe the competence and stiffness of rocks, respectively, and are the main input variables in rock mass geomechanical classifications (Bieniawski, 1989; Miranda et al., 2018), numerical models related to rock engineering problems (e.g., Abdelaziz and Grasselli, 2021 and references therein), ground deformation (Gudmundson, 2006; Zhan and Gregg, 2019), and slope stability analysis (e.g., del Potro and Hürlimann, 2008; Schaefer et al., 2013; Villeneuve and Heap, 2021; Mordensky et al., 2022). The full mechanical characterisation of rocks is achieved by triaxial tests, allowing to verify the behaviour of rocks transitions from brittle to ductile (e.g., Walton, 2021; see Chapter 2.2.2 Part C), and to estimate shear parameters, such as cohesion (c) and angle of internal friction (ϕ), using failure criteria (Jaeger et al., 2007; Chapters 2.2.4.2 and 2.2.4.4, Part C).

The variable structure of lava rocks leads to unpredictable deformation and properties, with several studies establishing porosity as the main factor influencing the strength of volcanic rocks (Rodríguez-Losada et al., 2009; Karaman and Kesimal, 2015; Pappalardo and Mineo, 2017; Pappalardo et al., 2017). Lavas are a widespread geotechnical material in volcanic islands and, therefore, interested by several engineering sites, explored as a geo-resource for construction and ornamental purposes, and compose, at a larger scale, volcano-hydrothermal systems that can host geothermal fields. São Miguel Island covers all these

aspects, with a history of destructive earthquakes, volcanic unrest episodes, and extreme meteorological events that favour landslides and rockfalls (Malheiro, 2006; Malheiro and Nunes, 2007; Silva et al., 2024). Studies on the mechanics of volcanic rocks are limited compared to those of other rock types (Chen et al., 2022), and Azorean lavas are no exception, with scarce and scattered research (Loaiza et al., 2012; Moreira and Wallenstein, 2013; Malheiro et al., 2018; Amaral et al., 2018; Pereira et al., 2025).

In this chapter a complete laboratory campaign on the study of intact rock is developed regarding different lavas from São Miguel. Several physical (n_{eff} , V_p , dry density ρ_{dry} , and saturated density ρ_{sat}) and mechanical properties ($\sigma_{c,UCS}$, indirect tensile strength σ_t , Poisson's ratio ν) were determined. Because investigations on the water-weakening effect on the tensile strength of volcanic rocks are lacking compared to those on the compressive strength (Heap and Violay, 2021), saturated samples were also tested for σ_t . This chapter also defines the crack stress initiation (σ_{ci}) and damage (σ_{cd}) based in the uniaxial test stress-strain curves (see Chapter 2.2.1 Chapter C), whose research is mostly limited to intrusive igneous rocks (Nicksiar and Martin, 2012; Nicksiar and Martin, 2013; Nicksiar and Martin, 2014) and metamorphic and sedimentary rocks (Pepe et al., 2018 and references therein; Peng et al., 2018 and references therein). Moreover, given the existence of lavas at depth composing the Fogo Volcano and its hosted Ribeira Grande geothermal field, triaxial tests were conducted to determine the effects of confinement on compressive strength and to calculate shear strength parameters (c and ϕ), which are rarely determined for volcanic rocks (Ball et al., 2018). The provided data contributes to worldwide databases on petrophysical and geotechnical properties (e.g., Zhang et al., 2012; Bär et al., 2020) and defines geomechanical parameters often overlooked for lava rocks.

Empirical equations for estimating $\sigma_{c,UCS}$, c and ϕ for a complete lava rock data set are also established to facilitate future mechanical characterisation on these rocks or similar ones, by avoiding time-consuming and expensive tests, where specimen size requirements are difficult to accomplish (e.g., Diamantis et al., 2009; Aladejare et al., 2021). Furthermore, this study aims to reduce the gap between rock mechanics and volcanology by supplying “upscaled” mechanical values. Their use in future volcanic and geotechnical models is envisaged to produce more accurate interpretations of slope stability and ground deformation.

5.2. Summary of materials and methods

5.2.1. Sample organisation

As described in Section 3.1.2, a total of 113 blocks with different textures and compositions were sampled and organised according to Fig. 3.6. Considering the mineralogical and chemical composition described in Chapter 4, basalts (*sensu lato* – s.l.) are used to refer to BP and BAF samples. In contrast, intermediate lavas (also basalts s.l.) are relative to the mugearites/ basaltic trachyandesites and benmoreites/trachyandesites collected as BF samples. Trachytes are mentioned separately from intermediate lavas.

Obtaining the minimum number of specimens according to ISRM (2007) from the same block for the uniaxial and triaxial tests was not possible; therefore, the subfacies (Fig. 3.6) were considered as an alternative to meet the requirement. The shape and size of the specimens were defined according to the test (see Sections 3.2.5.1, 3.2.5.2, and 3.2.5.3), consisting of discs (45–51 mm in diameter), cylinders ($L/D \sim 2$; 42–51 mm in diameter), and irregular lumps.

5.2.2. Methods

5.2.2.1. Index properties determination

Irregular lumps were used to obtain effective porosity (n_{eff}) and density (ρ) via the buoyancy and saturation technique described by ISRM (2007) and presented in Chapter 3.2.4.1.

The V_p was determined in oven-dried cylinders using the PROCEQ® Pundit Lab equipment, following the conditions specified in Chapter 3.2.4.4.

5.2.2.2. Mechanical tests

The $\sigma_{c,UCS}$ was determined using a uniaxial test performed at the GEOLAB. The test procedure and conditions are presented in Chapter 3.2.5.2.

Besides $\sigma_{c,UCS}$, the use of strain-gauges (SG) allowed the calculation of several elastic parameters based on the stress-strain curves, as these are found to differ (Małkowski and Ostrowski, 2017; Małkowski et al., 2018). The E_{tg} , E_{avg} , and E_{sec} were calculated according to Section 3.2.5.2. The homologous ν corresponds to the ratio of the lateral to axial strain in the same section of the curves.

The triaxial tests following the procedure and conditions specified in Chapter 3.2.5.3. Different confining pressures (P_{conf}) were selected for the triaxial test to mimic the depth of the subsurface geology from the Fogo Volcano and Ribeira Grande geothermal field (see Fig. 3.9) and to derive the c and ϕ .

The ITS was determined using the Brazilian test (ISRM, 2007), following the procedure and conditions outlined in Chapter 3.2.5.1. Contrary to compression tests, Brazilian tests were applied to both oven-dried and saturated specimens.

5.2.2.3. Data analysis

Statistical analysis

Simple and multiple regression analyses of physical and mechanical properties were performed, as described in the regression analysis section of Chapter 3.2.6.4.

The statistical significance of the models was determined using ANOVA, with a 95% confidence interval. The direction and robustness of linear and nonlinear correlations were determined through the Pearson's and Spearman's correlation coefficients.

Metrics are commonly applied to estimate the engineering properties of rocks (e.g., Diamantis et al., 2009; He et al., 2020). The coefficient of determination (R^2), root mean square error (RMSE; Eq. 3.26 mean absolute percentage error (MAPE; Eq. 3.27), and variance accounted for (VAF; Eq. 3.28) were calculated to check the performance of the σ_{c_UCS} -based empirical correlations.

Interpretation of crack stress thresholds

Crack thresholds were only obtained in uniaxial tests (Chapter 3.5.5.2). The σ_{cd} was determined using the reversal of the volumetric strain (Eq. 2.8 – Chapter 2.2.1 Part C), and σ_{ci} was determined via the LSRM, except for BF14A, where only the axial strain was considered (Basu and Mishra, 2014).

Failure criteria

Triaxial laboratory data were used as input to derive the fitting parameters (c and ϕ) of the Mohr-Coulomb (MC; Section 2.2.4.4, Part C) and Hoek-Brown (HB; Section 2.2.4.4, Part C) criteria, using the RocScience® RSDData software (see Chapter 3.2.6.3 for further explanation and equations). In addition, the HB was used to fit the rock mass internal friction angle (ϕ_{rm} ;

Eq. 3.21) and cohesion (c_{rm} ; Eq. 3.22), considering $D = 0$, a $GSI = 55$ (del Potro and Hürlimann, 2008; Schaefer et al., 2013; Miranda et al., 2018; Heap et al., 2020a; Villeneuve and Heap, 2021), and a $H_{slope} = 500$ m (see Section 3.2.6.3). The rock mass elastic modulus (E_{rm}) was calculated using the generalised Hoek and Diederich (2006) method (Eq. 2.12), recently reviewed by Heap et al. (2020a).

According to Labuz and Zhang (2012), at least three triaxial experiments are required to derive the MC criterion, whereas at least five (including σ_{c_UCS}) are necessary to derive the HB failure criterion (Hoek and Brown, 1997). To develop accurate models, the input data comprised values of the Brazilian, uniaxial, and triaxial tests for the same blocks, whenever possible. Although Brazilian test results are sometimes considered inadequate for modelling the Hoek-Brown envelope (Perras and Diederichs, 2014; Hoek and Brown, 2019), other studies have included these values (e.g., Mordensky et al., 2022). A preliminary analysis revealed consistency in the models, both with and without the inclusion of the tensile strength.

5.3. Results and discussion

5.3.1. Engineering properties

The engineering properties are listed in Table 5.1. A total of 324 irregular lumps were analysed for physical properties (n_{eff} , ρ_{dry} , ρ_{sat}), Vp was determined for 116 cylindrical specimens, σ_{c_UCS} refers to 66 cylindrical specimens, and 231 disc specimens were tested for σ_t . Further statistical descriptors and results per sample subgroup are presented in Appendix 5.1.

Overall, ρ_{sat} is higher than ρ_{dry} , regardless of the texture and rock type. In line with Chapter 4, dry densities will be focused on throughout the text.

BP basalts are massive and contain olivine and clinopyroxene (ferromagnesian minerals), which make them dense (~ 2.7 g/cm³) and with high Vp (4777 m/s) compared to the remaining samples. n_{eff} averages 6.06 % but has a wide range (2 to 25 %), varying from low-porosity to medium-porosity. A wide range is also verified for σ_{c_UCS} , which varies from 47 to 156 MPa, whereas σ_t averages 10.51 MPa. Baf contains more plagioclase, both as phenocrysts and in the groundmass (Pereira et al., 2025a; Chapter 4), with lower ρ_{dry} (2.6 g/cm³) and Vp (4410 m/s) with respect to BP basalts. $n_{eff} = 7.67$ %, and the average σ_{c_UCS} and σ_t are in the same range as BP. A value of $\sigma_t = 0.65$ MPa was obtained but considered an outlier for Baf and, therefore, excluded.

Table 5.1. Main descriptive statistics of several engineering variables characterising lava rocks sampled in São Miguel. avg $\pm$ std.dv: average $\pm$ standard deviation; N – number of specimens.

Statistical metrics	n_{eff} (%)	ρ_{dry} (g/cm ³)	ρ_{sat} (g/cm ³)	Vp (m/s)	σ_{c_UCS} (MPa)	σ_t (MPa)
	BP – low- and medium-porosity basalts (s.l.; Mosteiros parish)					
Avg ± std.dv	6.06 ± 5.47	2.721±0.260	2.782±0.219	4777±398	90.97±27.41	10.51±2.88
Range	1.58 - 25.31	1.973 - 3.070	2.112 - 3.108	3796 -5549	46.67 -155.67	3.97 - 17.51
N	88		35		21	68
	BAf –low-to-medium and medium-porosity basalts (s.l.; Sto. António parish)					
Avg ± std.dv	7.67±4.30	2.564±0.150	2.641±0.142	4410±537	85.07±34.59	10.33±4.11
Range	2.10 - 15.37	2.235 - 2.796	2.264 - 2.824	3511 -5196	43.63 -147.49	0.65 - 18.91
N	50		15		10	35
	BF – medium-to-high-porosity basalts (s.l.; Ribeirinha parish)					
Avg ± std. dev	18.03±5.15	2.213±0.183	2.394±0.146	3747±585	36.77±18.16	6.39±2.41
Range	7.03 - 36.05	1.738 - 2.694	1.936 - 2.790	2708 -4636	16.83 – 78.60	2.18– 14.66
N	102		39		20	76
	T – low-to-medium-porosity trachyte (Vale das Lombadas)					
Avg ± std.dv	4.51±4.01	2.419±0.187	2.464±0.152	4153±693	81.02±37.86	9.61±2.92
Range	1.03 - 20.37	1.813 - 2.690	2.016- 2.707	2711 -5027	29.81 -153.43	1.95 - 16.04
N	84		27		14	52

Appendix 5.1 indicates that the macroscopic distinction between low and medium porosity basalts (BP and BAf) is not completely accurate, as the presence of localised porous bands (high-concentration of pores of similar size, up to a millimetric diameter, in a localised zone of the specimens; in BP) and fissures in the specimens (in BAf and BP) can increase n_{eff} up to 20 % and decrease ρ_{dry} of BAf.A and BPA to values similar of those obtained in facies BAf.B and BP.B.

Density and n_{eff} for the studied basalts are aligned with those reported in the literature (Pereira et al., 2021 and references therein), while V_p is closer to results found by Yuksek and Demirci (2010) and the average value presented by Pereira et al. (2024a) for basalts (Fig. 2.11d). The results agree with the variable σ_{c_UCS} reported for basalts (Malheiro et al., 2018; Pereira et al., 2021 and references therein), while the values of σ_t are lower. Nevertheless, σ_t is 5–10 % of σ_{c_UCS} , as reported by González de Vallejo and Ferrer (2011).

BF samples include basalts (s.l.) from Fogo, with more plagioclase, mostly corresponding to intermediate basalts that range from basaltic trachyandesites to trachyandesites (Chapter 4). BF.B is an exception (Fig. 3.6) as it contains more olivine than the remaining BF samples.

The remaining BF lavas (BFA and BFC) correspond to intermediate lavas that were separated based on their macroscopic texture (Fig. 3.6). Results on Table 5.1 and Appendix 5.1 show that:

- BFB has an average $n_{eff} = 13.75\%$ combined with lower ρ_{dry} (2.5 g/cm^3), Vp (3834 m/s), and strength ($\sigma_{c,UCS} = 46.50 \text{ MPa}$ $\sigma_t = 8.17 \text{ MPa}$) (Appendix 5.1) with respect to Sete Cidades basalts. Nevertheless, BFB values are proximate with those of BAF.B and BP.B because of similar n_{eff} . BFB is also responsible for the maximum values of ρ , Vp , and strength in the BF sample (Table 5.1).
- Medium-porosity BFC ($n_{eff} = 13.11\%$; Appendix 5.1) show a decrease in ρ_{dry} (2.3 g/cm^3) and Vp (4437 m/s) compared to the low-to-medium porosity BP and BAF basalts. BFB and BFC have different mineral composition, but similar connected porosity ($\sim 13/14\%$). The strength of BFC ($\sigma_{c,UCS} = 77.81 \text{ MPa}$ and $\sigma_t = 9.66 \text{ MPa}$) falls within the strength range of BFB, whereas Vp is higher and ρ_{dry} is lower for BFC (Appendix 5.1). These values appear contradictory and result from the structural complexity of these lavas. For example, Vp variability was also reported for massive trachyandesites from Etna by Pappalardo et al. (2017), which was attributed to the widespread occurrence of microcracks.
- High-porosity BFA lavas ($n_{eff} = 19.37\%$; Appendix 5.1), characterised by a vesicular texture where many pores are elongated and have radius $> 1 \text{ mm}$, display a decrease of 0.146 g/cm^3 in ρ_{dry} , 765 m/s in Vp , and in strength ($\sigma_{c,UCS} = 31 \text{ MPa}$ and $\sigma_t = 5.39 \text{ MPa}$) compared with the massive homologous, BFC.
- BFA samples associate with lower standard deviation in strength compared to the remaining low-to-medium porosity lavas (Appendix 5.1), suggesting that vesicular lava rocks are univariably weaker but produce more consistent results and within a narrower range of values. As reported in Appendix 3.1, closed fissures are rarely observed in BFA samples.
- BFAI and BFAII (Fig. 3.6; Appendix 5.1) have a different porphyritic degree, as recognised at hand-sample. BFAII, with more plagioclase phenocrysts, has higher $\sigma_{c,UCS}$ and Vp values than BFAI, which has a more aphyric groundmass. The obtained values appear to contradict numerical simulations, where increased phenocryst content reduced strength (Heap et al., 2016; Heap and Violay, 2021).
- BFAIII ($n_{eff} = 21.58\%$; WGII-WGIII) produces the lowest ρ_{dry} and $\sigma_{c,UCS}$ of the BFA facies, whereas Vp minimum values are not necessarily the lowest of the facies (Appendix 5.1).

The strength of BF lavas is lower than the average values established by Pereira et al. (2024a) for unaltered andesites ($\sigma_{c_UCS} = 161$ MPa and $\sigma_t = 9$ MPa; Fig. 2.16a) but agree with the σ_{c_UCS} obtained by Malheiro et al. (2018) for vesicular basalts from the São Miguel. Results show that Azorean vesicular lavas also share similar dry density (Motta and Nunes, 2003; Malheiro et al., 2018).

Trachytes are felsic lava rocks with a lower density (2.4 g/cm^3) and massive trachytic texture (4.51% of n_{eff}). Low-porosity trachytes prevail in the T dataset, associating with higher standard deviation for Vp and σ_{c_UCS} compared to the other samples. σ_{c_UCS} ranges from 29 MPa to 153 MPa for T.AIII and T.AI, respectively, with low-porosity and slightly altered trachytes as competent as fresh BPA and BAf.A (Appendix 5.1). σ_t is lower than that of the basalts and, on average, similar to that of the BF lavas.

Drilling did not consider the preferred orientation of the crystals in the trachytes. Notwithstanding, for this study, it is suggested that the orientation of feldspars and microcracks influence σ_{c_UCS} and increase or hinder Vp , similar to what has been previously reported for micas by Charoensawa et al. (2021). In addition, the property variation across trachytic subfacies (Appendix 5.1) shows that moderately altered trachytes (T.AIII; Fig. 3.6) are weaker. In comparison with the literature, the obtained average σ_{c_UCS} is inferior to the values reported for other Azorean trachytes (Malheiro et al., 2018), which are more similar to T.AI. The remaining engineering properties are aligned with values reported by Motta and Nunes (2003) and for other trachytes worldwide (Heap and Violay, 2021; Pereira et al., 2024a; Fig. 2.16).

The specimen description (Appendix 3.1) indicates that the presence of structural features, such as fissures, large pores, porous bands, and veins, varies across specimens, rendering them heterogeneous. As a result, σ_{c_UCS} determination for accurate rock mass classification and better rock engineering design requires a representative set of specimens.

In addition, the preliminary microstructural study of Pereira et al. (2025a) (Chapter 4) and other research (Couves et al., 2016; Griffiths et al., 2017; Cant et al., 2018) reveal the complexity of the void space of lavas, composed of microcracks, micropores, and larger (pore radius $> 1 \text{ mm}$) pores, occurring in different proportions and with varying orientations. Thin-section analysis (qualitative) of low-porosity basalts (s.l.) and trachytes reveals that transgranular microcracks are common in the studied lavas. In contrast, the

void space of vesicular specimens is mostly composed of pores of different shapes, sometimes coalescent, whereas microcracks are less common.

The overall data suggest that *effective porosity* has a weakening effect on lavas, reducing their strength and ρ , confirming previous studies (Al Harti et al., 1999; Pappalardo and Mineo, 2017; Pappalardo et al., 2017). n_{eff} provides a first clue regarding rock strength, with the advantage of being easily and cost-effectively determined. However, it does not fully capture the effect of microcracks, which are volumetrically small compared to pores, and is a scalar, thereby precluding a complete understanding of the nature of the void space (Heap and Violay, 2021).

The range and standard deviation of the results, combined with previous microstructural research, suggest that microcracks may contribute to the variability of $\sigma_{c,UCS}$ and Vp in low-to-medium porosity rocks. Other factors, such as the type of porosity, pore size and microcrack orientation, may also contribute to sample heterogeneity (e.g., Hudson and Harrison, 2000; Gupta and Sharma, 2012; Navelot et al., 2018; Shen et al., 2020).

In turn, *composition* of the rock has an unclear effect, as n_{eff} is not maintained across the different rock types. From basalt to trachyte, ρ and the average Vp decrease because of the more felsic mineralogy, while strength reduction is not implied. Mineralogy appears to play a minor role in strength compared to porosity.

5.3.1.1. Saturation effect on indirect tensile strength

The *saturation effect* was evaluated for ρ (Table 5.1) and σ_t (Fig. 5.1a). ρ and σ_t increased and decreased, respectively, from oven-dried to saturated specimens, independent of the rock type. Increasing feldspar content does not imply higher water weakening, as reported previously (Heap and Violay, 2021). It is stressed that ITS weakening by water is independent of the porosity in lavas (Fig. 5.1b), confirming previous conclusions concerning $\sigma_{c,UCS}$ of volcanic rocks (Heap and Violay, 2021). The ratio of wet to dry σ_t is 0.77, indicating a reduction in the tensile strength of 33 % with the saturation of the specimens. Exceptions occurred for the two vesicular BF specimens and one BP basalt (Fig. 5.1b above the dashed line).

Water weakening in σ_t has been reviewed for sandstones and limestones (Wong et al., 2016), with σ_t exponentially decreasing and above 50 % because of saturation. The studied lava rocks have a lower σ_t reduction than those reported for sedimentary rocks, but in the same order of magnitude as that reported for $\sigma_{c,UCS}$ in volcanic rocks (Heap and Violay, 2021).

Because of the fresh state of most analysed rocks, clay-absent, water weakening is assumed to result mainly from a reduction in fracture toughness (e.g., Guha Roy et al., 2017).

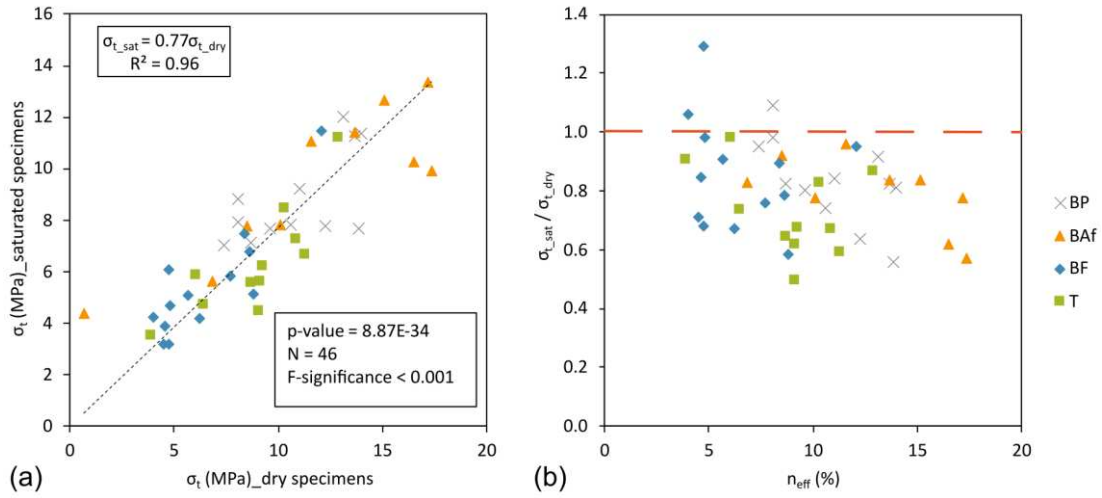


Fig. 5.1 Saturation effect on (a) indirect tensile strength (σ_t) of several lava rock types and the ratio of wet to dry σ_t with open porosity n_{eff} (b).

5.3.1.2. Elastic properties

Fig. 5.2 depicts the stress-strain curves of the uniaxial test. To assess the consistency and which method is better suited for determining the elastic properties of lavas, E and ν were determined for 28 and 22 specimens, respectively. Strain was not measured for all specimens due to material limitations or to a malfunction of SG during the test. Results in Fig. 5.3a show that there are minor discrepancies between the several elastic properties, especially for E .

Sete Cidades basalts are stiff materials, with an E_{avg} of ~ 45 GPa for BP basalts (Fig. 5.2a), while BAf (Fig. 5.2b) show lower E_{avg} (~ 37 GPa). Basalts have an average $\nu = 0.22$ – 0.24 (Fig. 5.3a), within the scope of values reported in the literature (e.g., González de Vallejo and Ferrer, 2011; Pereira et al., 2021; Pereira et al., 2024). Medium-porosity BF.C maintain similar stiffness (40–45 GPa) and ν to BP and BAF.

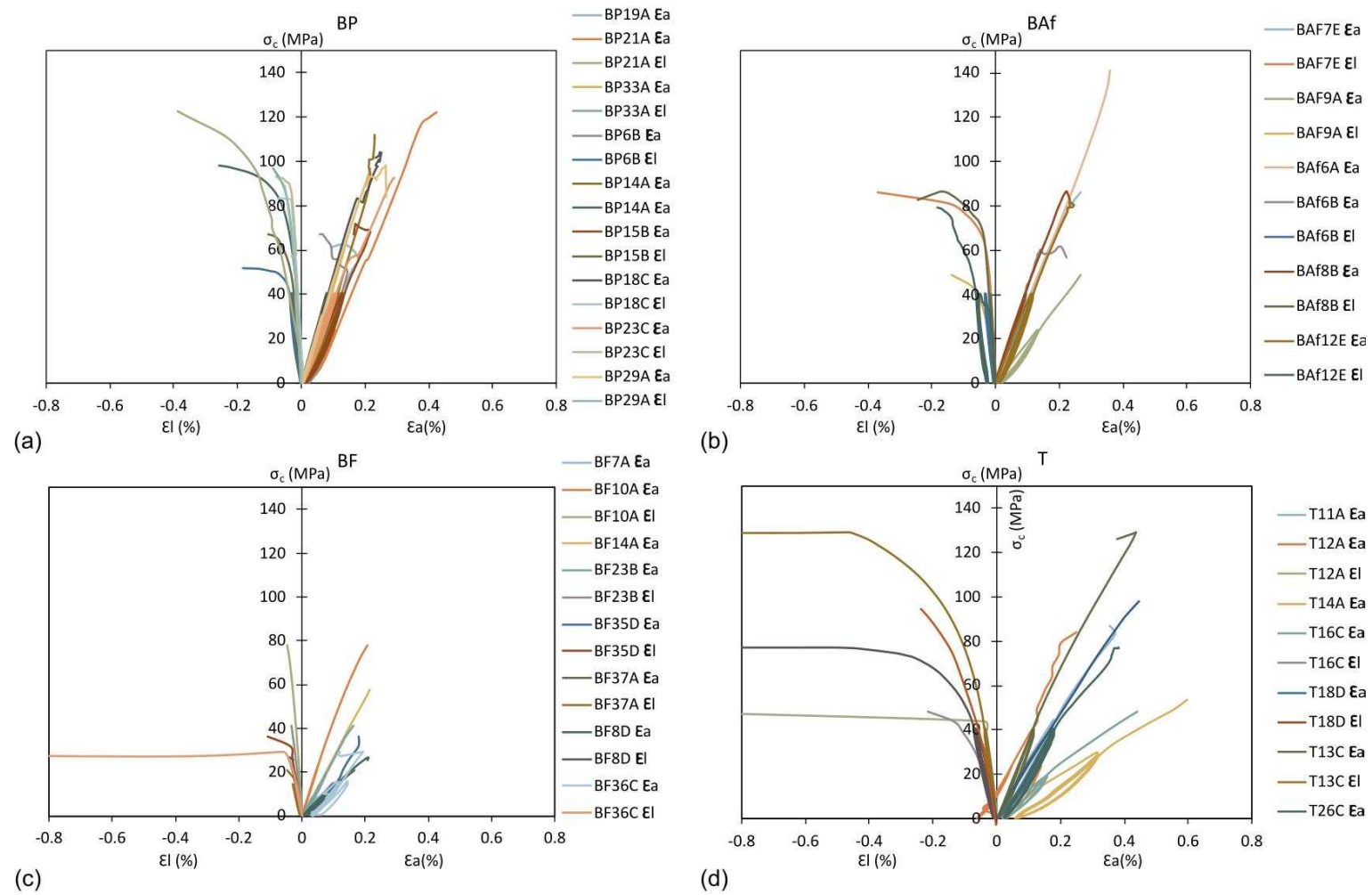


Fig. 5.2. Stress-strain curves obtained in the uniaxial test for (a) BP basalts, (b) Baf basalts, (c) BF intermediate lava rocks, and (d) T trachytes. E_a – axial strain; E_l – lateral strain.

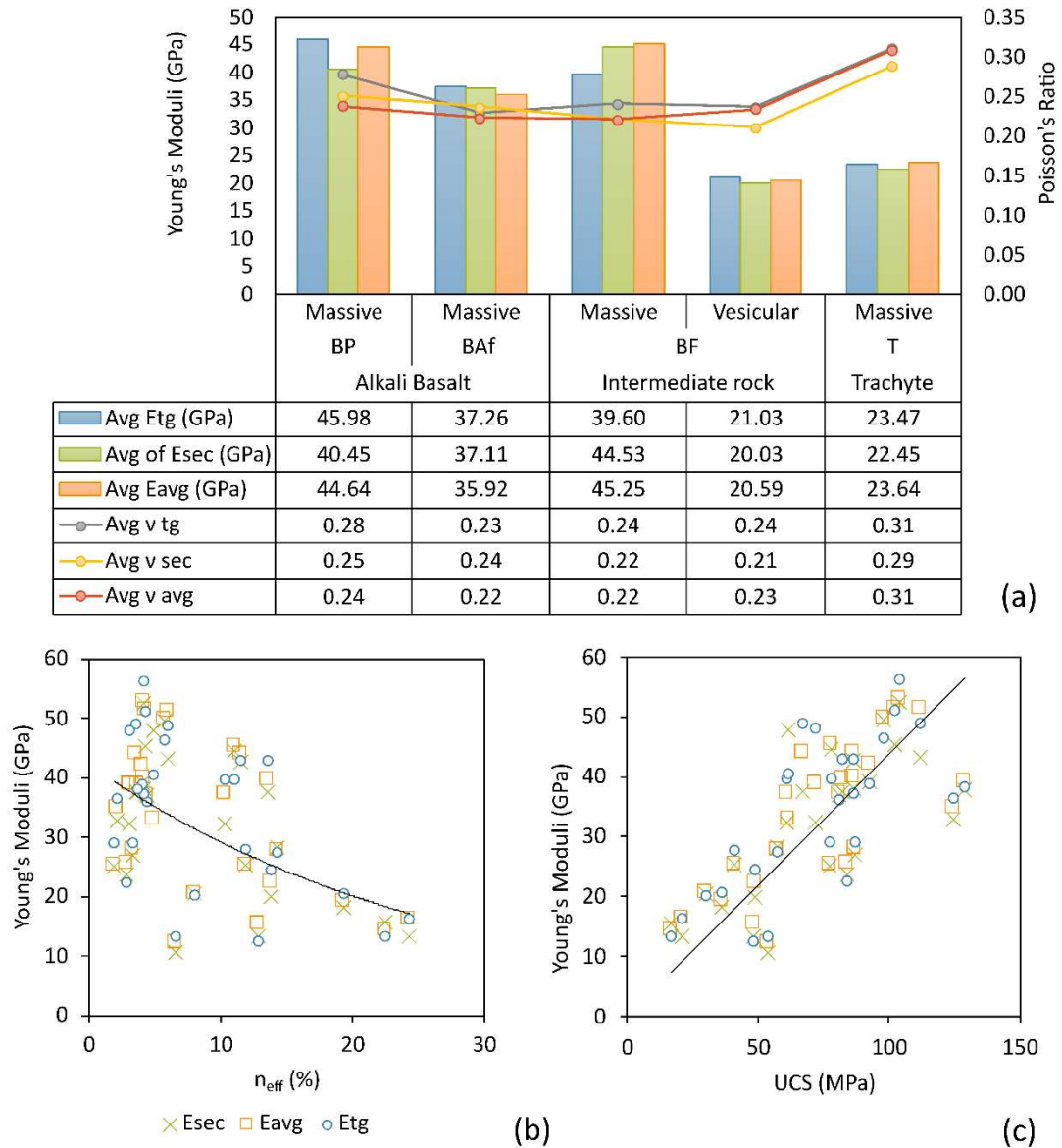


Fig. 5.3. Average values of several Young's moduli (E) and Poisson's ratios (ν) for different rock types and textures. avg, average; tg, tangent; s, secant (a). Correlation of various Young's moduli with open porosity (b) and unconfined compressive strength (c). Due to the low R^2 , no equations are displayed in (b) and (c).

The vesicular texture and high porosity of BFA decrease in E to ~ 20 GPa (Fig. 5.3a), presenting greater deformation (Fig. 5.2c) than low-to-medium porosity basalts. Macroscopically, the pores of BFA, many of which are larger than 1 mm, favour crack propagation and do not allow for specimens to resist high stress, controlling entirely the stress-strain curves, as previously reported for vesicular trachyandesites (Pappalardo et al., 2017). The $\nu = 0.23$ of the BF sample falls within the range for low-to-medium porosity basalts, indicating that the ratio remains constant despite increasing porosity. Results

suggest that porosity and ν have no or a minor dependence, as previously suggested by Heap et al. (2020a).

Trachytes (Fig. 5.2d) are the least stiff rock among the low-porosity lava rocks, with an average E varying between 22 and 24 GPa. The ν (~ 0.31) is the highest compared to other massive rocks, within the range of values established by Christensen (1996), Gercek (2007), and González de Vallejo and Ferrer (2011). The shift from massive basalts to trachytes, characterised by an increase in feldspar content, does not imply a reduction in strength; however, ρ and E invariably decrease, while ν increases. Although no clear correlation was found between ν and felsic and mafic minerals by Christensen (1996), it is suggested that the higher strain accommodation in the studied trachytes may be due to their mineral composition and higher alkali content ($\text{Na}_2\text{O}+\text{K}_2\text{O}$). For example, alkali feldspar ($\nu = 0.30$; Christensen, 1996) becomes prevalent in these rocks as shown in Chapter 4.

Considering all studied rock types, n_{eff} vs. E produces scattered data with an incipient nonlinear trend (Fig. 5.3b). Results support conventional thinking that porosity decreases the Young's modulus of a rock (Simmons and Brace, 1965; Guéguen and Kachanov, 2011; Gudmundsson, 2011), while simultaneously showing that the correlation is quite scattered, as observed by Heap et al. (2020a) for lavas. In this study, some of the low-to-medium porosity lavas (BP, BAf, T, and BF.C) show E values that are either lower or higher than their porosity suggests. For example, some specimens contain closed fissures (Appendix 3.1) and attain high E , and vice versa. E variability is also verified for vesicular BFA, which has a 6 MPa E_{avg} standard deviation, despite the narrow range of n_{eff} ($19.37 \pm 4.68 \%$). E and ν variability within and across samples suggests that, besides mineralogy and porosity, other factors, such as geometry (size and shape), orientation, and distribution of pores, may also play a role in the rock's mechanical behaviour (e.g., Gercek, 2007). Consequently, as stated by Heap et al. (2020a), E and σ_{c_UCS} cannot be used to distinguish between different lava types, given the variable texture.

The positive linear correlation between σ_{c_UCS} and E (Fig. 5.3c) shows a strong bond between them and establishes the modulus ratio (mr - ratio between E and σ_{c_UCS}), which is used in the Deere and Miller (1966) classification of rocks. A statistically significant regression analysis (low F -significance and p -value < 0.001) was conducted between several Young's moduli and σ_{c_UCS} to determine which E better suits the present dataset. The results (Table 5.2) show that E_{avg} has the highest determination coefficient (R^2) and the lowest standard error for the different lava rocks, being the most adequate.

Table 5.2. Regression analysis between σ_{c_UCS} and the different Young's moduli – average (E_{avg}), tangent (E_{tg}) and secant (E_{sec}), described by the regular (R^2) and adjusted coefficient of determination (Adj. R^2), standard error (Std. error) and modulus ratio (mr) for each rock type (number of specimens within parentheses) and all studied rocks.

Reg. Analysis	N	Ref.	Range E $\pm$ std. dv (GPa)	R^2	Adj. R^2	Std. error	mr
σ_{c_UCS} VS. E_{tg}	9	BP	(36.39 – 56.15) $\pm$ 6.45	0.937	0.812	43	473
	6	BAf	(24.31 – 42.86) $\pm$ 6.95	0.982	0.782	30	494
	5	BF	(13.13 – 39.60) $\pm$ 9.58	0.967	0.717	37	543
	7	T	(12.53 – 38.13) $\pm$ 9.26	0.959	0.792	26	311
All lava rocks (28)				0.925	0.888	24	442
σ_{c_UCS} VS. E_{avg}	9	BP	(34.75 – 52.81) $\pm$ 6.85	0.953	0.828	36	464
	6	BAf	(22.22 – 44.01) $\pm$ 7.64	0.997	0.797	12	482
	5	BF	(14.41 – 45.25) $\pm$ 11.30	0.968	0.718	33	569
	7	T	(12.15 – 38.92) $\pm$ 8.82	0.966	0.799	24	312
All lava rocks (28)				0.939	0.902	21	437
σ_{c_UCS} VS. E_{sec}	9	BP	(32.17 – 52.49) $\pm$ 7.61	0.955	0.830	32	423
	6	BAf	(19.80 – 47.83) $\pm$ 9.45	0.958	0.758	46	492
	5	BF	(13.26 – 44.53) $\pm$ 11.51	0.970	0.720	32	559
	7	T	(10.65 – 37.60) $\pm$ 8.97	0.958	0.792	25	297
All lava rocks (28)				0.926	0.889	23	416

BP is also well described by E_{sec} , which comprises the initial curvature of the stress-strain curve (closure of microcracks). Previous studies have selected the E_{tg} as the most accurate elastic modulus (Malkowski and Ostrowski, 2017; Malkowski et al., 2018). However, tests were conducted on sedimentary rocks using an LVDT, in contrast to this research that calculated E based on SG strain measurements.

All lava rocks have an mr of 416–442 (437 considering E_{avg}), basalts (s.l.) produce an mr of 423–494 (on average 473 for E_{avg}), and trachytes of 297–312 (312 for E_{avg}). Trachytes show low to high strength and are less stiff than BP and BAf basalts, which are mainly medium-to-high strength rocks (Fig. 5.4). Conversely, vesicular lavas (BF) have very low-to-medium strength and medium stiffness, explaining the $mr > 543$. Some low-to-medium porosity lavas may have $mr > 543$ because of the presence of macroscopic closed fissures (BP6B), porous bands (BP19A) and a large-sized pore in the specimen (T18D). On the other hand, BP21A had closed wedge-shaped fissures, reached high UCS, while producing a lower E_{avg} than expected.

The overall results indicate that *porosity* plays a key role in both the stiffness and strength of the rock, with high-porosity samples being weaker than massive lavas, although exceptions may occur. In addition, the effect of mineralogy was notorious in the average mr of the massive lavas, typically lower for felsic rocks than mafic ones.

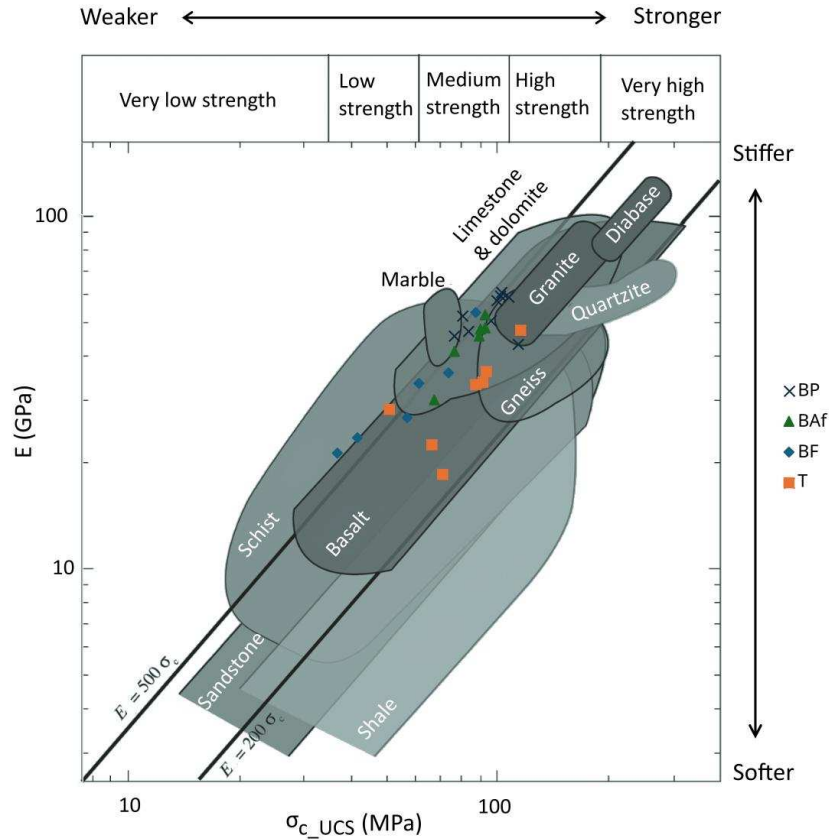


Fig. 5.4. Deere and Miller diagram (1966) containing the analysed lava rocks, ranging from alkali basalts (BP and BAF) and intermediate rocks (BF) to trachytes (T).

5.3.1.3. Crack initiation and crack propagation

Deformation of the intact rock and its ultimate failure result from progressive damage accumulation, marked by the nucleation, propagation, and coalescence of micro- and macrocracks (Li et al., 2024 and references therein). According to the theoretical strain-stress curve (Fig. 2.13), several stages of damage occur as described in Chapter 2.2.1 (Part C). σ_{ci} and σ_{cd} are important indicators of progressive damage in brittle materials. σ_{cd} also defines the long-term strength of the material (Schmidtke and Lajtai, 1985; Martin and Chandler, 1994). Data on lava rocks (22 σ_{ci} and 24 σ_{cd} ; see Appendix 5.2) allowed the establishment of several statistically significant σ_{c_UCS} -based equations (p -values < 0.0001 and low F -significance; Fig. 5.5).

Data scattering is observed for σ_{ci} (Fig. 5.5a) because low σ_{ci} vs. σ_{c_UCS} (< 30 % of the peak stress) occurs for T12A and T26C ($n_{eff} = 1.92\text{--}2.94$ %) and one BAF.B basalt (BAf12E; $n_{eff} = 13.65\%$). The medium porosity and possible microcracks, also combined with low V_p , favours earlier crack initiation in BAF12E. Low-porosity T26C has a considerable V_p (~ 4429 m/s), but displays slight alteration and a marked trachytic texture (Fig. 5.5a; Appendix 3.1).

T12A also has an evident trachytic texture and has a closed wedge-shaped fissure (Appendix 3.1), that may also explain the low V_p (4097 m/s). As these features do not act systematically, it is concluded that a set of features, such as the orientation of the fractures with respect to the loading axis (e.g., Hudson and Harrison, 2000) and the geometry of the pores (e.g., Gercek, 2007), hinders the establishment of a clear pattern.

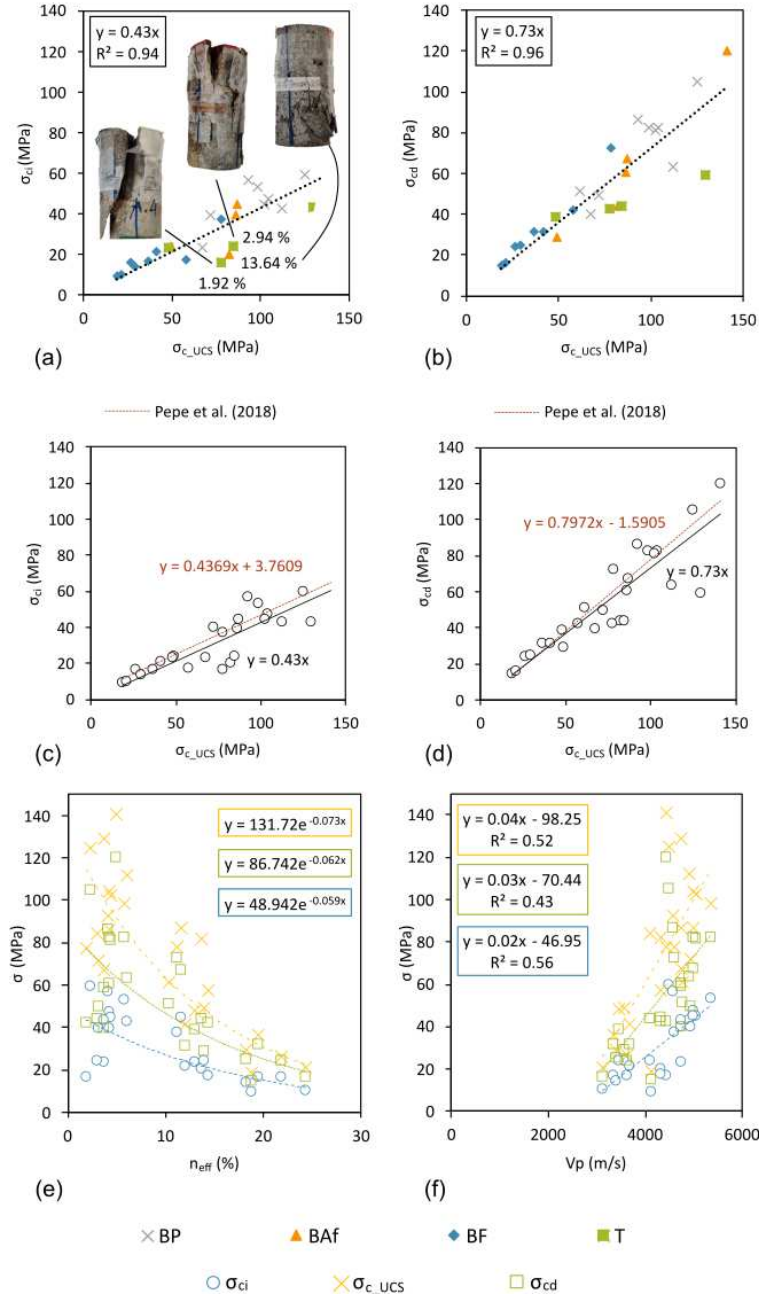


Fig. 5.5. Crack stress thresholds. Crack initiation stress (σ_{ci} ; a) and crack damage stress (σ_{cd} ; b) against the unconfined compressive strength (σ_{c_UCS}) and linear trendlines that better adjust to the results obtained. Linear regression models were compared to the equations of Pepe et al. (2018) for σ_{ci} (c) and σ_{cd} (d) versus σ_{c_UCS} . The red line represents the model of Pepe et al. (2018), and the black line reports to this work. Plots representing the correlation of several stress values with effective porosity (n_{eff} ; e) and P-wave velocity (V_p ; f).

σ_{ci} is on average 45 %, 47 % and 33 % of the peak stress in all samples, basalts (s.l.) and trachytes, respectively. For basalts (s.l.), the ratio of σ_{ci} to the peak stress was maintained independently of the rock texture/porosity (vesicular – 49 % vs. massive – 46 %), despite some exceptions, where σ_{ci} was achieved at lower stress levels despite reaching significant σ_p . The studied trachytes, although represented by only four points, display lower σ_{ci} despite reaching σ_{c_UCS} in the order of BP and Baf basalts (Fig. 5.5b). This trend is not followed by the T.AIII specimen, whose moderate alteration affects both σ_{ci} and σ_p . Can the granularity, trachytic texture, and alkali mineralogy (as suggested before by Nicksiar and Martin, 2013) decrease σ_{ci} , or is this only due to sample-to-sample heterogeneity? Further studies would be required to draw firmer answers. For now, the obtained σ_{ci} to peak stress ratio (45 %) is similar to the ratio of 45 ± 5 % established for low-porosity crystalline rocks, which suggests that the ratio is independent of the texture and porosity (Nicksiar and Martin, 2013; Nicksiar and Martin, 2014; Peng et al., 2018).

σ_{cd} is less scattered (Fig. 5.5b) than σ_{ci} when plotted against σ_{c_UCS} , with a linear regression with a higher R^2 . σ_{cd} is in average 73 % of the peak stress – average ratios of 76 %, 80 % and 58 % for massive basalts (s.l.), vesicular lavas (s.l.), and trachytes, respectively – within the range established by Hoek and Martin (2014) and close to the ranges defined by Xue et al. (2014) and Peng et al. (2018). Rocks with previously low σ_{ci} also initiate unstable crack growth at lower stress levels, in addition to other low-porosity rocks (T13C; BP6B; BP14A) and with $n_{eff} > 12.5$ % and WG_{I-II} (BAf9A). These results suggest that σ_{cd} inherits the already accumulated damage, but is also affected by newly formed fractures, which do not necessarily lead to a lower σ_p . In addition, the σ_{cd} to σ_p ratio is not significantly affected by porosity in the selected lavas, contradicting previous findings for sedimentary rocks (Xue et al., 2014; Peng et al., 2018), where higher porosities were found to decrease the ratio. After σ_{cd} , it is assumed that the mechanical performance of the rock depends on the cracking process, as reported before by Pepe et al. (2018).

Lower σ_{ci}/σ_p and σ_{cd}/σ_p ratios may relate to fissures, porphyritic and trachytic textures, and higher alkali content, but variability is high, and trends are not systematic. Considering the general results, the ratios seem independent of texture, grain size, and porosity. Such a conclusion is further verified in the regression models for σ_{ci} and σ_{cd} against the peak stress, which are close to those established by Pepe et al. (2018) (Fig. 5.5c and 5.5d) for low-porosity igneous rocks.

On the other hand, n_{eff} (Fig. 5.5e) has a nonlinear negative relationship with both crack thresholds and σ_{c_UCS} , in agreement with the typical trends for volcanic rocks (e.g., Heap and

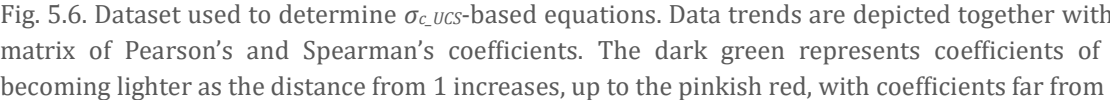
Violay, 2021; Pereira et al., 2024a). Data scattering is also more significant for low-to-medium porosity lavas, as these can contain fissures and very possibly microcracks, as evidenced in the petrographic analysis by Pereira et al. (2025) (Chapter 4). Maintaining the nonlinear trend supports that crack thresholds ratios to the peak stress are independent of the initial porosity. Furthermore, V_p values plotted against σ_{ci} , σ_{cd} , and σ_{c_UCS} are scattered (Fig. 5.5f), with an incipient positive linear correlation in σ_{ci} vs. V_p . Regardless, n_{eff} and V_p are not good predictors of the progressive damage in brittle lavas.

5.3.2. Regression models between physical properties to predict unconfined compressive strength

n_{eff} , V_p , and σ_t are considered for empirical equations because n_{eff} and V_p are index properties determined in a non-destructive way, whereas σ_t is more easily obtained for disc specimens through the Brazilian test than σ_{c_UCS} . Multivariate and bivariate regression analyses were performed on data considering 47 lava rock specimens (Fig. 5.6) and correlations are statistically significant for a two-tailed significance value of < 0.05 . V_p and σ_{c_UCS} correlate directly because they were obtained for the same rock specimen. n_{eff} and σ_t correlate through their average values with σ_{c_UCS} , as they are established for irregular lumps and discs, respectively, obtained from the same blocks as σ_{c_UCS} cylinders.

The average value $\pm$ standard deviation is defined in Fig. 5.6 together with Pearson's and Spearman's rank correlation coefficients; all > 0.61 in absolute value. Despite the low difference between the two correlation coefficients (< 0.065), absolute Spearman's correlation is consistently higher than absolute Pearson's correlation, which indicates a nonlinear relationship between the variables, except when n_{eff} correlates with ρ_{dry} , visibly negative linear.

The coefficient value of a descriptor can be arbitrary. Franzblau (1958) established a classification system that was used effectively by Pereira et al. (2021) for correlations between the properties of basalts. This research focuses on a wider scope of lava rocks, and moderate to strong correlations are established between σ_{c_UCS} and σ_t , n_{eff} and σ_{c_UCS} , n_{eff} and ρ_{dry} , σ_t , and n_{eff} . n_{eff} has a negative relationship with the remaining variables (Fig. 5.6).



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Table 5.3. Empirical correlations (Eqs. 5.1–5.5) to estimate the unconfined compressive strength and its performance, defined by the coefficient of determination (R^2), root mean squared error (RMSE), mean absolute percentage error (MAPE), and variance accounted for (VAF). Each performance parameter is classified with a rank value (S), and the sum of all results in a total score (TS). Statistical representativity was established using the p -value determined through analysis of variance (ANOVA).

Empirical equations to estimate σ_{c_UCS} Data range: 16.83 - 153.43 MPa. N= 47	p -value ANOVA	R^2	S	RMSE (MPa)	S	MAPE (%)	S	VAF (%)	S	TS
(5.1) $\sigma_{c_UCS} = 2.751 \sigma_t - 2.157 n_{eff} + 0.0165 Vp$	1.4E-27	0.92*	5	8.49	3	24.78	3	72.66	4	15
(5.2) $\sigma_{c_UCS} = 3.150 \sigma_t - 3.0957 n_{eff} + 76.535$	2.0E-13	0.72*	1	8.52	2	22.83	4	73.52	5	12
(5.3) $\sigma_{c_UCS} = 0.01753 Vp$	1.4E-21	0.87	3	8.63	1	52.22	1	32.35	1	6
(5.4) $\sigma_{c_UCS} = 8.453 \sigma_t$	3.2E-25	0.91	4	8.42	4	34.91	2	53.37	2	12
(5.5) $\sigma_{c_UCS} = 128.46 e^{-0.07 n_{eff}}$	2.7E-16	0.78**	2	8.23	5	21.86	5	68.68	3	15

A 95 % confidence interval level is considered.

*Adjusted R^2 since more than one independent variable is considered.

** R^2 is calculated considering the linear regression analysis of $\ln(\sigma_{c_UCS}) = \ln(a) + bx$.

The ranking of each performance metric was performed with “rank.avg()” equation of Microsoft® Excel, that returns a number relative to the considered list of results. S – score; TS – total score.

The established empirical equations are particularly useful for future engineering works in São Miguel Island. However, the use of these empirical equations can be extended to lavas found in other Azorean and volcanic islands, which show similar mineralogy and properties (Motta and Nunes, 2003; Malheiro et al., 2018).

Multiple regression models might produce good total scores, but they require the determination of more than one variable to estimate σ_{c_UCS} , whereas the linear regressions described by Eq. 5.4 and Eq. 5.5 in Table 5.3 are more practical and efficient. Eq. 5.4 (Table 5.3) establishes a σ_{c_UCS} to σ_t ratio of 8.45, which is slightly above the value defined by Hernández-Gutiérrez (2014) for several volcanic rocks and Pereira et al. (2021) for basalts. The present dataset includes trachytes, whose ratio is 10.76 against a ratio of 7.76 for basalts (s.l.), possibly explaining the differences compared to literature results.

An exponential empirical equation is considered for σ_{c_UCS} vs. n_{eff} (Eq. 5.5 – Table 5.3), as nonlinear relationship is frequently defined in the literature especially for volcanic rocks (e.g., González de Vallejo and Ferrer, 2011; Pappalardo et al., 2017; Heap and Violay, 2021; Pereira et al., 2021). As stated above and as depicted in Fig. 5.7, vesicular BF specimens have a narrower range of σ_{c_UCS} than low-porosity lavas, that is, trachytes and compact basalts.

These conclusions are similar to observations regarding σ_{c_UCS} results of volcanic rocks by Heap and Violay (2021).

n_{eff} comprises the effects of microcracks, fissures, and pores and indicates whether the mechanical properties are influenced by each individually or a combination of both (e.g., Pappalardo et al., 2017). In this study, low-porosity lava rocks with $n_{eff} < 8 \pm 2 \%$ comprise scarce isolated pores visible in the hand samples, sometimes fissures, mostly closed. Microscopic observations and MIP results in Chapter 4 (Pereira et al., 2025a) show that similar samples contain mainly micropores ($> 80 \%$) and, sometimes, scarce microcracks, which are not always recognised by V_p , but are assumed to induce variable σ_{c_UCS} , together with fissures.

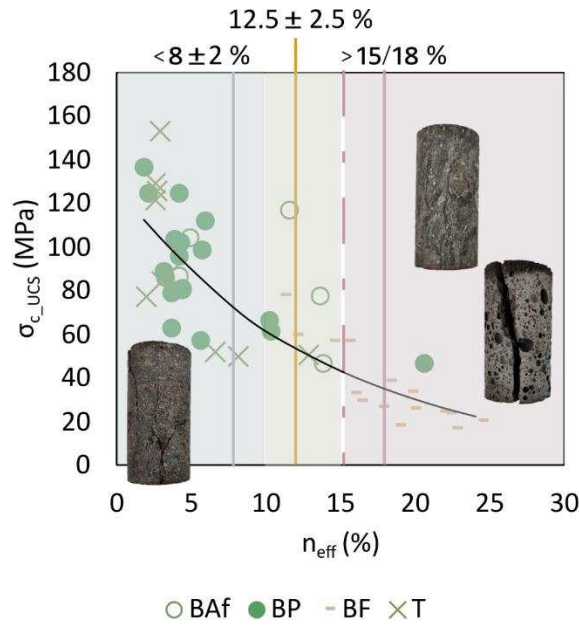


Fig. 5.7. Correlation of σ_{c_UCS} with open porosity (n_{eff}), defining n_{eff} thresholds based on the obtained data. The threshold $n_{eff} = 8 \pm 2 \%$ separates low-porosity lava rocks, whose strength is controlled by microcracks and rare fissures, rather than pores, which are of reduced size and number. $n_{eff} = 12.5 \pm 2.5 \%$ defines lavas with a medium porosity, where σ_{c_UCS} results from the combined influence of higher number of pores of millimetric size with more fissures and microcracks. High-porosity/vesicular lavas ($n_{eff} > 15/18 \%$) that have strength controlled by the size of pores (millimetric and centimetric).

Lavas with $n_{eff} \sim 12.5 \pm 2.5 \%$ correspond to medium-porosity samples with millimetric pores, distributed throughout the entire specimen (e.g., BF.B, BF.C., BAF.B, T.AIII). These pores are, nevertheless, smaller than the pores observed in the BFA facies. The lavas with this intermediate porosity have lower ρ , V_p , σ_{c_UCS} , and σ_t values than low-porosity lavas, also assumed that their σ_{c_UCS} is controlled by the combined effect pre-existing microcracks and porosity. On vesicular lavas ($n_{eff} > 15/18 \%$), the higher porosity and the larger pores have a

dominant effect on strength, producing lower of $\sigma_{c,UCS}$ and σ_t (Table 5.1), confirming previous findings (e.g., Bubeck et al., 2017; Griffiths et al., 2017; Section 2.2.5.3., Part C). The connectivity in vesicular lavas is due to pore coalescence and pore-linking fractures, which are associated with more macropores and a higher r (Pereira et al., 2025a; Fig. 4.7, Table 4.2). Pore shape also has a significant role in dictating E and UCS (Section 2.2.5.3, Part C). However, these investigations were outside the scope of this chapter, as no specimens were drilled considering the pore elongation. Such a topic is explored in Chapter 6 instead.

According to Pappalardo et al. (2017), trachyandesites from Etna with total porosities above 10 % have their UCS controlled by pores, and secondarily by microcracks. Below this cut-off, the strength is defined by the microcracks. Although total porosity was not determined in this work, it can be assumed that n_{eff} is approximately 40–50% of the total porosity, as verified for other lavas by Pappalardo and Mineo (2017) and Pappalardo et al. (2017). Thus, the threshold of $n_{eff} < 8 \pm 2$ %, corresponding to a total porosity of 16 ± 4 % is higher than the cut-off established by Pappalardo et al. (2017). Total porosity determination and microstructural research would be necessary to align these thresholds better, defining when pore size and microcracks control strength.

5.3.3. Mechanical behaviour of lava rocks under confinement

5.3.3.1 Triaxial test data

Triaxial test results (Fig. 5.8) allow for complete mechanical characterisation of the studied materials. Within the studied subgroups of samples, generally, increasing P_{conf} increases σ_c (Fig. 5.8g). In comparison to $\sigma_{c,UCS}$, $P_{conf} = 10$ MPa increases σ_c by ~ 1.5 to 2 times independent of rock type and texture. Increments were greater for BFA (2.5 times) and TA.II (~ 3.2 times). Most studied lavas are brittle, with a stress drop after failure combined with the development of macroscopic shear fracture(s) of varying dip angle. Nevertheless, for $n_{eff} > 12.5$ %, some transitional state between brittle and ductile is achieved by the rocks, evidenced by a large stage of plastic behaviour before collapse and post-peak plateaus in the stress-strain curves.

The terms “yield stress” and “yielding” are used here to define the point where the stress-strain curve reflects a permanent deformation and where the accumulation of strain is evident at lower increments of stress.

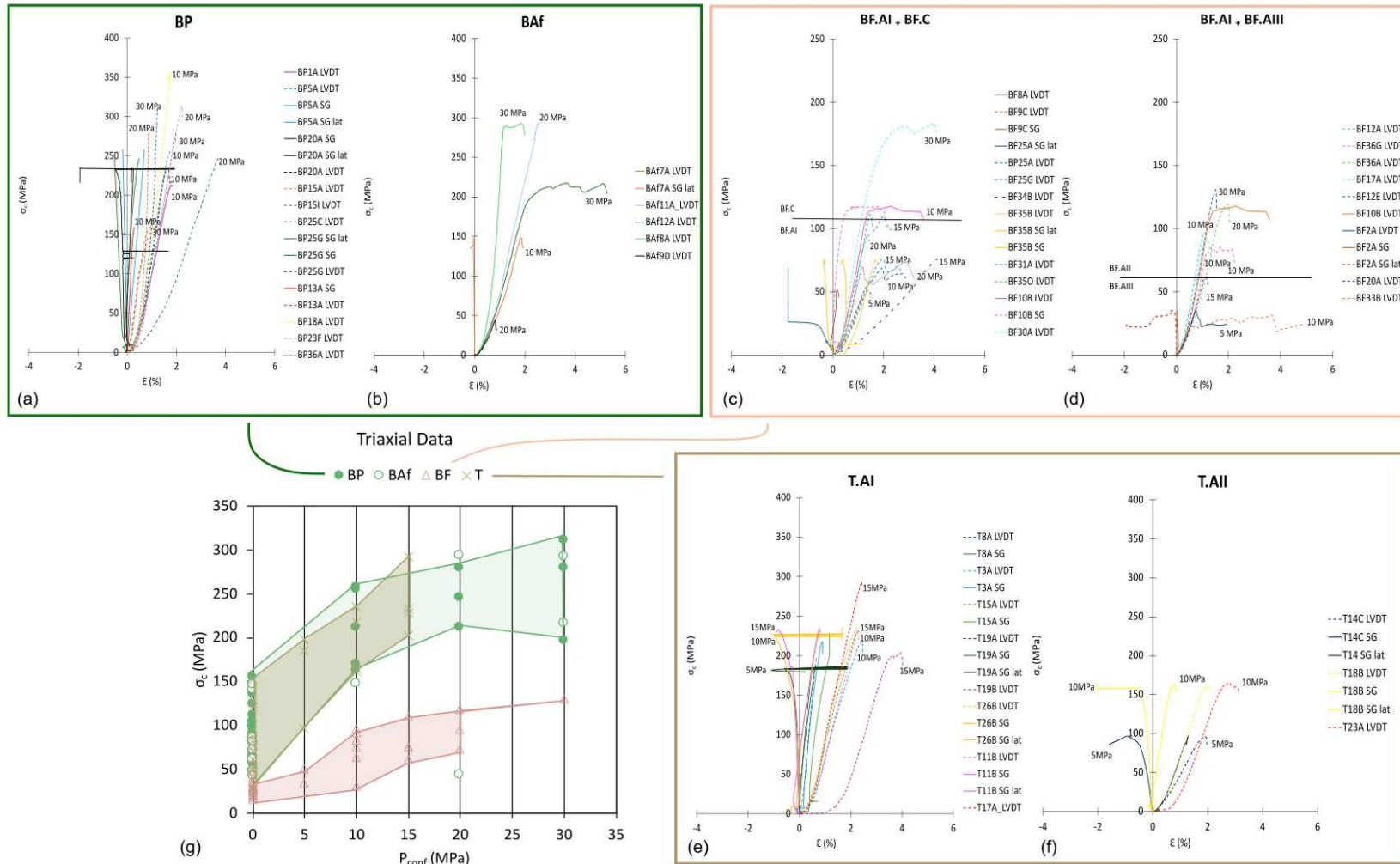


Fig. 5.8. Triaxial test results. Stress-strain curves of the BP basalts (a), Baf basalts (b), BF intermediate lavas (c and d), and T trachytes (e and f). Values of compressive strength (σ_c) according to confining pressure (P_{conf} , g).

In the performed triaxial tests, SG were damaged frequently due to confinement, preventing the determination of volumetric strain. Moreover, it was not possible to use porosity reduction as a proxy to verify whether the rocks re-enter a phase of net compaction after the peak stress or if no net dilation occurs at all, as Heap et al. (2015) and Marmoni et al. (2017) did.

Although performed in lava specimens of different sizes at distinct loading rates, the obtained stress-strain curves for triaxial tests are qualitatively similar to data for other basalts (Adelinet et al., 2013; Zhu et al., 2016; Section 2.2.2, Part C), trachyandesites, basaltic trachyandesites (Loaiza et al., 2012; Zorn et al., 2018; Heap and Violay, 2021), and andesites (Heap et al., 2015). In addition, results align with those of other studied basalts (Adelinet et al., 2013; Zhu et al., 2016), which were ductile only at effective pressures (P_{eff}^1) > 75–80 MPa.

BP basalts (Fig. 5.8a), all from BPA, are competent brittle rocks under confinement, failing through shear fractures of varying dips. It is assumed that the microstructure (e.g., microcracks) is responsible for producing lower σ_c than expected in some rocks, as no fissures were observed in the specimens. The BAf basalts (Fig. 5.8b) show variable σ_c values owing to subgroups with different porphyritic indices and porosities. BAf.A specimens show an increase in σ_c with confinement. A plastic behaviour is at $P_{conf} = 30$ MPa for a lava from BAf.B facies ($n_{eff} > 12.5$ %).

Medium-porosity intermediate lavas (BF.C – BF10 and BF30 – Fig. 5.8c) have a σ_c (118–183 MPa) that is 1.6 and 1.4 times lower than other basalts, for a confinement of 10 and 30 MPa, respectively. In addition, these samples show a plateau in the stress-strain curve, behaving plastically.

High-porosity intermediate rocks (BF.AI–AIII; Fig. 5.8c and 5.8d) have lower σ_c values owing to their vesicular texture composed of millimetric and centimetric pores. For $P_{conf} = 10$ MPa, vesicular specimens have a ~2.5 times strength reduction with respect to BF.C, with σ_c ranging between 31 MPa and 97 MPa for a BFAIII lava (WG_{III}) and a BFAII lava (WG_{I-II}; with several plagioclase phenocrysts), respectively. Plateaus in stress-strain curves are common, especially in BFAIII lavas under low confinement (5–10 MPa), associating with stress recovery and less pronounced stress drops. The remaining BFA samples, mostly fresh, are plastic at $P_{conf} = 10$ MPa. Notwithstanding, for the applied confinements, the rocks remain

¹ Effective pressure equals to the confining pressure minus the pore pressure, usually up to 10 MPa (e.g., Heap and Violay, 2021). In this work, only P_{conf} is considered as pore pressures is null.

brittle, or at least are not fully ductile, as all lavas develop evident shear fractures combined with visible stress drop and did not show “barrelling”.

Results on the vesicular lavas agree with the literature for other intermediate lavas (Fig. 2.14). The Volvic trachyandesites (21 % of porosity) studied by Heap and Violay (2021) were only fully ductile above 70 MPa, given the absence of shear fractures, although net compaction started at $P_{eff} = 30$ MPa. Similarly, Heap et al. (2015) demonstrated that compaction in andesites depends on porosity – when porosity is less than 10 %, andesites are dilatant up to 70 MPa, whereas when porosity exceeds 17 %, andesites have net compaction and transition to ductile behaviour at $P_{eff} = 30$ MPa. In turn, Loaiza et al. (2012) suggest that high-porosity Azorean trachyandesites (18 %) are fully ductile for $P_{conf} > 95$ MPa (~ 4 km depth), remaining brittle for $P_{conf} = 50$ MPa. However, microstructural observations on trachyandesites to basaltic trachyandesites ($n_{eff} > 25$ %) by Zorn et al. (2018) showed that distributed microcracking, pore crushing, and compaction bands are produced under confinements as low as 3 MPa. Microscopic post-deformation observation of the studied lavas would be required to verify if these micromechanisms occur, defining a transitional behaviour between ductile and brittle.

Vesicular samples show that pores remain macroscopically unaffected with confinement, which can be explained by the fact that they are less compressible than microcracks (Bustos and Adam, 2023), which are known to close with the confinement (Nara et al., 2011; Hoek and Martin, 2014). At a larger scale (upper crust), pores are expected to be less affected by depth than fractures (Guéguen and Kachanov, 2011; Bubeck et al., 2017; Bustos and Adam, 2023), while enabling a transition from brittle to ductile at lower P_{conf} , which is associated with inelastic pore collapse or formation of localised deformation bands (Heap et al., 2015; Zorn et al., 2018).

Trachytes (Fig. 5.8e and 5.8f; T.AI and T.AII) are brittle up to 15 MPa, forming macroscopic shear fractures associated with an evident stress drop. Trachytes remain competent when confined, with $\sigma_c = 96\text{--}198$ MPa, $\sigma_c = 162\text{--}236$ MPa and $\sigma_c = 203\text{--}293$ MPa for P_{conf} of 5, 10, and 15 MPa, respectively, being as competent as basalts. T.AII specimens, slightly altered, are weaker than T.AI.

5.3.3.2. Fitting parameters derived from failure criteria

All specimens are considered brittle since they develop macroscopic fractures combined with an evident stress drop. Table 5.4 summarises the shear parameters of the intact rock subgroups obtained using the MC and HB criteria. In addition, the rock mass parameters were derived using the generalised HB criterion for a GSI of 55.

Appendix 5.3 includes the results for blocks where the minimum number of specimens was obtained. Consistency is found between the data from single blocks and the subgroup to which they belong. Because the specimens required for triaxial testing may be difficult to obtain in such heterogeneous materials, the failure criteria can be, instead, calibrated using subgroup triaxial data.

On average, BP and BAf basalts have $c = 14\text{--}16$ MPa, $\phi = 45\text{--}49^\circ$, and $m_i = 13\text{--}20$. The mean values are reduced because of BAf.B ($n_{eff} > 12.5\%$), where the fitting parameters are lower ($c = 9$ MPa; $\phi = 39^\circ$; $m_i = 7$) compared to BAf.A facies. BF.C has similar proximate values of c (12 MPa), ϕ (40°) and m_i (8) to BAf.B, whereas the BF.A vesicular sample ($m_i \sim 8$) has decreased c (5–7 MPa) and ϕ ($28\text{--}36^\circ$) and similar m_i with respect to BF.C. These results show that high-porosity lavas with centimetric sized-pores are less cohesive and enhance shear fracturing at lower angles – as verified in the triaxial tests and by Renani and Martin (2018) – than the low-to-medium porosity lavas. Within BF.A samples, the weathered BF.AIII shows the lowest c (5 MPa), ϕ (28°) and m_i (4) of the whole dataset.

TA.I show c and ϕ in agreement with their high σ_c , with cohesion (17 MPa) in the order of BP and BAf.A basalts and displaying the highest ϕ (54°) of the tested samples. T.AII maintain the high ϕ and m_i even increases from 22 to 38. However, c decreases to values similar to BAf.B (~ 9 MPa).

Overall, c values are lower than other fresh lavas reviewed by Pereira et al. (2024a; Fig. 2.16d) and Villeneuve and Heap (2021). Conversely, the values of ϕ agree with those reported by Villeneuve and Heap (2021) and Rodríguez-Losada et al. (2009). Different specimen size and test conditions might explain the lower c , which is also more variable across lava rocks than ϕ .

Table 5.4. The Mohr-Coulomb failure criterion and Hoek-Brown criterion considering GSI = 55 and $D = 0$. RSS – residual sum of squares; c - cohesion; ϕ - angle of internal friction; σ_{ci_MC} – fit of unconfined compressive strength to Mohr-Coulomb criterion; σ_{ci_HB} - fit of unconfined compressive strength to Hoek-Brown criterion; m_i – Hoek-Brown constant; E_i – intact rock Young's modulus; m_b , s and a – Hoek-brown constants for the rock mass; σ_{3max} - upper limit of confining stress; c_{rm} – cohesion of the rock mass; ϕ_{rm} – angle of internal friction of the rock mass; σ_{rm} – rock mass global strength; E_{rm} – rock mass Young's modulus. BFA – vesicular facies from the BF sample.

Lithotypes sub-categories	BP	BP.A	BAf	BAf.A	BAf.B	BF. A	BF.AI	BF.AII	BFAIII	BF.C	T	T.AI	TA.II
Mohr-Coulomb (MC) criterion													
RSS	68884	63217	62014	22505	12737	10709	2705	4549	461	2459	73582	34463	1337
c (MPa)	15.83	16.17	13.96	16.63	9.05	6.02	5.82	7.49	4.86	12.00	14.75	16.69	8.63
ϕ (°)	49.01	48.99	45.28	49.42	39.45	36.87	36.28	38.72	27.79	40.39	52.78	54.30	55.24
σ_{ci_MC} (MPa)	84.70	86.48	67.86	89.97	38.32	24.06	23.00	31.21	16.12	51.95	87.59	103.63	55.14
Hoek-Brown (HB) Classification													
σ_{ci_HB}	94.61	96.90	86.06	101.43	57.37	31.85	29.62	48.45	20.21	77.09	83.45	118.92	50.13
m_i	19.92	19.21	13.12	21.03	7.08	7.94	7.85	7.15	3.49	7.50	34.26	22.22	38.48
E_i (GPa)	44.64	44.03	35.92	38.43	30.89	19.42	19.22	27.74	15.35	45.25	23.64	29.37	16.32
Hoek-Brown criterion ($D = 0$; GSI = 55)													
RSS	36828	34324	47647	10756	11882	8287	1652	874	286	52	36735	12839	1347
m_b	3.99	3.85	2.63	4.22	1.42	1.59	1.57	1.43	0.70	1.50	6.87	4.45	7.71
s	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
a	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
σ_{3max} (MPa)	9.25	10.01	10.65	10.85	10.25	7.14	7.09	8.99	7.98	9.76	9.57	11.02	9.55
Mohr-Coulomb fit													
c_{rm} (MPa)	3.34	3.51	3.20	3.85	2.30	1.51	1.46	1.99	1.06	2.57	3.75	4.16	3.30
ϕ_{rm} (°)	45.82	45.06	40.23	45.54	31.76	30.90	30.27	31.54	20.15	35.08	49.07	47.18	45.94
Rock Mass Parameters													
σ_{rm} (MPa)	25.49	25.66	19.01	28.05	9.56	5.59	5.17	8.11	2.51	13.18	29.26	33.78	18.61
E_{rm} (GPa)	18.22	17.97	14.66	15.69	12.61	7.93	7.85	11.33	6.27	18.47	9.65	11.99	6.66

The results for m_i (Table 5.4) show their variability with respect to the rock type and structure. Hoek and Brown (1997) estimated m_i values of 17, 19, and 16 for basalts, andesites, and rhyolites, respectively, whereas RSData provides a tabled m_i value of 25 ± 5 for all lavas. However, the variability of m_i has been previously addressed in a data compilation of volcanic rocks (Villeneuve et al., 2022), where m_i ranged from 2 to 38 for andesites with distinct textures and alteration degrees. This work, aligned with observations by Villeneuve et al. (2022), also verifies that the tabled m_i is narrow and does not include the typical heterogeneity of the lava rocks.

Fig. 5.9 shows how c , ϕ , and m_i vary with other proprieties (σ_{c_UCS} – Fig. 5.9a; Fig. 5.9b; Fig. 5.9c; V_p – Fig. 5.9d; Fig. 5.9e; Fig. 5.9f; n_{eff} – Fig. 5.9g; Fig. 5.9h; Fig. 5.9i; m_i – Fig. 5.9j; Fig. 5.9k; E – Fig. 5.9l). c has a positive relationship with σ_{c_UCS} and V_p and varies linearly with σ_{c_UCS} . The linear regression model is less effective describing ϕ vs. σ_{c_UCS} ($R^2 = 0.60$) and no goodness-of-fit measure is found with V_p . Both c and ϕ have a strong negative linear trend with n_{eff} ($R^2 > 0.86$), while a moderate nonlinear trend ($R^2 = 0.66$) is established in m_i vs. n_{eff} . m_i is not adequate to predict σ_{c_UCS} , V_p , and E , as evidenced by the scatter plots. Conversely, c vs. m_i can be described by a polynomial trend, while ϕ varies linearly and positively with m_i ($R^2 = 0.81$). Indeed, this strong relationship is expected since m_i is described as an approximately analogous of ϕ (Eberhardt 2012, Tsikrikis et al., 2024). Overall, porous rocks are less cohesive, have lower ϕ and m_i than the massive counterparts.

n_{eff} is easily determined and was previously used as a dependent in equations estimating E (Heap et al., 2020a), c and ϕ (Villeneuve and Heap, 2021). Villeneuve and Heap (2021) empirical models produce ϕ in good agreement with the present data (Fig. 5.9m), while c values are overestimated (Fig. 5.9n). Conversely, estimations of E using the Heap et al. (2020a) model produce underestimated values for basalts but are adequate for trachytes (Fig. 5.9o). Due to deviations from the present dataset, which accounts for basalts to trachytes, a new statistically significant (p -value < 0.001 ; F -significance < 0.0001) univariate regression analysis was performed. The new equations can be applied in future geological and geotechnical endeavours to estimate c and ϕ based on n_{eff} (Eqs. 5.6 and 5.7) and σ_{c_UCS} (Eq. 5.8) of lavas from São Miguel, other Azorean islands, or similar lavas worldwide.

$$R^2 = 0.88 \quad c \text{ (MPa)} = -0.633n_{eff}(\%) + 18.534 \quad (5.6)$$

$$R^2 = 0.88 \quad \phi \text{ (}^\circ\text{)} = 1.064n_{eff}(\%) + 56.218 \quad (5.7)$$

$$R^2 = 0.86 \quad c \text{ (MPa)} = 0.176\sigma_{c_UCS} \text{ (MPa)} \quad (5.8)$$

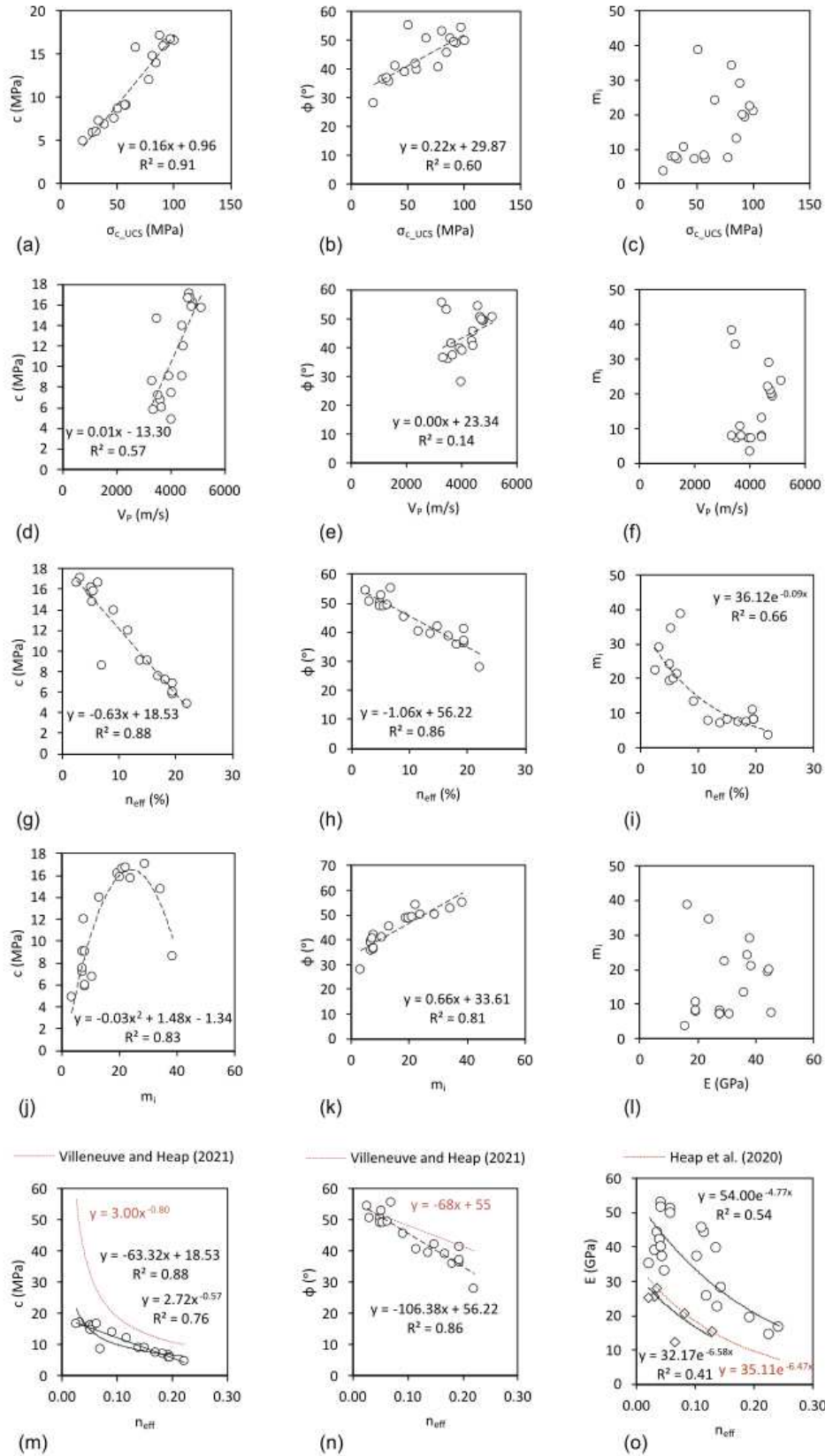


Fig. 5.9. Correlations of cohesion (c), angles of internal friction (ϕ), and Hoek-Brown constant (m_i) against unconfined compressive strength (a, b, c), P-wave velocity (V_p ; d, e, f) and effective porosity (n_{eff} ; j, k, l). Comparison of trendlines established with the obtained n_{eff} and with other models from the literature (m, n, o).

5.3.4. Lava rocks as intact rocks and “upscaling” to a volcano-hydrothermal setting

The present research demonstrates that defects in the intact rock (e.g., microcracks, vesicles, weathered and altered components) affect the mechanical properties of lavas, which cannot be considered homogeneous and isotropic materials. Indeed, the dilatancy of lavas is described as a result of the interplay between crystals and voids (e.g., Heap et al., 2014; Zhu et al., 2016); therefore, samples selected for the intact rock study should contemplate these defects, as previously suggested by Hoek and Brown (2019), and as performed in this work.

The derived rock mass parameters (Table 5.4) confirms that values are lower than those of the intact rock, which are obtained in the laboratory, where tests are conducted at higher loading rates on specimens that exclude the effects of discontinuities (Hoek and Brown, 1997). At the rock mass scale, the interlocked blocks contain intact rock defects besides discontinuities. The brittleness of rocks and defects affect the overall stability of the rock mass (Zhao et al., 2023), define the severity of failure of a rock engineering structure, and control the extent of fracture development (Walton, 2021).

Considering a $GIS = 55$ (Table 5.4), a rock mass composed of these lavas has a 75–79 % reduction in cohesion, independently of the rock’s texture and mineralogy. ϕ_{rm} is approximately 7 % lower than ϕ for low-porosity lavas, whereas those with $n_{eff} > 12.5$ % show a reduction between 13 and 20 %. For the entire dataset, σ_{rm} and E_{rm} are 92 % and 21 % lower, respectively, than their intact rock counterparts, regardless of the composition, texture, and porosity. It is stressed that E depends on depth (Heap et al., 2020a), and a slightly higher E_{rm} is expected for deep volcanic rocks.

In the Azores, risk assessments in the islands and rock mass geomechanical classifications can greatly benefit from accurate values of E and $\sigma_{c,UCS}$ that comprise the influence of defects and other rock mass heterogeneities in lavas, as they lead to complex fracture patterns and unpredictable rock failures (Zhao et al., 2023). For example, volcanic cavities are problematic from a geotechnical perspective (Malheiro et al., 2015; Miranda et al., 2018), whereas seismic activity can induce instability in previously coherent and stable lava rock slopes (Fernández et al., 2025). Coastal erosion and steepness of cliffs, aggravated by human activity, pose a risk to local populations and infrastructure (Malheiro, 2006). On the other hand, volcanic lavas are vastly used in various buildings on the São Miguel and are exposed to earthquakes and extreme meteorological events. As discussed in Pereira et al. (2025a; Chapter 4), vesicular lavas are prone to rock failure over time, underlining the need for careful selection and routine inspection to ensure adequate performance. The present work

not only provides firmer support to such a conclusion but also stresses the importance of inspecting microcracks in massive lavas.

On a larger scale, volcanoes are heterogeneous over time and space and are composed of layers of materials with distinct properties (e.g., Gudmundson, 2006). Even “hard” geotechnical lava units are variable and prone to unpredictable instability and failure. Indeed, brittle deformation of lavas influences the stability of volcanic edifices and their flanks during unrest periods characterised by magma accumulation and dyking (Voight and Elsworth, 1997; Voight, 2000; Villeneuve and Heap, 2021; Mordensky et al., 2022 – see Chapter 2.2.1., Part B and Chapter 2.2.4.1., Part C). The brittle failure of rocks is often thought to trigger volcano-tectonic earthquakes (Kilburn and Voight, 1998; Smith, 2013), and tensile and shear fractures occur, especially in divergent regimes, during dyke emplacement or the rupture of a magma chamber (e.g., Zhan and Gregg, 2019; Acocella, 2021). Modelling these processes requires the input of the c , ϕ , and σ_t of the host rocks. In addition, brittle failure creates fracture networks at depth that allow fluid percolation, thus defining the sustainability of geothermal reservoirs (Pirajno, 2009). Considering water as a percolating fluid, the decrease in σ_t is favoured, as evidenced here.

Fig. 5.10 shows a schematic diagram of the Ribeira Grande geothermal field located on the northern flank of Fogo and its subsurface geology. Fresh rocks are considered, precluding the effects of hydrothermal alteration that may induce a BDT transition at shallower depths (Section 2.5.6, Part C; Pereira et al., 2024a; Chapter 7). This extensive laboratory campaign constitutes the first step toward a better understanding of the properties of lava rocks from the Azores. Fluid circulation within the geothermal system promotes the weakening of the host rocks, as well as vesicular lavas, which become more plastic for P_{conf} as low as 10 MPa, and more prone to alteration.

Filling the gap between rock mechanics and volcanology requires considering the values of intact rock and “upscaling” them to the typical conditions of a volcanic rock mass. The comprehensive laboratory study performed taggles several geomechanical variables commonly disregarded for volcanic rocks, such as c and ϕ (Ball et al., 2018). The supplied values can be considered for future endeavours in engineering geology and for volcanic models.

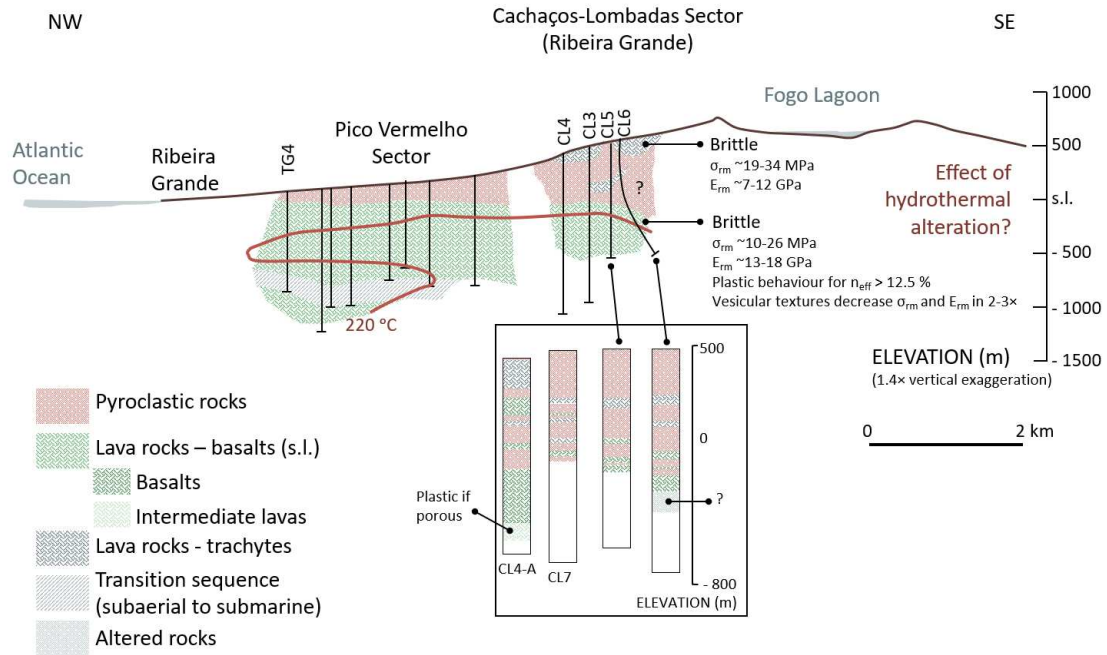


Fig. 5.10. Schematic diagram of the Ribeira Grande geothermal field, located on the northern flank of Fogo volcano (adapted from GeothermEx, 2008). The lithology logs of the Cachaços-Lombadas (CL) geothermal wells (adapted from Franco, 2016), which are located at higher elevations in the flank. The subsurface geology comprises superficial trachytes interlayered with pyroclastic rocks followed by basalts (s.l.) at depth. Mechanical results were obtained for a GSI of 55 and $H_L = 500$ m. The effects of hydrothermal alteration were not considered.

5.4. Conclusions

A complete physical and mechanical characterisation of lava rocks from São Miguel Island was developed. The samples are basalts to trachytes with a texture varying from vesicular (high porosity) to massive (low-to-medium porosity). The assessment of results contributes to the literature on the mechanical properties of lava rocks. Moreover, the obtained data is useful in producing more complete geotechnical and petrophysical databases. The main findings are as follows:

- The defined sample subgroups effectively capture the main structural and textural features that produce variable physical and mechanical properties. This approach offers an alternative when the required number of specimens from a single block is not attainable.
- Effective porosity is a key factor controlling mechanical properties. Low-porosity lavas ($n_{eff} < 8 \pm 2 \%$) show variable strength, whereas vesicular lavas ($n_{eff} > 18/15 \%$) are weaker and less stiff within a narrower range of values. Vesicular lavas display a

more pronounced plastic behaviour under confinement, especially when weathered (WG_{II} to WG_{III}).

- Despite textural differences, the Poisson's ratio (ν), crack initiation (σ_{ci}), and crack damage (σ_{cd}) stress ratios remain consistent across the several lavas. The ratio of the crack thresholds to the peak stress are also similar to those obtained for other igneous rocks, indicating that the ratio is independent of the rock type and texture.
- Water saturation reduces the tensile strength (σ_t) by 33 %, highlighting its impact on mechanical resistance.
- Massive basalts show medium-to-high strength ($m_r \sim 473$) with properties influenced by plagioclase and ferromagnesian mineral proportions. The basalts remain brittle at a confinement of 30 MPa, exhibiting some plasticity when the $n_{eff} > 12.5$ %.
- Massive trachytes have a broader strength range ($m_r \sim 312$), with higher Poisson's ratios, and their felsic composition contributing to greater strain accommodation. Although low-porosity trachytes reach a high compressive strength and remained brittle up to 15 MPa confinement, they experience crack initiation and damage at lower stress levels.
- Estimating the mechanical parameters to a rock mass (GSI of 55) indicates reductions in strength, stiffness, and cohesion, demonstrating that even "hard" lava units may contain discontinuities and become unstable when facing natural hazards on volcanic islands. Furthermore, challenges arise in the design of stable structures in these regions.

These findings highlight the complexity of lava rocks and volcanic rock masses, showing how porosity, texture, and scale influence their mechanical response. The new empirical equations introduced in this study for estimating key strength parameters ($\sigma_{c,UCS}$, c , and ϕ) are practical tools for future geotechnical applications in volcanic regions worldwide and for more accurate volcano stability modelling.

Although laboratory results provide a strong foundation for understanding lava rocks, field inspections are necessary to better understand each rock mass and define more accurate geomechanical parameters.

By bridging rock mechanics and volcanology, this study deepens the knowledge of the mechanical behaviour of lava rocks and its dependence on physical properties while promoting safer and more resilient geotechnical practices in volcanic environments.

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Fresh Azorean Lava Rocks

Chapter

Pore-scale heterogeneity
and its impact on the physical
and mechanical properties
of different Azorean lava rocks

Pore-scale heterogeneity and its impact on the physical and mechanical properties of different Azorean lava rocks

This chapter extends the research presented in the EGU25 Assembly (Vienna, Austria) as a poster. The presented data incorporate the results of Pereira et al. (2025b)¹, which were developed within the scope of the doctoral research. Selected results and adapted excerpts are cited and integrated throughout this chapter following Universidade dos Açores rules, also aligning with the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0).

6.1. Preliminary note

In Section 2.1.1 (Part A), the concept of *heterogeneity* is introduced. Such a phenomenon is ubiquitous in lava rocks, resulting from varying structures that reflect the variable processes subjacent to their origin. This heterogeneity manifests not only at the scale of intact rock, where defects influence mechanical behaviour (e.g., Mogi, 2006), but also at the rock mass scale, where variations in fracturing, porosity, and weathering further affect rock properties. Consequently, it remains difficult to predict the mechanical and physical behaviour of lava rocks, with significant implications for the development of accurate volcanic models, as well as engineering applications.

While heterogeneity has been more extensively studied in layered volcanic rock masses (e.g., González de Vallejo et al., 2008; Rodríguez-Losada et al., 2009), its effects on intact lava rock remain relatively underexplored. Laboratory analyses provide valuable insights into the mechanical and physical processes in volcanic rocks and are often regarded as the first step towards field-scale interpretations (Bubeck et al., 2017; Bustos and Adam, 2023). Despite their inherent variability, lava rocks that compose volcanoes are commonly saturated or subject to fluctuations in water content, both spatially and temporally (Heap et al., 2023). These hydrological conditions can reduce the overall stability of volcanic edifices,

¹ Pereira, M.L., Cueto, N., Pappalardo, L., Buono, G., Falasconi, A., Moreira, M., Zanon, V., and Fernandes, I., 2025b, Characterisation of the heterogeneity of vesicular lava rocks from Fogo Volcano (Azores, Portugal) combining conventional laboratory methods with X-ray microtomography: *EGU General Assembly 2025*, Vienna, Austria, 27 Apr–2 May, Abstract EGU25-9505, <https://doi.org/10.5194/egusphere-egu25-9505>. Licensed under CC BY4.0.

especially after intense rainfall events, which are associated with increased frequency of landslides and slope failure (Heap et al., 2023, and references therein).

Ultrasonic wave velocity and capillary water absorption are effective, non-destructive methods for assessing rock heterogeneity (e.g., Cueto, 2006; Vairé et al., 2024). Ultrasonic velocity serves as an indirect proxy for other properties such as fracturing, porosity, and density, and can, therefore, be used to infer mechanical behaviour. Capillary water absorption offers insights into unsaturated flow mechanisms, although it remains less studied in volcanic rocks (e.g., Çelik and Kaçmaz, 2016, Dinçer and Bostancı, 2019; Çelik and Sert, 2020; Cueto et al., 2018, 2024a, 2024b; Çelik, 2024; Hamon et al., 2025) compared to sedimentary lithologies. In contrast, saturated water flow, defined by permeability, has been more widely examined in volcanic materials (e.g., Lavallée and Kendrick, 2021 and references therein).

Under subaerial conditions, fluid sorption in lava rocks is governed by intrinsic and extrinsic parameters, including the mean pore radius (r), pore size distribution (PSD), and relative humidity (RH) (Cueto, 2020). These variables influence the dominant kinematic mechanisms that govern the fluid sorption process (Fort, 1996; Benavente, 2011; Graue et al., 2011). To investigate spontaneous imbibition, PSD is typically analysed using mercury intrusion porosimetry (MIP).

Complementary to MIP, advanced 3D imaging techniques, such as X-ray microtomography (μ CT) and image analysis (rock digital physics), have proven effective for characterising the pore architecture of lava rocks (see Chapter 4; Pereira et al., 2025a). These methods enable the development of pore network models and facilitate the quantitative assessment of pore/vesicle and crystal shape, size, and orientation (e.g., Pereira et al., 2025a; Chapter 4). Most studies on the influence of pores on rock properties rely on numerical modelling (e.g., Heap et al., 2016; Griffiths, 2017) or hybrid approaches combining experiments and simulations (e.g., Bubeck et al., 2017; Vairé et al., 2024). However, further experimental validation remains essential to fully capture the variability of natural materials (Section 2.2.5.3, Part C).

This chapter builds upon the findings presented in Chapters 4 and 5, which, respectively, define the microstructure of lavas from São Miguel and comprehensively characterise the physical and mechanical properties of the intact rock, indicating that lava rocks are heterogeneous. The present research aims to elucidate further the role of heterogeneity in the physical and mechanical behaviour of Azorean lavas, spanning from basalts to trachytes and from massive (low and medium porosity) to vesicular (high porosity) textures, also

providing new results regarding water transport mechanisms and their microstructural explanation. Measurements of P-wave velocity (V_p), S-wave velocity (V_s), dry density (ρ), connected porosity (n_{eff}), capillary water absorption coefficients (C), mean pore radius (r), and mercury-intruded porosity (n_{eff_Hg}) were obtained using a range of complementary techniques. Cubic specimens were tested in three orthogonal directions to assess heterogeneity in ultrasonic wave velocity and capillary absorption. Additionally, five specimens were extracted from two vesicular cubes to assess the directional effects of pore structure on unconfined compressive strength (σ_{c_ucs}) and indirect tensile strength (σ_t) using time-resolved mechanical tests.

This study provides novel data relevant to geotechnical and hazard assessment in volcanic environments, such as those in São Miguel Island. Ultrasonic velocity measurements contribute to the interpretation of field-scale seismic data, while understanding capillary absorption in conjunction with pore structure is critical in regions subject to heavy rainfall (Marques et al., 2008) and hydrothermal circulation at depth (Carvalho et al., 2006), conditions typical of the São Miguel Island.

6.2 Summary of materials and methods

6.2.1. Materials

Table 6.1 summarises the samples and respective subfacies, and the number, size, and shape of the specimens per analysis method. Some of these samples have been previously analysed as larger specimens (~45 mm diameter) in Chapter 5. The sample collection and organisation (Fig. 3.6) is described in Section 3.1.2. ~

Summarising, BP and T samples are low-porosity massive basalts (BP.A) and trachytes (T.AI), respectively. It is stressed that BP25 cylinders contain localised porous bands with millimetric pores, uniformly distributed throughout these bands. Although BP25 cubes fully collect these porous bands, occupying the entire specimen and resulting in a medium-porosity, BP25 is still considered a BP.A sample (Fig. 3.6). BF intermediate basalts are all vesicular (high-porosity) but differ in the porphyritic degree (BF35 – BF.AI; BF6 and BF12 – BF.AII; WG_I) and weathering grade (BF33 – BF.AIII; WG_{III} – see Section 3.1.2).

Ultrasonic wave velocity and capillary absorption were analysed along three orthogonal directions – X, O, and Δ – to assess the effect of elongated pores and phenocrysts. Elongated pores (for basalts) and phenocrysts (for trachytes) were visually organised as oriented parallel (O), perpendicular (Δ), or in between (X) concerning the measurement axis (Fig.

6.1). Three cylinders were extracted from cube BF35.1 along the X, O, and Δ directions, and two discs were cored from cube BF35.2 along O and Δ (Table 6.1; Fig. 6.1) for mechanical tests.

Table 6.1. Number, size, and shape of the samples (and specimens) tested for the different methods explored in this research. D – diameter; L – length; L/D – length-to-diameter ratio; X – tested. MIP – mercury intrusion porosimetry; μ CT – X-ray microtomography; ITS – indirect tensile strength or Brazilian test; UCS – unconfined compressive strength test.

N	Sample (subfacies)	Saturation and buoyancy	Ultrasonic wave velocity – through transmission	Capillary absorption	MIP	μ CT + UCS/ITS	Available data
	Size Shape	28-31 mm size cubes	28-31 mm size cubes tested in three orthogonal directions		7-13 x 17- 20 mm prisms	Cylinder s and discs*	Cylinders and discs**
3	BP25 (BP.A)	X	X	X	X ^a		X
3	BP8 (BP.A)	X	X	X	X ^b		X
3	BP13 (BP.A)	X	X	X	X ^c		X
3	BP23 (BP.A)	X	X	X	X ^d		X
3	BAf11 (BAf.A)	X	X	X	X ^e		X
6	BF35 (BF.AI)	X	X	X	X ^f	X ^l	X
2	BF6 (BF.AII)	X	X	X	X ^g		
2	BF12 (BF.AII)	X	X	X	X ^h		X
1	BF33 (BF.AIII)	X	X	X	X ⁱ		X
3	T13 (T.AI)	X	X	X	X ^j	X ^m	X
2	T9 (T.AI)	X	X	X	X ^k		X

* Cylinders: D = 7.7 mm; L/D ~ 2. Discs: D = 13.2 mm; L/D~0.6

**Cylinders: D = 45-51 mm; L/D ~ 2. Discs: D = 45-51 mm; L/D~0.4-0.7

The selected specimens for MIP and μ CT from the cubes are:

^aBP25.1; ^bBP8.3; ^cBP13.3; ^dBP23.3; ^eBAf11.5; ^fBF35.6; ^gBF6.2; ^hBF12.1 - cylinder with 7.7 mm diameter; ⁱ from another specimen; ^jT13.1; ^lT9.2; ^lBF35.1 and BF35.2; ^mT13.1

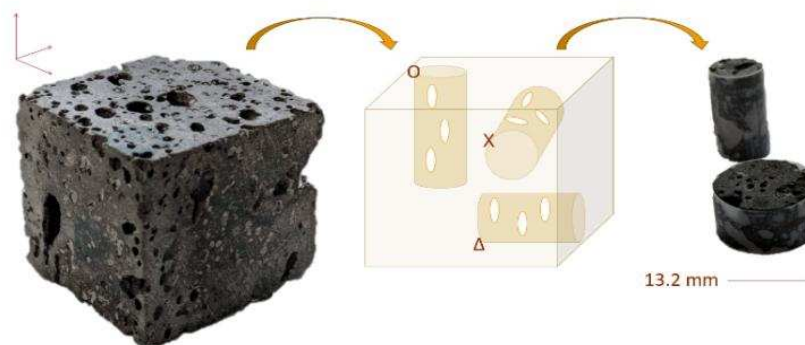


Fig. 6.1. Cubic specimen with elongated pores. Representation of the directions with pores (or crystals) parallel (O), perpendicular (Δ), or mixed (X) for the measurement axis. Cylinders were cored along O, Δ , and X (BF35.1) and discs along O and Δ (BF35.2).

6.2.2. Methods

6.2.2.1. Laboratory methods

Oven-dried cubic samples were tested using the saturation and buoyancy technique (ISRM, 2007 – see Section 3.2.4.1 for the procedure), regardless of the sample direction, to obtain the n_{eff} (Eq. 3.3) and ρ (Eq. 3.4).

The same cubes were analysed using the through-transmission method under dry conditions to determine ultrasonic wave velocities along the X, O, and Δ directions (see Section 3.2.4.4). Note that V_p values in Chapter 5 were obtained using different equipment. V_p , V_s , and V_p/V_s ratio were determined and other dynamic parameters— E_d (Eq. 3.9), ν_d (Eq. 3.10), G (Eq. 3.11), and K (Eq. 3.12)—were derived from V_p , V_s , and ρ . G depends solely on V_s , while both V_p and V_s influence the other parameters.

Capillary water absorption was measured according to the NP-EN 1925:2000 standard (see Section 3.2.4.3), using oven-dried cubes tested along the three orthogonal directions (X, O, Δ), as with ultrasonic wave velocity. Time intervals varied based on sample texture, as described in Chapter 3.2.4.3 – 48 h and 24h for low-porosity and medium-to-high porosity samples (BF series and BP25), respectively.

Capillary-connected porosity (n_{cc} ; Eq. 3.8), water absorption over time (Y ; Eq. 3.7) and the capillary water absorption coefficient (C_{EN} ; Annex A of NP EN 1995:2000) were calculated and used to plot the capillary absorption curves. Since C_{EN} may not accurately represent materials with non-uniform pore size distributions (Pereira et al., 2025b; Section 2.1.2.2), the Sharp Front (SF) model (Philip, 1957; Ioannou et al., 2008, 2009; Hall and Hoff, 2021), was used to determine the initial (C_e), intermediate anomalous (C_a), and late (C_m) absorption coefficients from the capillary curves (see Section 3.2.4.3). According to the model, water absorption is the sum of two distinct processes ($C_e = C_a + C_m$). C_a represents the section of the curve that deviates from the $t^{1/2}$ kinetics, representing water absorption by larger pores with low water uptake, while C_m represents the late linear in $t^{1/2}$ absorption due to fine pores.

Anisotropy in both the V_p/V_s ratio and C_{EN} was evaluated by dividing the maximum by the minimum value of each parameter, following Benavente et al. (2018).

To characterise the micropore network, MIP (see Section 3.4.2.2) was employed. PSD, r , and mercury-accessible connected porosity (n_{eff_Hg}) were determined. Prismatic samples (Table 6.1), cut from cubes previously tested for ultrasonic wave velocity and capillary absorption, were analysed without considering the orientation.

BF35 was selected for further investigation via μ CT and time-resolved mechanical testing (Section 3.2.5.4) to assess the influence of elongated pores. Cylinders were scanned using μ CT at 90 kV, 111 μ A, and 0.4 $\times$ magnification (Table 3.3), generating 801 projections over a 180° rotation, which yielded a resolution of ~ 15 μ m. Scans were performed before and after uniaxial compressive strength (UCS) testing (see Section 3.2.5.4). For Brazilian tests (ITS), only real-time imaging was obtained using the same μ CT settings to monitor crack propagation during brittle failure.

6.2.2.2. Data analysis

Image analysis (Section 3.2.6.2) enabled the calculation of total (n_T) and connected porosity (n_{eff}), centroid path tortuosity (T), and the simulation of absolute permeability (k) for BF35. Label analysis was used to derive pore aspect ratio, equivalent radius, and inclination (dip angle relative to the horizontal of the specimen: perpendicular to loading direction, 0°, to parallel to the loading direction, 90°) for pores in each cylinder. The aspect ratio was determined from 3D measurements (length, width, thickness) as the ratio of the major axis to the minor axis. Pores typically exhibit aspect ratios between 1:1 and 1:10, while microcracks often exceed 1:100 (Heap et al., 2014a). Dip and equivalent radius were extracted using the *lengthphi* and *equivalent diameter* modules from PerGeos® (PerGeos, 2021). To compare pore sizes across cylinders, equivalent radii were normalised and used to develop a ranking system, where higher ranks represent larger pores.

A principal component analysis (PCA; Pearson, 1901 – see “Multivariate Statistical Analysis” in Chapter 3.2.6.4) was performed on the obtained parameters to identify relevant dimensions that structure their relationship.

6.3 Results and discussion

6.3.1. Laboratory pore space characterisation

Table 6.2 presents the pore size interval and r derived from MIP analysis, where pore radii span approximately from 0.0015 to 180 μ m. A 15 μ m cut-off was used to distinguish micro- from macropores, following the approach of Pereira et al. (2025a) (Chapter 4) and Franzson et al. (2010) (Table 2.2). Most lavas, especially low-porosity types, are micropore-dominated, independent of lithology. Medium-porosity BP25 shows more macropores than the low-porosity lavas. Within vesicular samples, BF35 and BF12 contain a higher proportion of macropores (pore radius >15 μ m). The r values are consistent with those reported by Pereira et al. (2025a) for comparable rocks.

Table 6.2. Mean porous radius (r) and pore size interval obtained by mercury intrusion porosimetry (MIP) for the analysed lava rocks with different texture/porosity. 15 μm is the cut-off defined by Franzson et al. (2010) for macropores and micropores. BAF and BP basalts have low porosity, except for BP25, with medium porosity. The colours represent the water transport mechanisms of Fig. 6.2.

Sample		r (μm)	Micropores (%) ($< 15 \mu\text{m}$)	Macropores (%) ($\geq 15 \mu\text{m}$)	Pore size interval in μm (%)					
					<0.01	$0.01-0.1$	$0.1-1$	$1-10$	$10-100$	>100
Low porosity	BAf11	0.129	88.3	11.7	0.91	16.83	41.36	22.66	15.21	3.02
	BP8	0.032	91.2	8.8	12.62	30.53	41.94	4.85	7.38	2.68
	BP13	0.080	94.7	5.3	1.06	31.41	43.89	16.64	5.90	1.10
	BP23	0.179	91.6	8.4	0.89	13.31	14.67	51.91	18.36	0.87
Medium porosity	BP25	0.089	86.5	13.5	0.27	34.57	32.16	11.94	20.24	0.82
	BF35	0.278	65.9	34.1	0.10	12.92	16.76	20.77	47.82	1.64
High porosity	BF6	0.131	89.8	10.2	0.38	23.85	15.13	44.35	15.48	0.81
	BF12	0.107	58.3	41.7	3.00	9.38	20.80	17.62	38.35	10.85
	BF33	0.023	72.4	27.6	17.98	24.59	15.75	9.13	29.19	3.36
Low porosity	T13	0.009	93.5	6.5	37.36	23.72	20.01	10.63	6.83	1.47
	T9	0.010	93.0	7.0	31.26	32.01	26.01	2.68	6.37	1.68

Most massive basalts (s.l.) have dominant pore radii between 0.1 and 1 μm , except for BP23, which shows a peak in the 1–10 μm range (Table 6.2), likely due to the presence of microcracks. Fresh vesicular (BF35; BF6; BF12) samples have more than 50 % pores within the radius of 1–100 μm , whereas the weathered specimen (BF33) has 10–100 -sized pores combined with others below 0.1 μm . In trachytes (low porosity), most pores are smaller than 1 μm .

The PSD and the cumulative pore volume curves provide information about the uniformity of the pore system and pore geometry (Hamon et al., 2025). The curves are presented in Fig. 6.2. for the 11 samples, including the pore size range where sorption kinematic mechanisms are most liable to occur under subaerial conditions, according to Benavente (2011) and Benavente et al. (2018) (see Fig. 2.9). Vapour adsorption occurs for pores with radii $< 0.01 \mu\text{m}$, while capillary absorption starts in 0.1 μm until 1 mm. Capillarity condensation is the predominant transport mechanism between 0.01 μm and 0.1 μm , overlapping the interval for the initial occurrence of capillary imbibition at radii of 0.1–1 μm . According to Winkler (1997), Benavente (2011), and Benavente et al. (2018), capillary imbibition begins in pore

sizes of 0.1 μm , but the range of 1 μm to 100 μm promotes high water absorption rates. In fact, sorption processes depend on a set of parameters like r , PSD, and RH, as mentioned above.

Cumulative pore volume curves were classified as stair- or S-shaped, following Pereira et al. (2025a), and interpreted using the definitions of Tuğrul (2004) and Dinçer and Bostancı (2019), which distinguish uniform, semi-uniform, and non-uniform trends. Uniform curves, S-shaped with a sharp drop, indicate a narrow pore size range. In contrast, non-uniform curves span a wider range with evenly distributed pore sizes, while semi-uniform curves display intermediate characteristics.

None of the 11 lavas show a uniform S-shaped curve, in contrast to two basalts in Pereira et al. (2025a) and the andesites reported by Dinçer and Bostancı (2019). Semi-uniform, smooth stair-shaped curves were observed in massive basalts (BAf11, BP8, BP13) and trachytes (T9, T13), while strong stair-shaped, non-uniform curves characterise BP23, BP25, and vesicular basalts (BF), reflecting their heterogeneous pore structure. In BP23 and BP25 (Table 6.2), this non-uniformity coincides with either a higher r (BP23) or a larger proportion of macropores (BP25).

PSD plots reveal polymodal distributions in six samples (BAf11 – Fig.6.2a, BF6 – Fig.6.2.g, BF12 – Fig. 6.2h, BF33- Fig.6.2i, T13 – Fig.6.2j, and T9-Fig.6.2k) and bimodal distributions in the remaining five (BP8- Fig.6.2b, BP13 – Fig.6.2c, BP23 – Fig.6.2d, BP25 .- Fig.6.2e, and BF35 – Fig.6.2f). None of the lavas display a unimodal distribution, unlike BAF14, BP38, and T29 in Pereira et al. (2025a; Fig. 4.6). The coloured intervals of Fig. 6.2, representing the dominant sorption mechanisms (Benavente 2011; Benavente et al., 2018; Fig. 2.9), support the pore size intervals in Table 6.2. For the considered pore radii range ($< 180 \mu\text{m}$), several low-porosity lavas (e.g., BAF11, BP23) and fresh vesicular samples show abundant capillary pores, which facilitate water uptake via capillarity imbibition. In contrast, low-porosity trachytes and basalts BP8 and BP13 display PSD more favourable to capillarity condensation and vapour adsorption.

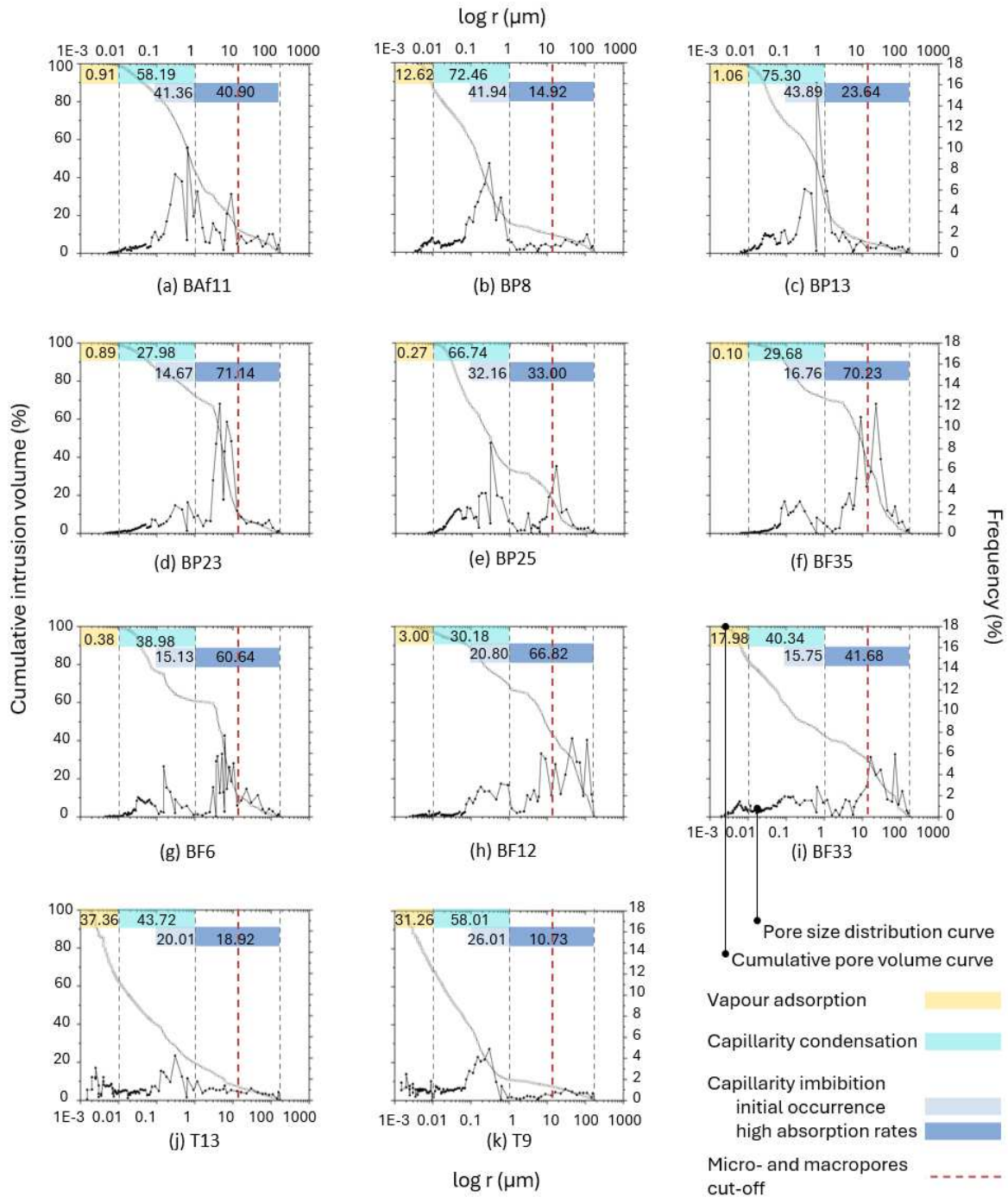


Fig. 6.2. Cumulative mercury intrusion and pore size distribution (solid circles) curves of the lava rocks. Low-porosity massive basalts correspond to (a) BAf11, (b) BP8, (c) BP13, (d) and BP23. (e) BP25 is a medium-porosity massive basalt with centimetric to millimetric pores and $n_{eff} > 10$ %. Vesicular specimens are represented by (f) BF35, (g) BF6, (h) BF12, and (i) BF33, which is weathered. Trachytes include (j) T13 and (k) T9. Pore radii are also related to the water transport mechanisms (vapour adsorption, capillarity condensation, and capillarity imbibition). All cumulative intrusion volume curves show a non-uniform strong stair-shaped trend – (d) to (i) – to a semi-uniform smooth stair-shaped trend – (a) to (c) and (j) to (k).

PSD is a proxy for constraining bubble nucleation, growth, and coalescence (Pappalardo et al., 2018, and references therein), with vesiculation exerting a main control on eruptive style as well as on the physical and geological properties of volcanic rocks (e.g., Toramaru, 1989, Wasantha et al., 2023). The studied vesicular samples display bimodal to polymodal PSD, confirming the presence of multiple pore-size generations and prolonged bubble evolution through repeated nucleation and/or coalescence during ascent. In contrast, massive lavas suggest more limited nucleation overall, yet the variability observed in their PSD indicates that different vesiculation and degassing pathways operated before solidification (e.g., Shea, 2017).

The PSD influence the water transport mechanisms, which further affects the behaviour of rocks when exposed to deleterious agents. Capillary imbibition is one of the most important parameters in the degradation of building stones (İnce et al., 2021). The associated deterioration mechanisms induced by solute transport during water uptake, such as salt crystallisation, are accepted as one of the most aggressive phenomena (Cueto et al., 2018). Although not directly investigated in this study, salt-induced deterioration is a relevant process in volcanic islands such as São Miguel. Salt crystallisation occurs with stress effectiveness within pore radii of 0.1–10 μm (Benavente et al., 2018; Cueto et al., 2018), which corresponds to the pore size range observed in the studied low-porosity lavas through MIP analysis. As a result, it is suggested that these massive lavas are more prone to salt crystallisation, and further investigations could be carried out in this sense.

6.3.2. Physical and water transport properties of the lava rocks

Table 6.3 presents the average values and standard deviations for key physical and water transport properties. A total of 93 V_p and n_{cc} , 31 n_{eff} and ρ , and 11 n_{eff_Hg} measurements were conducted. The V_p/V_s ratio was derived from the corresponding V_p and V_s velocities. Results are analysed by lithology, with porosity discussed first, followed by ultrasonic velocities and dynamic moduli, and finally capillary water absorption.

To support the data in Table 6.3, Appendix 6.1 includes pivot plots of ultrasonic wave velocities and dynamic moduli by direction (X, O, Δ), while Appendix 6.2 presents C_{EN} and n_{cc} values by specimen and direction.

Table 6.3. Average values $\pm$ standard deviation of the physical properties tested in the cubic specimens. V_p and V_s are presented as the V_p/V_s ratio. Anisotropy (ratio of the highest to lowest value) was determined when the three orthogonal directions were assessed. n_{eff} – open porosity; ρ – dry density; n_{eff_Hg} – mercury-accessible connected porosity; V_p/V_s – P-wave velocity to S-wave velocity ratio; E_d – dynamic Young’s modulus; ν_d – dynamic Poisson’s ratio; G – shear modulus; K – bulk modulus; C_{EN} – capillary absorption coefficient; n_{cc} – capillary connected porosity; $A(V_p/V_s)$ – anisotropy of V_p/V_s , $A(C_{EN})$ – Anisotropy of C_{EN} . * n_{eff_Hg} for this specimen.

Sample	n_{eff} (%)	ρ (g/cm ³)	n_{eff_Hg} (%)	V_p/V_s	E_d (GPa)	ν_d	G (GPa)	K (GPa)	C_{EN} (g/m ² s ^{0.5})	n_{cc} (%)	A (V_p/V_s)	A (C_{EN})
BAf11	7.81 $\pm$ 0.71	2.733 $\pm$ 0.016	6.65	1.87 $\pm$ 0.21	40.56 $\pm$ 7.04	0.28 $\pm$ 0.06	15.91 $\pm$ 3.39	32.41 $\pm$ 5.09	2.50 $\pm$ 0.32	4.34 $\pm$ 0.56	0.83	0.92
BAf11.3	6.92	2.743		1.75 $\pm$ 0.06	40.63 $\pm$ 3.63	0.26 $\pm$ 0.03	16.17 $\pm$ 1.77	28.02 $\pm$ 1.52	2.35 $\pm$ 0.02	4.15 $\pm$ 0.10	0.93	0.98
BAf11.5	7.97	2.744	*	1.97 $\pm$ 0.26	39.11 $\pm$ 7.70	0.32 $\pm$ 0.06	14.97 $\pm$ 3.48	36.24 $\pm$ 5.25	2.27 $\pm$ 0.08	3.89 $\pm$ 0.13	0.80	0.94
BAf11.6	8.54	2.712		1.87 $\pm$ 0.26	41.92 $\pm$ 10.94	0.28 $\pm$ 0.08	16.58 $\pm$ 5.35	32.98 $\pm$ 4.75	2.88 $\pm$ 0.29	4.97 $\pm$ 0.51	0.76	0.84
BP8	3.89 $\pm$ 0.17	3.036 $\pm$ 0.028	5.17	1.94 $\pm$ 0.40	29.69 $\pm$ 11.85	0.27 $\pm$ 0.14	11.81 $\pm$ 4.87	28.08 $\pm$ 15.64	1.34 $\pm$ 0.08	2.35 $\pm$ 0.13	0.72	0.89
BP8.1	3.84	3.070		1.66 $\pm$ 0.24	28.38 $\pm$ 13.27	0.17 $\pm$ 0.18	12.09 $\pm$ 4.89	18.20 $\pm$ 14.68	1.32 $\pm$ 0.10	2.31 $\pm$ 0.19	0.75	0.87
BP8.2	4.11	3.033		2.21 $\pm$ 0.46	24.50 $\pm$ 3.64	0.34 $\pm$ 0.10	9.07 0.73	34.42 $\pm$ 20.07	1.34 $\pm$ 0.06	2.36 $\pm$ 0.10	0.65	0.92
BP8.3	3.73	3.006	*	1.95 $\pm$ 0.38	39.44 $\pm$ 18.13	0.30 $\pm$ 0.10	15.50 $\pm$ 8.21	33.39 $\pm$ 2.18	1.35 $\pm$ 0.10	2.37 $\pm$ 0.15	0.76	0.87
BP13	6.50 $\pm$ 2.02	2.832 $\pm$ 0.061	3.74	1.89 $\pm$ 0.29	43.51 $\pm$ 7.60	0.28 $\pm$ 0.10	17.35 $\pm$ 4.42	36.33 $\pm$ 10.60	1.48 $\pm$ 1.00	2.49 $\pm$ 1.67	0.78	0.52
BP13.1	8.98	2.784		2.00 $\pm$ 0.32	39.71 $\pm$ 8.25	0.32 $\pm$ 0.07	15.18 $\pm$ 3.72	38.26 $\pm$ 7.85	2.72 $\pm$ 0.08	4.56 $\pm$ 0.12	0.75	0.95
BP13.2	4.35	2.912		2.03 $\pm$ 0.21	40.68 $\pm$ 6.26	0.33 $\pm$ 0.05	15.29 $\pm$ 2.73	42.45 $\pm$ 11.28	0.88 $\pm$ 0.49	1.49 $\pm$ 0.83	0.81	0.28
BP13.3	6.17	2.799	*	1.65 $\pm$ 0.24	50.12 $\pm$ 4.95	0.18 $\pm$ 0.12	21.59 $\pm$ 4.06	28.27 $\pm$ 10.07	0.84 $\pm$ 0.50	1.41 $\pm$ 0.84	0.78	0.34
BP23	4.24 $\pm$ 0.35	2.819 $\pm$ 0.087	16.39	1.92 $\pm$ 0.34	41.62 $\pm$ 9.08	0.29 $\pm$ 0.08	16.44 $\pm$ 4.50	34.82 $\pm$ 7.75	0.92 $\pm$ 0.35	1.53 $\pm$ 0.58	0.75	0.50
BP23.1	3.77	2.779		2.14 $\pm$ 0.46	35.19 $\pm$ 8.47	0.34 $\pm$ 0.08	13.29 $\pm$ 3.77	39.52 $\pm$ 11.18	1.14 $\pm$ 0.28	1.90 $\pm$ 0.47	0.67	0.62
BP23.2	4.51	2.745		1.89 $\pm$ 0.29	42.50 $\pm$ 10.81	0.29 $\pm$ 0.08	16.76 $\pm$ 5.27	34.48 $\pm$ 5.34	0.72 $\pm$ 0.19	1.21 $\pm$ 0.32	0.74	0.60
BP23.3	4.43	2.934	*	1.72 $\pm$ 0.16	47.17 $\pm$ 5.62	0.23 $\pm$ 0.08	19.26 $\pm$ 3.45	30.47 $\pm$ 5.01	0.89 $\pm$ 0.49	1.49 $\pm$ 0.82	0.83	0.29
BP25	15.56 $\pm$ 1.48	2.567 $\pm$ 0.041	8.88	1.83 $\pm$ 0.22	32.56 $\pm$ 5.38	0.27 $\pm$ 0.07	12.93 $\pm$ 2.62	25.03 $\pm$ 5.80	5.19 $\pm$ 0.56	9.11 $\pm$ 1.02	0.82	0.96
BP25.1	14.01	2.611		1.73 $\pm$ 0.18	34.75 $\pm$ 2.73	0.24 $\pm$ 0.07	14.01 $\pm$ 0.44	23.85 $\pm$ 9.38	4.61 $\pm$ 0.07	8.08 $\pm$ 0.10	0.84	0.97
BP25.2	15.28	2.573	*	1.91 $\pm$ 0.36	31.33 $\pm$ 9.04	0.28 $\pm$ 0.12	12.54 $\pm$ 4.65	25.67 $\pm$ 6.27	5.08 $\pm$ 0.16	8.89 $\pm$ 0.10	0.69	0.94
BP25.3	17.40	2.517		1.86 $\pm$ 0.09	31.61 $\pm$ 3.97	0.29 $\pm$ 0.03	12.24 $\pm$ 1.72	25.56 $\pm$ 2.02	5.87 $\pm$ 0.07	10.37 $\pm$ 0.21	0.92	0.98

Table 6.3. (continued).

Sample	n_{eff} (%)	ρ (g/cm ³)	$n_{\text{eff,Hg}}$ (%)	Vp/Vs	E_d (GPa)	ν_d	G (GPa)	K (GPa)	C_{EN} (g/m ² s ^{0.5})	n_{cc} (%)	A (Vp/Vs)	A (C_{EN})
BF35	19.68±0.57	2.290 ±0.020	12.81	1.76 ±0.25	16.78 ±3.29	0.23 ±0.11	6.98 ±1.88	11.22 ±2.64	2.98±0.15	5.10 ±0.31	0.81	0.96
BF35.1	19.63	2.290		1.67±0.26	17.57 ±3.87	0.18 ±0.12	7.57 ±2.28	9.90 ±2.35	2.99±0.05	5.05 ±0.05	0.77	0.97
BF35.2	19.78	2.299		1.83 ±0.25	16.41 ±3.04	0.27 ±0.07	6.50 ±1.51	12.54 ±2.37	2.77±0.03	4.67 ±0.03	0.79	0.98
BF35.3	20.12	2.280		2.08 ±0.18	12.27 ±1.14	0.34 ±0.04	4.57 ±0.56	13.49 ±1.99	2.89±0.03	4.90 ±0.04	0.84	0.98
BF35.4	20.18	2.262		1.71 ±0.11	16.68 ±1.60	0.23 ±0.05	6.77 ±0.81	10.63 ±1.65	3.05±0.02	5.17 ±0.07	0.90	0.99
BF35.5	18.51	2.325		1.57 ±0.14	19.20 ±1.12	0.14 ±0.12	8.51 ±1.04	9.40 ±2.67	3.21±0.13	5.61 ±0.24	0.83	0.93
BF35.6	19.87	2.283	*	1.71 ±0.33	18.57 ±4.18	0.19 ±0.15	7.97 ±2.47	11.40 ±3.96	2.94±0.08	5.17 ±0.11	0.70	0.95
BF6	21.86±0.09	2.263 ±0.025	16.19	2.09 ±0.42	24.52 ±9.71	0.32 ±0.10	9.58 ±4.55	24.31 ±3.88	2.18±0.41	3.81 ±0.70	0.72	0.81
BF6.1	21.78	2.287		1.91 ±0.50	29.76 ±11.41	0.26 ±0.12	12.12 ±5.37	22.70 ±5.27	1.87±0.18	3.26 ±0.31	0.64	0.83
BF6.2	21.95	2.240	*	2.28 ±0.28	19.28 ±4.83	0.38 ±0.03	7.04 ±1.90	25.91 ±1.46	2.49±0.31	4.35 ±0.51	0.80	0.78
BF12	16.72±0.31	2.249 ±0.004	10.16	1.79 ±0.12	28.75 ±4.34	0.27 ±0.04	11.40 ±2.00	20.72 ±3.03	3.89±0.54	6.90 ±0.94	0.92	0.93
BF12.1	17.01	2.245	*	1.87 ±0.10	25.71 ±4.18	0.30 ±0.03	9.93 ±1.72	21.25 ±4.05	4.37±0.12	7.74 ±0.20	0.90	0.95
BF12.2	16.44	2.253		1.70 ±0.07	31.80 ±1.39	0.24 ±0.03	12.88 ±0.72	20.18 ±2.39	3.42±0.18	6.07 ±0.28	0.93	0.90
BF33	18.72	2.137	17.30	2.10 ±0.14	17.40 ±2.79	0.35 ±0.02	6.43 ±0.95	20.05 ±6.02	1.31±0.05	2.28 ±0.07	0.88	0.93
T13	2.93±0.24	2.551 ±0.017	2.79	2.05 ±0.22	29.46 ±6.91	0.34 ±0.04	11.91 ±3.05	32.45 ±2.67	1.30±0.07	2.29 ±0.10	0.84	0.93
T13.1	2.84	2.530	*	2.01 ±0.16	31.57 ±7.04	0.33 ±0.03	11.67 ±2.73	30.75 ±0.97	1.29±0.07	2.28 ±0.06	0.86	0.90
T13.2	3.23	2.568		2.23 ±0.21	30.98 ±6.58	0.37 ±0.03	9.75 ±2.32	34.52 ±2.31	1.36±0.05	2.39 ±0.09	0.83	0.94
T13.3	2.71	2.554		1.91 ±0.19	26.62 ±5.69	0.30 ±0.05	14.30±2.94	32.08 ±3.35	1.24±0.03	2.20 ±0.02	0.82	0.96
T9	2.61 ±0.05	2.551 ±0.008	2.75		37.11 ±6.26	0.38 ±0.03	8.97±1.60	35.20 ±2.44	1.19±0.15	2.06 ±0.26	0.87	0.80
T9.1	2.56	2.544		2.23 ±0.15	24.72 ±3.93	0.37 ±0.02	9.52 ±1.43	34.10 ±1.29	1.15±0.15	2.01 ±0.27	0.87	0.80
T9.2	2.66	2.558	*		26.07 ±3.49	0.41	7.32	38.50	1.22±0.16	2.12 ±0.31		0.80

6.3.2.1. Massive basalts

Porosities

Results indicate that BP25 has the highest n_{eff} (15.56 %) and the lowest dry density (average 2.6 g/cm^3) among the massive basalts analysed, which display n_{eff} values between 3.84–8.98 % and ρ ranging from 2.7 to 3.1 g/cm^3 . Discrepancies are observed between n_{eff} and n_{eff_Hg} in massive basalts. For BP25, BP13, and BAF11, the n_{eff_Hg}/n_{eff} ratio is less than one (0.58–0.83), indicating limited pore accessibility to mercury. Conversely, BP8 and BP23 have higher n_{eff_Hg} values than n_{eff} , with BP23 displaying the greatest discrepancy, having a n_{eff_Hg} value 3.70 times that of n_{eff} . Such differences may result from variations in test pressure – 800 Pa for water saturation and 414 MPa for MIP – and from a microstructure (e.g., microcracks not accessible to water) that facilitated mercury intrusion (Pereira et al., 2025a). This interpretation is supported by the higher r and greater proportion of pores $> 1 \mu\text{m}$ of BP23 (Fig. 6.2d; Table 6.2), consistent with the fissure threshold defined by Cueto et al. (2006, 2009).

Dynamic properties

Ultrasonic wave velocities are influenced by mineralogy, density, and pore structure. No preferential phenocryst orientation was observed in BP and BAF samples, suggesting that crystal alignment had minimal impact on wave propagation. Vp/Vs anisotropy is generally associated with ratios above 0.70, except for BP8.2, BP23.1, and BP25.2, which exhibit lower Vs values (Appendix 6.1a). The obtained Vs may result from challenges in accurately identifying their arrival times in massive BP samples.

BP25 presents an average Vp/Vs ratio of 1.83, comparable to the other BP and BAF basalts (1.75–2.14). However, mechanical parameters derived from Vp and Vs demonstrate that higher porosity and lower density do not necessarily correspond to reduced E_d , G , K , or increased ν_d . For example, BP8, despite being the least porous ($\sim 4 \%$), most dense (3.0 g/cm^3), and having the smallest r (Table 6.2), shows the highest Vp/Vs but the lowest G ($\sim 12 \text{ GPa}$) and relatively low E_d ($\sim 30 \text{ GPa}$). Its K ($\sim 28 \text{ GPa}$) slightly exceeds that of BP25. A reduction in Vp and Vs is observed in the X direction for BP8 (Appendix 6.1). Despite a higher r , BP23 and BP13 have greater mechanical competence than BP8 and BP25.

ν_d varies between 0.17 and 0.34 across low and medium porosity basalts, with smaller intra-sample variation, indicating lower sensitivity compared to other dynamic moduli.

Water absorption by capillary imbibition

The n_{cc} values for massive basalts range from 1.21 % to 10.37 %, with the lowest observed in BP23 and the highest in BP25 (Table 6.3 and Appendix 6.2). As expected, n_{cc} is 0.36–0.60 lower than n_{eff} , depending on the specimen. Although BP8 has the lowest n_{eff} , it shows the highest n_{cc} among the basalts, which indicates that a significant portion of its connected porosity actively contributes to spontaneous imbibition. Conversely, BP13 and BP23 exhibit low n_{cc} despite their higher n_{eff} and substantial proportion of capillary pores (Table 6.2). For these basalts, less than 50 % of the interconnected pore network, potentially including microcracks, effectively participates in spontaneous imbibition.

The C_{EN} values for basalts range from 0.72 to 5.87 g/m²·s^{0.5}, classifying them as rocks with low capillary absorption according to Snethlage (2005, in Graue et al., 2011). However, the absorption curves (Y) plotted against $t^{1/2}$ (Fig. 6.3) reveal a nonlinear imbibition process that deviates from ideal $t^{1/2}$ kinetics (Fig. 6.5), as explained by the SF model. The model-derived absorption coefficients (C_a , C_m) are shown in Fig. 6.3. Some rocks had a single linear trend associated solely with C_e .

It is assumed that low-porosity basalts did not reach full saturation after 48 h, since capillary curve did not reach a clear plateau, a pattern also observed in andesites by Çelik (2024). Incomplete saturation during imbibition may result from the structure of the pore network, where narrow throats inhibit full wetting of connected pores (Heap et al., 2023). As a result, the measured C values reflect only partial water uptake under the test conditions. BP samples with capillary curves with a linear behaviour are the ones that generate more anisotropy of C_{EN} along the X, Δ , and O directions. Conversely, the medium-porosity BP25, tested for 24h, approaches sooner a plateau in the curve of the water absorption.

The studied basalts generally display a nonlinear water absorption trend, except for samples BP23, BP13.2, and BP13.3. Specimens with a n_{eff} greater than 6 % and a proportion of macropores above roughly 9-10 % tend to show enhanced capillary imbibition and deviations from the linear $t^{1/2}$ kinetics. Cueto et al. (2018) reported that such deviations are more pronounced when the proportions of large and fine pores are similar. PSD and r appear to have a lesser effect.

Based on the classification by Snethlage (2005, in Graue et al., 2011), the studied basalts vary from rocks with low (BP13.2, BP13.1, BP8, BP23) to moderate (BAf11, BP13.1) to high (BP25) water capillary absorption. Although Graue et al. (2011) describe basalts as highly weathering-resistant building materials, the Azorean massive basalts indicate microstructural variability that can result in moderate to high spontaneous imbibition.

Capillary absorption may combine with salt crystallisation, as several pores fall within the critical radius interval for this phenomenon (Fig. 2.9).

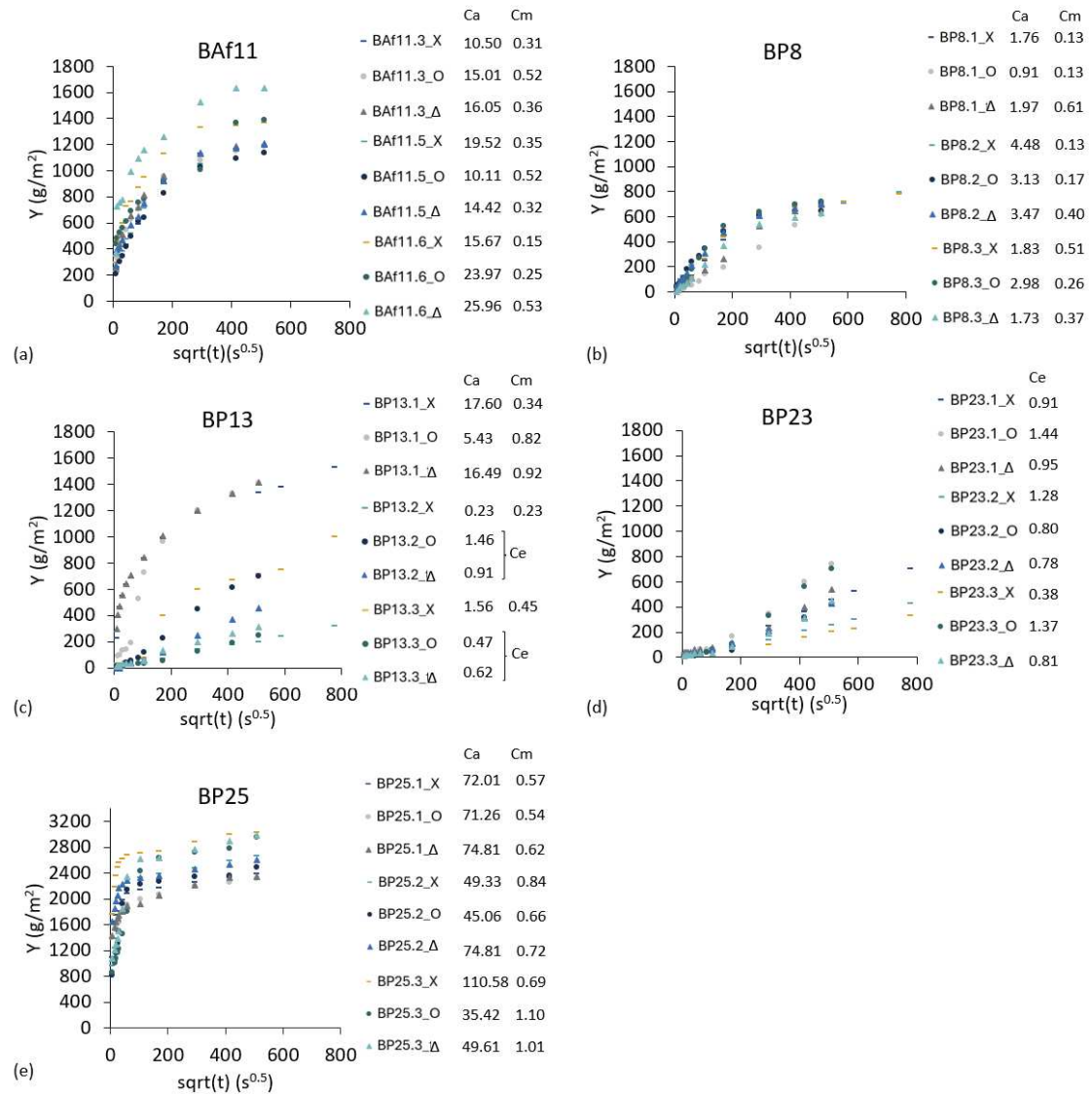


Fig. 6.3. Water absorption curves along $t^{1/2}$ for massive basalts - (a) BAF11; (b) BP8; (c) BP13; (d) BP23; (e) BP25 – along three orthogonal directions (X, O, Δ). Y is the water absorption. Initial (C_e), intermediate anomalous (C_a), and late (C_m) absorption coefficients are in $\text{g/m}^2 \cdot \text{s}^{0.5}$. For rocks with nonlinear trends, C_a and C_m were included, whereas C_e is presented for rocks with a single linear trend.

In general, higher n_{eff} and larger pore sizes correspond to increased capillary water absorption and vice versa, as observed in samples BAF11, BP8, and BP25. Although not included in this research, thin-section observation on similar materials has revealed a connectivity of the pore network between both larger and finer pores, which is also suggested as an enabler of capillary water absorption. BP13 shows directional heterogeneity ($A(C_{EN}) = 0.52$), primarily due to the higher n_{eff} in BP13.1 ($\sim 9\%$) compared

to the other specimens ($< 6\%$). BP13.2 and BP13.3 show lower V_p and V_s (Appendix 6.1), indicating a more occluded pore network. In contrast, BP25 displays minimal directional variation in water absorption and a negligible difference between specimens ($A(C_{EN}) = 0.96$), indicating a homogenous water uptake, which is combined with the non-uniform and bimodal PSD (Fig. 6.2e).

Although BP23 has a substantial proportion of capillary pores and a high r (Fig. 6.2c), its capillary absorption curves suggest a compact structure with narrow pore throats accessible to mercury intrusion but not contributing to spontaneous imbibition. Conversely, BP25 has a smaller proportion of capillary pores compared to other massive basalts, but the higher n_{eff} suggests that capillary absorption is influenced not only by pore size but also by overall porosity, connectivity, and pore network architecture, in line with findings by Beck et al. (2003).

6.3.2.2. Vesicular intermediate basalts

Porosities

As shown in Table 6.3, vesicular textures increase n_{eff} ($\sim 16.44\text{--}21.95\%$) and reduce ρ ($2.1\text{--}2.3\text{ g/cm}^3$). WG_{III} of BF33 further contributes to the lowest density among the vesicular lavas. n_{eff_Hg} ranges from 60 % (BF12) to 92 % (BF33) of n_{eff} . BF samples contain pores often exceeding 1 mm, which surpasses the upper detection limit of MIP (180 μm). The relationship between n_{eff} and pores in volcanic rocks depends on the pore network architecture and pore coalescence (Pereira et al., 2025a; Chapter 4).

Porosity types can be classified by their petrophysical effects, similar to Lucia's (2007) scheme for carbonate rocks. Lucia (2007) (also in Benavente, 2011) groups intergranular and intercrystalline porosities as interparticle porosity, whereas vuggy porosity corresponds to voids within grains or that are significantly larger than the grain size. This type of porosity is subdivided by connectivity into *separate vugs* (linked by interparticle pores) and *touching vugs* (forming large, connected pore systems). This classification cannot be directly applied to volcanic rocks because of their fundamentally different porous structures but can be used to define a new classification for lavas. According to microscopic observations by Pereira et al. (2025a) (Chapter 4), massive lavas (basalts, s.l., to trachytes) include intercrystalline isolated pores, typically of regular shape, with an angularity defined by the habit of the groundmass crystals. Intracrystalline pores and voids along the boundaries of crystals can also be included in this category, despite their more irregular appearance. When present, the connectivity of intercrystalline pores is enabled by the sparse microcracks, typically transgranular, and the lava behaviour becomes controlled by

the mixed interplay between pores and microcracks (Cant et al., 2018). Conversely, the counterpart to the vuggy porosity in lavas is the vesicular texture, which can contain both isolated and connected pores, similar to the touching vugs. Isolated pores are more spherical, while connected pores are spheroidal due to the coalescence phenomenon and the enhanced connectivity by pore-linking fractures, as observed in BF13 and BF15 (Pereira et al., 2025a; Chapter 4).

Dynamic Properties

The high porosity of vesicular samples reduces E_d (12–32 GPa), G (5–13 GPa), and K (9–26 GPa) compared to low-to-medium porosity basalts, while average ν_d slightly increases (0.23–0.35). Among vesicular lavas, BF35 is the least competent (Appendix 6.1b), whereas porphyritic intermediate lavas, such as BF6 and BF12, display higher moduli. Both lavas also show high V_p (Appendix 6.1), although BF6 shows a decrease in V_s , resulting in an anomalous V_p/V_s ratio exceeding 2 (Table 6.3). Still, the average V_p/V_s (1.79–2.10) and ultrasonic wave anisotropy (0.72–0.92) for BF samples are similar to values for massive basalts, indicating that additional factors (e.g., porphyritic degree, mineralogy, pore size) influence V_p and V_s beyond porosity alone.

In BF33, higher weathering grade lowers V_s relative to V_p (Appendix 6.1), increasing V_p/V_s and K , while resulting in lower E_d , G , and higher ν_d (Table 6.3).

Pereira et al. (2025b) observed an incipient trend in BF35, with V_p higher in the O direction and lower in the Δ direction. No clear trend was found for V_s regarding pore orientation. Data in Appendix 6.1 show that, generally, samples with a vesicular texture often display reduced V_p in the Δ direction. Elongated pores aligned perpendicular to the wave path may act as barriers to the transmission of ultrasonic waves. Conversely, millimetric to centimetric, elongated pores aligned with wave propagation (O direction) may form extended empty spaces, which also reduce ultrasonic velocity. Although some patterns emerge, the influence of pore elongation on dynamic properties remains inconclusive. Overall, the elongated pores with an apparent elongation did not reduce the ultrasonic velocity anisotropy with respect to massive basalts.

Water absorption by capillary imbibition

In this study, capillary parameters ($n_{cc} = 2.28\text{--}7.74\%$; $C_{EN} = 1.31\text{--}4.37\text{ g/m}^2\cdot\text{s}^{0.5}$) fall within the range reported for basalts. n_{cc} represents only 12–32 % of n_{eff} in BF, and the C_{EN} classifies the studied vesicular lavas as having low capillary absorption, with few pores contributing to spontaneous imbibition. The limited capillary uptake is attributed to the presence of large pores, many exceeding 1 mm in radius, which lie above the upper limit for capillary-active

pores (100 μm ; Benavente et al., 2018; see also Fig. 2.9), indicating that gravitational forces dominate water transport. According to Jurin's Law for a wetting liquid, in a pore radius of 1 mm, the capillary rise achieves only a height of ~ 1.5 mm, indicating negligible water movement by capillarity. The measured C_{EN} and n_{cc} values support this interpretation and are consistent with findings for other high-porosity rocks, including basalts (Cueto et al., 2024a) and sedimentary lithologies (Benavente et al., 2011).

Benavente et al. (2007), García-del-Cura et al. (2012), and Benavente et al. (2015) observed that in sedimentary rocks with $n_{eff} > 10$ % and pore radii > 1 mm, capillary absorption can remain high if interparticle micropores connect the vugs. Such a phenomenon may apply to BP25, which contains finer pores that participate in the spontaneous imbibition, but does not hold for the BF samples. They are characterised by interconnected or coalescent pores, that contributes to the overall rock's connectivity but not significantly to capillary water uptake.

The values of $A(C_{EN}) > 0.80$ for vesicular rocks characterise them as more homogenous in absorbing water than massive basalts. The orientation of pores along X, Δ , and O directions does not significantly influence C_{EN} , as depicted in water absorption curves (Fig. 6.4). Elongated pores aligned with the vertical uptake direction (O) do not consistently result in the highest C_{EN} or $C_a + C_m$, with higher absorption often occurring along the X and Δ directions.

Similar to massive basalts with $n_{eff} > 6$ %, the vesicular rocks display nonlinear water absorption curves due to deviations from the classic $t^{1/2}$ kinetics. Within 24 h, the curves approach a plateau, indicating near-saturation. Absorption rates are comparable to those of BP13.1 and BAF11, but lower than those of BP25. The combined effects of C_a and C_m (Fig. 6.4), as explained by the SF model, classify these samples as having medium capillary absorption, consistent with findings for trachyandesites with $a n_{eff} \approx 13$ % (Çelik, 2024). The parameters C_m and C_a also suggest that C_{EN} underestimates capillary absorption in vesicular rocks, as noted in massive basalts.

BF35 specimens (Fig. 6.4a–c) display greater homogeneity across specimens and directions compared to BF6 (Fig. 6.4d) and BF12 (Fig. 6.4e). Regardless, all vesicular samples maintain nonlinear water absorption along time. Despite the high n_{eff} , the steep drop in the cumulative pore volume curve in the 1–10 μm radius interval (Fig. 6.2g), BF6 absorbs less water than BF35 and BF12.

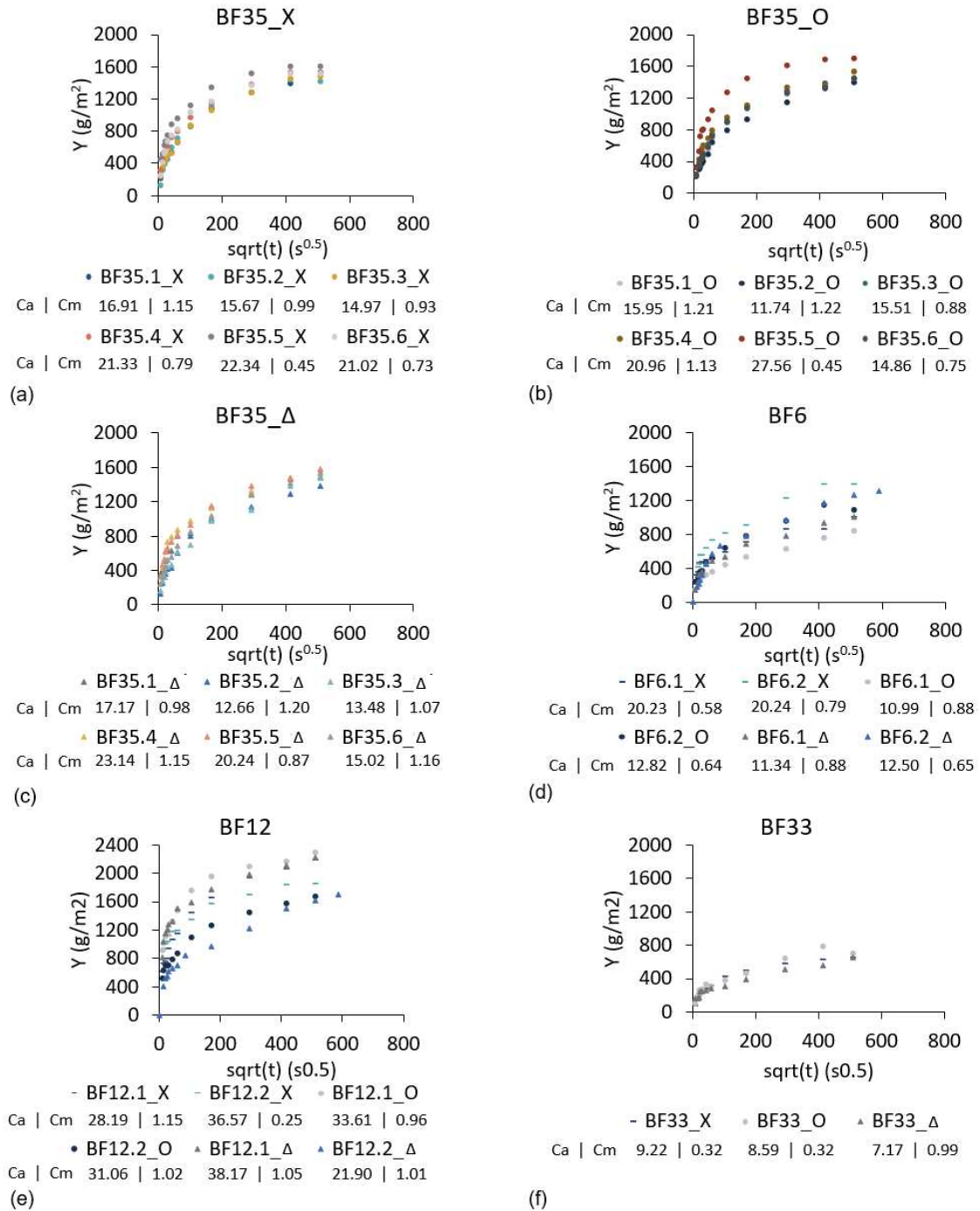


Fig. 6.4. Water absorption curves along $t^{1/2}$ for massive basalts - (a) BF35_X; (b) BF35_O; (c) BF35_Δ; (d) BF6; (e) BF12; (f) BF33 – along the three orthogonal directions (X, O, Δ). Y is the water absorption. All rocks exhibit nonlinear behaviour, and therefore, intermediate anomalous (C_a) and late (C_m) absorption coefficients, in $\text{g/m}^2 \cdot \text{s}^{0.5}$, were considered.

BF12 displays the highest n_{cc} among the vesicular lavas, supported by high capillary water absorption (C_{EN} values and $C_a + C_m$) and a structure with $\sim 88\%$ capillary pores ($0.1\text{--}100\ \mu\text{m}$). The pore volume curve (Fig. 6.2h) suggests a more evenly distributed pore size that likely contributes to the observed nonlinear absorption (Cueto et al., 2018). Although BF12

has a lower r than BF35 and BF6, this parameter appears less indicative of capillary absorption than PSD.

BF33 (Fig. 6.4f; WG_{III}), presents low to medium water capillary absorption, despite n_{cc} representing 92 % of n_{eff} . The overall low capillarity may result from lower n_{eff} , smaller r , and a high proportion of pores $<1\ \mu\text{m}$, likely due to void infill by secondary minerals.

6.3.2.3. Massive trachytes

Porosities

The analysed trachytes are massive, with n_{eff} and n_{eff_Hg} around 3 %. Despite this low porosity, their mineral composition results in a density comparable to that of BP25.

Dynamic properties

These rocks show high Vp/Vs ratios (Table 6.3), primarily due to elevated Vp , whereas Vs remain similar to those of high-porosity (or vesicular) lavas (Appendix 6.1). As verified in Chapter 5, trachytes contribute to higher Poisson's ratios than typically expected for massive lavas, averaging between 0.34 and 0.38 (Table 6.3). E_d indicates that these rocks are comparatively stiff, varying from 30 to 37 GPa, and K averages 32–35 GPa, surpassing those of some basalts, particularly vesicular types. However, as the G is solely dependent on Vs , it remains low, indicating that these trachytes are less resistant to shear stress than BP and BAf basalts.

Water absorption by capillary imbibition

The massive nature of the trachytes reflects on their low capillary absorption coefficients ($C_{EN} = 1.15\text{--}1.36\ \text{g/m}^2\cdot\text{s}^{0.5}$) and reduced n_{cc} . Samples T13 and T9 are homogeneous for both Vp/Vs ratio and C_{EN} (anisotropy > 0.80), indicating negligible directional variation along the X, Δ , and O directions. Furthermore, n_{cc} represents approximately 80 % of n_{eff} , suggesting that most connected voids participate in spontaneous imbibition.

Water absorption curves over time (Fig. 6.5) further confirm this homogeneity. Both T13 (Fig. 6.5a) and T9 (Fig. 6.5b) display low capillary absorption, not reaching a plateau in the water absorption curve after 48 h, limiting conclusions regarding full capillary behaviour. During the observation period, absorption followed the linear $t^{1/2}$ kinetics with no significant deviations, similar to the behaviour of BP13 (Fig. 6.3c) and BP23 (Fig. 6.3d) massive basalts.

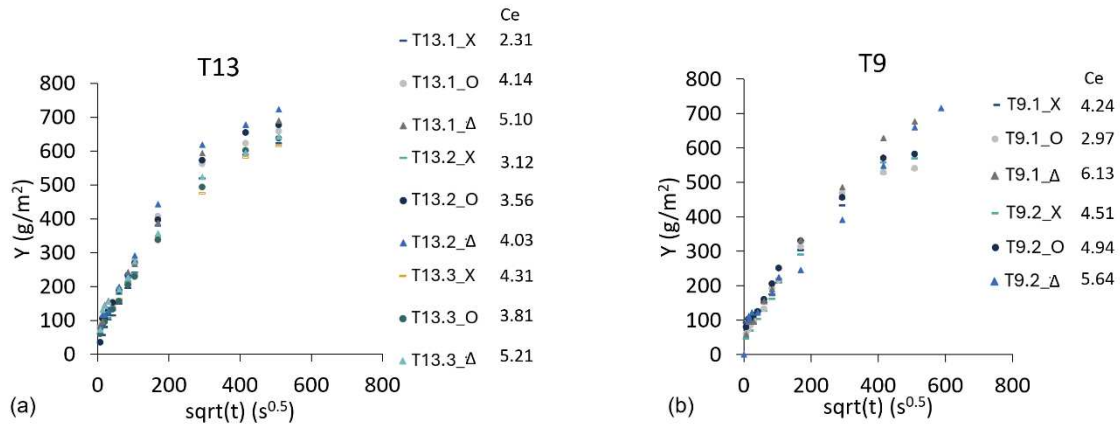


Fig. 6.5. Water absorption curves along $t^{1/2}$ for massive trachytes - (a) T13 and (b) T9 – along three orthogonal directions (X, O, Δ). Y is the water absorption. Initial (C_e) absorption coefficient is in g/m²·s^{0.5} and is the only coefficient considered, as the rocks follow the linear $t^{1/2}$ kinetics.

Graue et al. (2011) studied trachytes with low to medium capillary absorption, evidencing their vulnerability to salt weathering, which may lead to scaling and fracturing. Like massive basalts, saturated trachytes retain moisture for extended periods, which can affect their mechanical strength and deformability over time. Such considerations should be considered for the analysed trachyte or to similar rock materials.

6.3.2.4. Pore-scale heterogeneity on the hydraulic behaviour: A summary

The overall results demonstrate that PSD and n_{eff} are defined by the primary pore structure of the lavas, though post-eruption processes, such as weathering, modify the pore system. Both parameters influence the dynamic properties, alongside mineralogy, and the water absorption via capillarity, yielding novel results of C for these rocks. Lavas with $n_{eff} > 6$ % are better explained by the SF model. Pore-scale heterogeneity is more pronounced between samples, even within the same rock type, while inter-specimen variability occurs in both vesicular (BF12) and massive (BP23) lavas. Conversely, directional heterogeneity is limited for the studied materials.

6.3.3. Microstructure and mechanical behaviour

Capillary imbibition is governed by microporosity, but the internal orientation of pores in rock cannot be visually determined. The inherent variability of lava rocks further complicates analysis and limits the direct applicability of results from numerical models. To address this, μ CT was conducted on a vesicular lava specimen (BF35) to investigate the influence of pore size and shape on unconfined compressive and indirect tensile strengths. Results per direction are presented in Table 6.4. The selected resolution (15 μ m) is adequate, as the image analysis n_{eff} is close to the n_{eff} reported in Table 6.3 for BF35.

Table 6.4. Characterisation of the physical, water transport, and mechanical properties of the vesicular lava BF35 in the X, Δ , and O direction. n_T – total porosity; n_{eff} – effective porosity; T – tortuosity; k – absolute permeability; Fp – feldspar content; σ_{c_UCS} – unconfined compressive strength; σ_t – indirect tensile strength.

Sample	Cylinders										Discs
	Pre-deformation (before test)					Post-deformation (after collapse)					σ_t (MPa)
	n_T (%)	n_{eff} (%)	k (mD)	T	Fp (%)	n_T (%)	n_{eff} (%)	k (mD)	T	σ_{c_UCS} (MPa)	
BF35_X	24.52	18.61	6.63	1.8	16.00	25.75	22.65	30.42	1.84	35.99	-
BF35_O	23.38	20.06	1.68	1.9	19.40	24.67	23.11	31.54	1.68	15.45	3.89
BF35_ Δ	22.68	20.66	0.66	2.1	18.88	24.02	22.62	4.47	1.81	32.46	1.97

6.3.3.1. Pore network models

PNMs generated for cylindrical specimens along the X, Δ , and O directions are shown in Fig. 6.6. These models represent pores by their equivalent radius and connect them via throats of defined channel length. The PNM for BF35.1 closely resembles those previously developed for BF13 and BF15 (Chapter 4; Pereira et al., 2025a).

The core extracted along the X direction contains a higher number of small pores (blue in Fig. 6.6 - equivalent radius < 950 μm). In contrast, the Δ and O direction cores have a wider pore structure that preserves large pores (yellow to red in Fig. 6.6 –equivalent radius > 950 μm).

The X-direction core displays the lowest n_{eff} among the three, as indicated by the PNM and in Table 6.4, which suggests that small-sized pores (< 950 μm) contribute less to overall connectivity compared to larger pores. Large pores (equivalent radius > 950 μm) are predominantly located near the core boundaries, and coalescent pores, comprising one or two spheres, are also visible. Throats connecting large pores tend to be longer (thicker in Fig. 6.6) in the X and O directions. In the Δ direction, longer throats are distributed more evenly throughout the specimen, coinciding with higher T . Although the capillary water absorption and V_p/V_s ratio remain similar across all directions for BF35.1, the pore architecture varies with orientation.

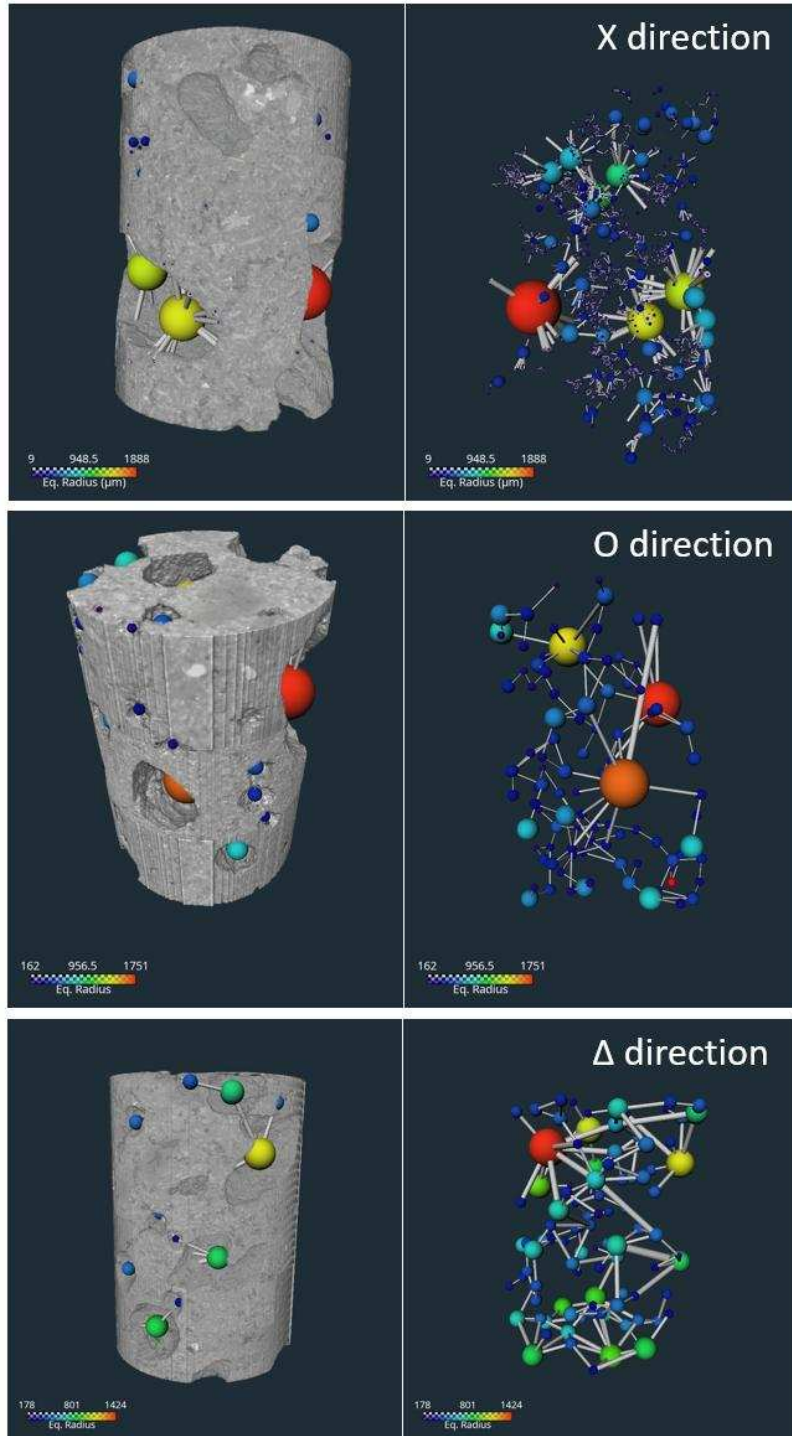


Fig. 6.6. Pore network model (PNM) of BF35.1 specimen for the cores produced along X, O, and Δ directions.

The PNM quantitative results are depicted in Figs. 6.7a to 6.7c for vesicles/pores and in Figs. 6.7d and 6.7e for throats.

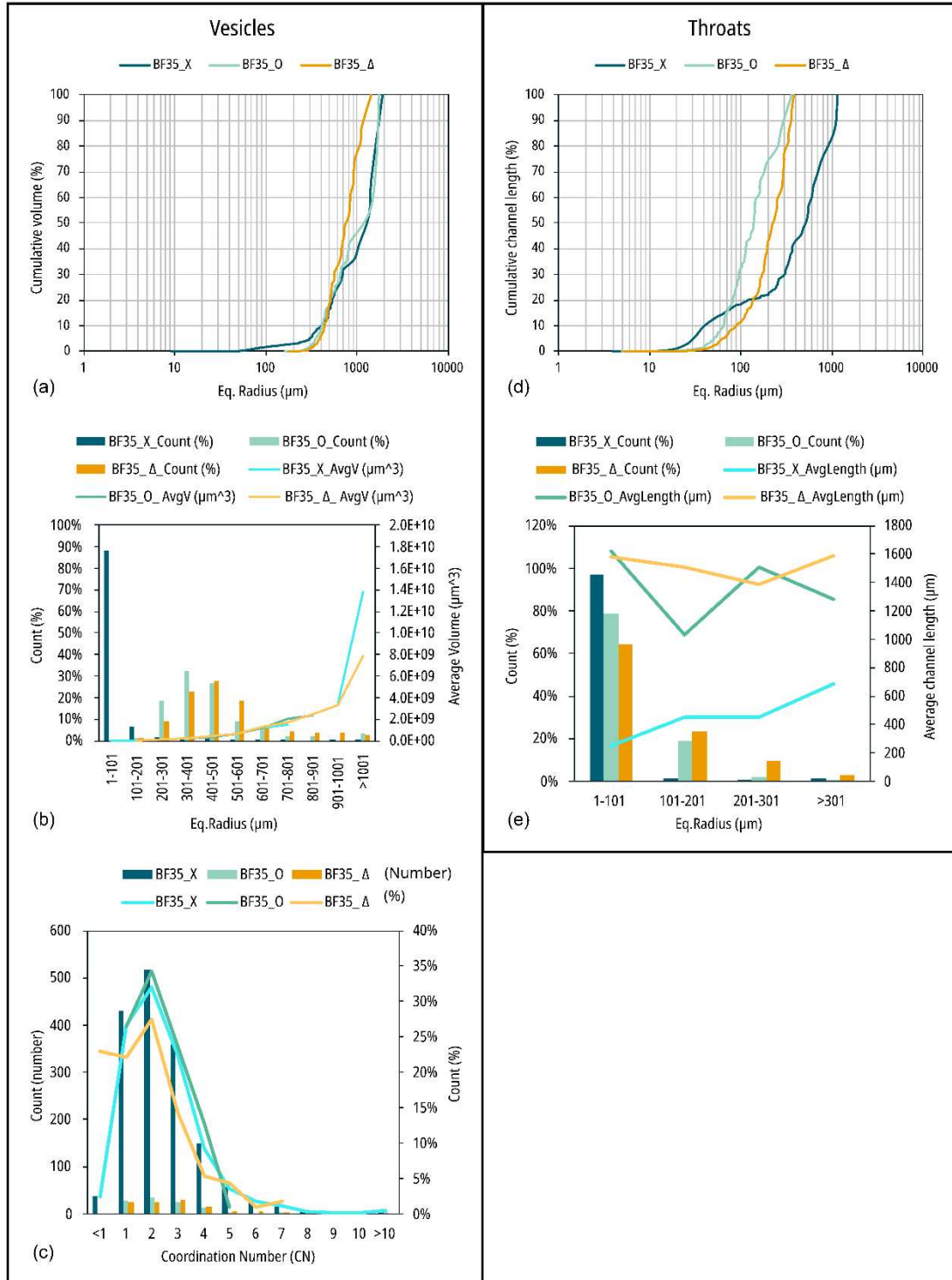


Fig. 6.7. Quantitative results of the pore network models produced in the X, Δ , and O cylinders of BF35. All pores are larger than $15\ \mu\text{m}$ (the selected nominal voxel size). Information regarding pores/vesicles is presented in: (a) cumulative average volume along equivalent radius of the pores; (b) number of pores per each group of equivalent radii; and (c) coordination number and its number (bars) and percentage to the total (lines). Information on the throats is present in: (d) cumulative average channel length along equivalent radius of the throats; (e) number of throats per each group of equivalent radii.

Fig. 6.7a shows that most pores have radii greater than 100 μm , which is consistent with the MIP results (Table 6.2). In addition, the PNM effectively captures pores $> 1\text{ mm}$, where gravitational forces primarily govern water transport. The cumulative pore volume curves are steep, especially for BF35_Δ, indicating a uniform distribution dominated by pore radii between 100 and 1100 μm , which contrasts with the irregular distribution observed for pores smaller than 180 μm (Fig. 6.2f). The other cores have similar cumulative pore volume trends, aligning with their comparable n_{eff} .

Pore/vesicle counts further support the visual PNM interpretation: BF35_X contains a higher number of vesicles, many of which are within the 1–101 μm range, while the other cores predominantly feature vesicles between 201 and 601 μm (Fig. 6.7b). Nevertheless, pores with larger equivalent radii yield higher average volumes.

Coordination number (CN; Fig. 6.7c) shows that most pores have one to three connections, consistent with findings for BF13 and BF15 (Chapter 4). Pores with a $\text{CN} > 2$ contribute significantly to overall connectivity and permeability (Table 6.4). Despite its lower n_{eff} BF35_X displays higher k (7 mD), attributed to the numerous pores with $\text{CN} > 2$, some of which exceed seven connections.

As illustrated in Fig. 2.9 and supported by Benavente et al. (2015; 2018), pore radius larger than 10 μm start to impact the mechanical strength of the rock, especially above 100 μm . Consequently, the mechanical integrity of Azorean vesicular lavas may be compromised due to their pore geometry and PSD.

The cumulative throat length curve for BF35_X is less uniform and displays a stair-step pattern, with most throats ranging from 20 to 1000 μm . In contrast, BF35_Δ and BF35_O show uniform, steeper curves (Fig. 6.7d), with throat radii primarily within 50 to 120 μm . Fig. 6.7e indicates that, across all cylinders, most throats fall within the 1–101 μm radius range. BF35_X contains shorter throats compared to the other specimens, as observed in Fig. 6.6, and displays a broader distribution of channel lengths across varying radii.

These findings suggest that throat length is not the main determinant of rock permeability. Instead, a wide range of equivalent radii and a non-uniform distribution across throat sizes have a greater influence. Throats with equivalent radii $> 10\text{ }\mu\text{m}$ can act as sinks for supersaturated solutions, promoting, for example, salt crystallisation without necessarily inducing stress damage (Benavente, 2011).

6.3.3.2. Post-deformation parameters

All specimens are brittle under UCS and ITS tests (Fig. 6.8). Failure occurs through tensile splitting, often involving coalescent cracks that form a dominant fracture. Cracks propagate along the edges and tips of elongated pores, indicating these boundaries act as stress concentrators. Under the Brazilian test, vesicular rocks develop crack patterns that go beyond the typical central or central-multiple types described by Basu et al. (2013), often fracturing perpendicular to the loading direction due to the influence of pores. In UCS tests, both minor and major fractures develop parallel to the loading direction, consistent with microstructural (e.g., Heap et al., 2014a; Pereira et al., 2025a) and macroscopic observations (Chapter 5).

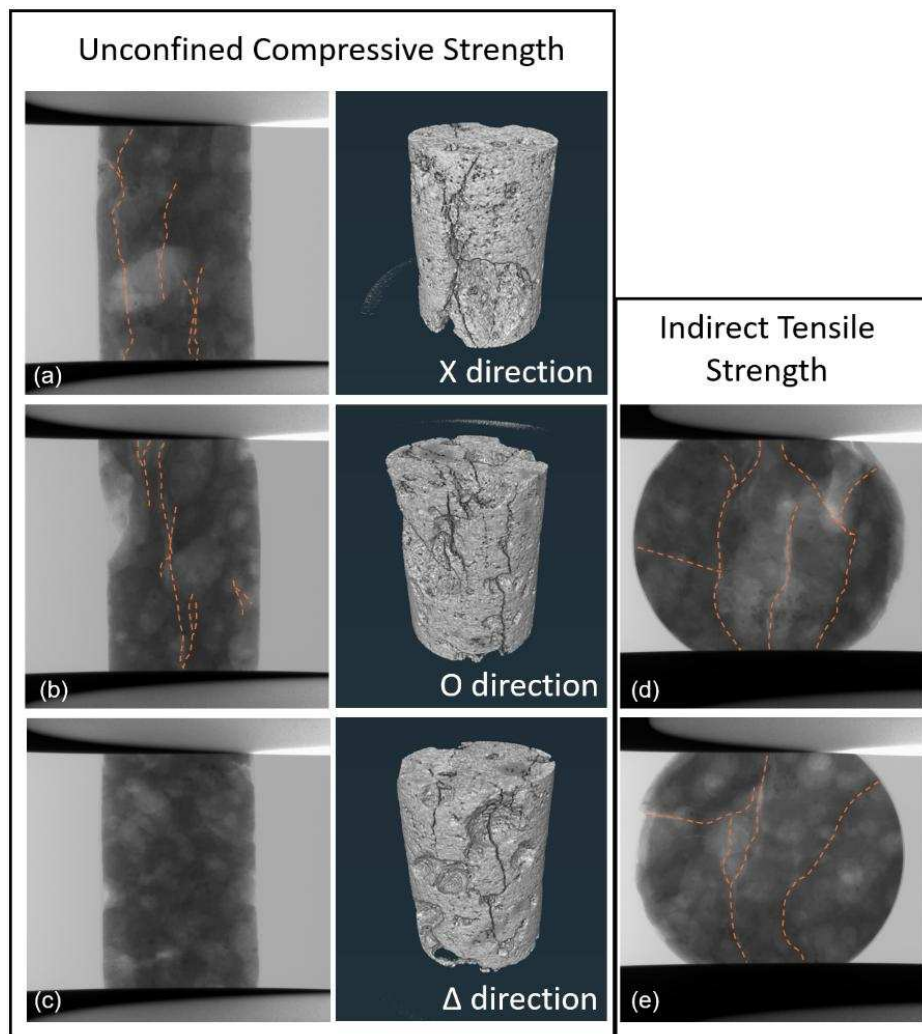


Fig. 6.8. Mechanical test and post-deformation fracture pattern for BF35. Unconfined compressive strength test is represented by (a), (b), and (c) (cylinders cored from BF35.1), and indirect tensile strength was obtained via Brazilian test, represented in (d) and (e) (discs cored from BF35.2). All specimens fail by multiple tensile splitting. Deviations of the fracture pattern are induced by the larger pores. (d) Associates with the O direction, as most pores are parallel to the loading direction, while (e) translates from Δ direction, with most pores perpendicular to the loading direction.

Contrary to ultrasonic wave velocity and capillary absorption, which are kept relatively similar across directions (Appendix 6.1 and Appendix 6.2), σ_{c_UCS} decreases by half (~ 15 MPa) when elongated pores align parallel to the loading direction (O direction). The other cylinders show similar strength (32–36 MPa). The σ_t values are 4 MPa for BF35_O and 2 MPa for BF35_Δ, indicating that pores oriented perpendicular to the loading direction reduce σ_t , consistent with Heap et al. (2021; see Chapter 2.2.5.3). However, this interpretation remains limited due to the small number of tested specimens.

The σ_{c_UCS} and σ_t values align with those reported in Table 5.1 for 45 mm diameter samples, suggesting that strength is independent of specimen size when L/D is constant, in agreement with findings by Van Stappen et al. (2019) for limestones.

Visual classification of pores across the three orthogonal directions can be misleading, as it does not account for internal pores. Therefore, pore dip angles (Section 6.2.2.2) were measured and grouped in 10° intervals (Fig. 6.9a). Horizontal (perpendicular to the loading axis) pores ($< 40^\circ$) are more prevalent than vertical (parallel to the loading axis) or diagonal ones ($> 40^\circ$), contradicting macroscopic observations. For example, BF35_O contains both large (average equivalent radius $> 60 \mu\text{m}$) vertical and numerous smaller ($\sim 27 \mu\text{m}$) horizontal pores.

Average aspect ratios by dip group are shown in Fig. 6.9b. Ranking was applied only to the equivalent radius, which varied more than the aspect ratio, and pore count was excluded due to its higher number in BF35_X. Ranks range from 1 (smallest average radius) to 27 (largest) as shown in Fig. 6.9c.

Fig. 6.9c shows that the mean aspect ratio is independent of direction and pore dip, yielding proximate values that average 0.437, indicating spheroidal pores. In comparison to the literature, the BF35 has more elongated pores (lower aspect ratio) than those of andesites from Volcán de Colima (Heap et al., 2014a). Moreover, low aspect ratios have been found to produce relevant V_p/V_s variations in trachyandesites (Bustos and Adam, 2023). Although BF35_Δ has lower V_s and, therefore, a higher V_p/V_s ratio, the directional heterogeneity is minimal for BF35 (Table 6.3; Appendix 6.1).

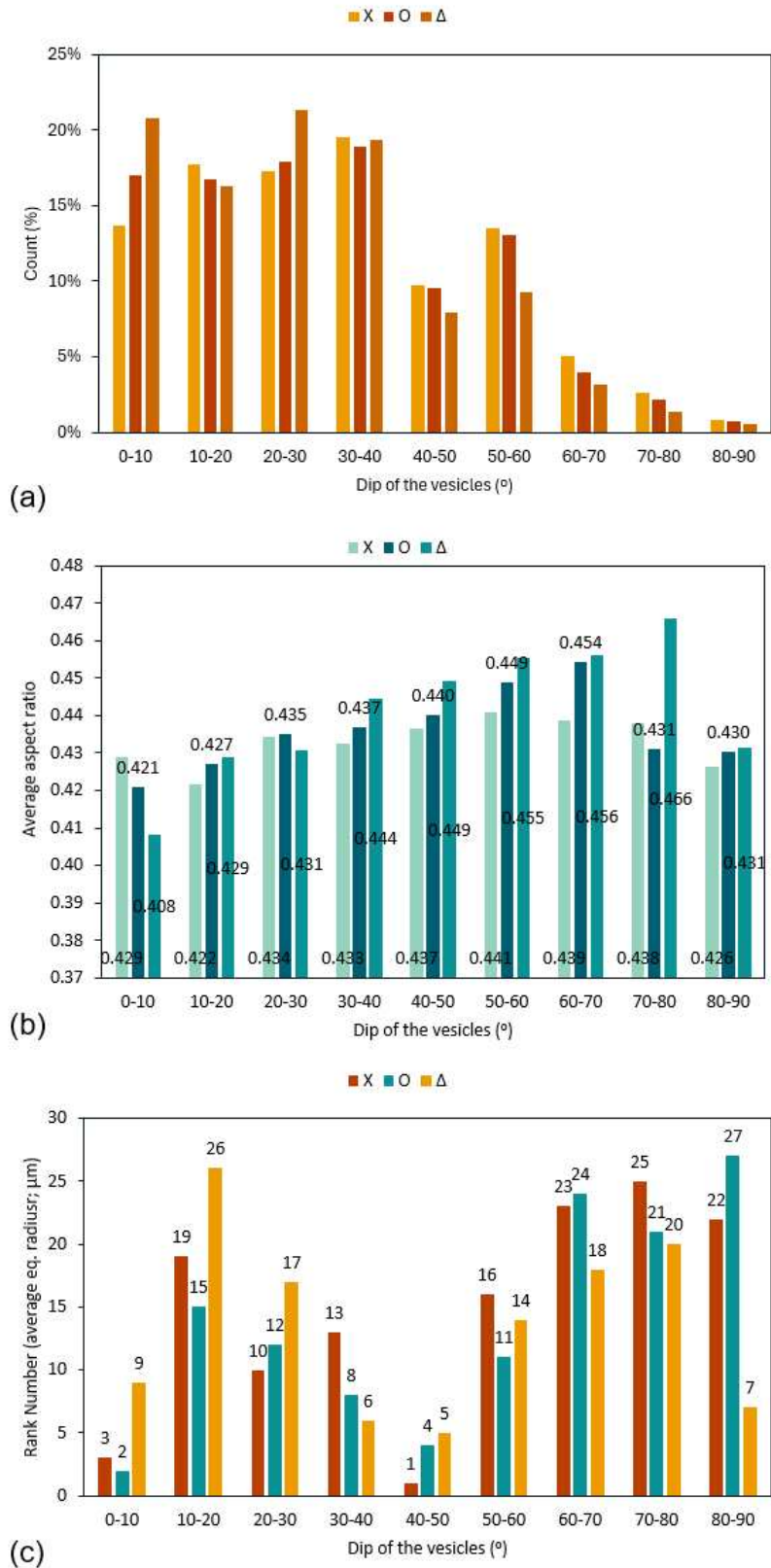


Fig. 6.9. Variation of the average aspect ratio and a ranking system for the average equivalent radius for different inclinations/dip groups of the pores present in the cylinders produced along X, O, and Δ directions.

Fig. 6.9c also reveals that pores with larger equivalent radii are concentrated in the 60–70°, 80–90°, and 10–20° dip intervals for BF35_X, BF35_O, and BF35_Δ, respectively. Among these, BF35_X shows the broadest size distribution across dip angles. BF35_Δ contains a predominance of horizontally aligned pores, alongside a significant number of vertically oriented ones. In BF35_O, vertical pores dominate. Both BF35_X and BF35_O include pores with dips > 60°, yet they produce the lowest and highest $\sigma_{c,UCS}$, respectively. The weakening of BF35_O results from a large vertical vesicle extending nearly half the specimen's length and positioned near the edge. These conditions favour stress concentration and fracture propagation. Therefore, the performed tests suggest that $\sigma_{c,UCS}$ can be significantly affected by the spatial distribution of large pores relative to specimen length.

This observation supports numerical modelling studies, which show that larger, closely spaced, and non-uniform-sized pores, can reduce rock strength (Heap et al., 2014b; Bubeck et al., 2017). However, elongated pores oriented perpendicular to the loading direction do not necessarily result in weakening, as previously proposed (Bubeck et al., 2017; Vairé et al., 2024). In BF35, pores are distributed across multiple dip angles, which mitigates the weakening effect due to directional elongation.

Increased crystallinity has also been identified as a potential weakening factor (Heap et al., 2016). 3D microstructural observations indicate that the BF35_O cylinder contains a greater abundance of plagioclase phenocrysts compared to the other cylinders. The phenocrysts have disequilibrium textures and host intragranular pores and cracks, which promote fracture nucleation and propagation (Chapter 4). Nonetheless, it remains unclear to what extent the presence of phenocrysts contributes to mechanical weakening relative to the influence of large, elongated pores.

As shown in Table 6.4, BF35_X presents the highest strength and n_T , but the lowest n_{eff} . Following failure, n_{eff} increases markedly and permeability rises, suggesting that a higher initial number of small pores promotes enhanced connectivity upon fracturing. In contrast, BF35_O, which initially has the highest n_{eff} , records the lowest strength and a substantial post-failure increase in k , indicating that high initial n_{eff} contributes to improved fluid connectivity after deformation. BF35_Δ shows only a slight increase in k , likely due to a lower number of vesicles and throats, and the presence of large, horizontally aligned pores that contribute less effectively to permeability.

6.3.3.3. Pore-scale heterogeneity on the mechanical behaviour: A summary

Directional heterogeneity, not reflected by C or V_p/V_s , becomes apparent at the pore scale when assessed through digital rock physics. In sample BF35, variations in PNM, physical,

and mechanical properties across different orientations indicate variability within the specimen, producing local different porosities. However, the mechanical behaviour is broadly consistent with that of 45 mm BF35 cylinders. Exceptions occur when surface large pores, relative to the total core length, promote failure at lower stress levels. Although BF35 shows variability in pore size and orientation, features commonly observed in natural materials, these characteristics did not yield systematic patterns in relation to mechanical behaviour.

6.3.4. Overview and principal component analysis

Heterogeneity in C and ultrasonic wave velocity is more pronounced between different samples than within individual sample groups. The directional influence of elongated pores and aligned phenocrysts along the X, Δ , and O directions appears limited, as no consistent trends were observed in ultrasonic wave velocities, dynamic moduli, or capillary absorption.

Although changes in C or V_p/V_s ratios were not significant, 3D microstructural analysis of BF35 confirms that rock strength and crack propagation are significantly influenced by pore size and spatial distribution, resulting in directional variations in strength. Results evidence the inherent complexity of natural lava rocks, which often have a combination of pores (spherical to spheroidal) and microcracks (e.g., penny-shaped fractures) in variable proportions (Cant et al., 2018; Pereira et al., 2025a). This complexity limits the ability to isolate the effects of pore or crystal size and shape on the physical and mechanical properties of rocks. As such, the use of numerical models is essential for understanding the underlying mechanisms, as demonstrated in works by Bubeck et al. (2017), Griffiths et al. (2017), and Vairé et al. (2024).

Nonetheless, some trends have been verified for several parameters. n_{eff} , ρ , ultrasonic velocities, derived dynamic moduli, σ_{c_UCS} , and σ_t are influenced by the interplay between petrological and structural characteristics, including mineralogy, texture, porosity, and pore network architecture. Rock strength is particularly sensitive to pore size and its spatial arrangement. In contrast, C appears less dependent on mineralogy and is instead primarily governed by connected porosity, pore type, size, and distribution.

PCA was applied to several variables (n_{eff_Hg} , n_{eff} , ρ , r , C_m , n_{cc} , C_{EN} , C_e , V_s , E_d , and V_p) to explore the structural relationships between them. Among the dynamic moduli, only E_d was included due to its mechanical significance. The Kaiser-Meyer-Olkin (KMO) measure yielded

a value of 0.68, which is considered moderate but acceptable for PCA (Reis, 2006), while Bartlett's test of sphericity confirmed the significance of the analysis.

The PCA accounts for 84 % of the total variance in the dataset, distributed across three principal components: PC1 (49.3 %), PC2 (25 %), and PC3 (9.5 %). The rotated component loadings (Fig. 6.10) indicate that PC1 groups variables related to pore system characteristics. PC2 includes parameters associated with dynamic properties. PC3 encompasses the variables that describe water transport behaviour, particularly those related to capillary absorption. The biplots indicate an inverse correlation between n_{eff} and ρ , as shown in Table 6.3. ρ is also influenced by mineralogical composition (Table 6.3), but the analysis suggests that porosity and pore size exert a more pronounced effect. The variable C_e , which characterises the early stage of spontaneous imbibition, aligns with PC3, whereas C_m is more closely associated with PC1. This result supports the interpretation that late-stage imbibition is primarily controlled by pore structure, particularly the presence of finer pores.

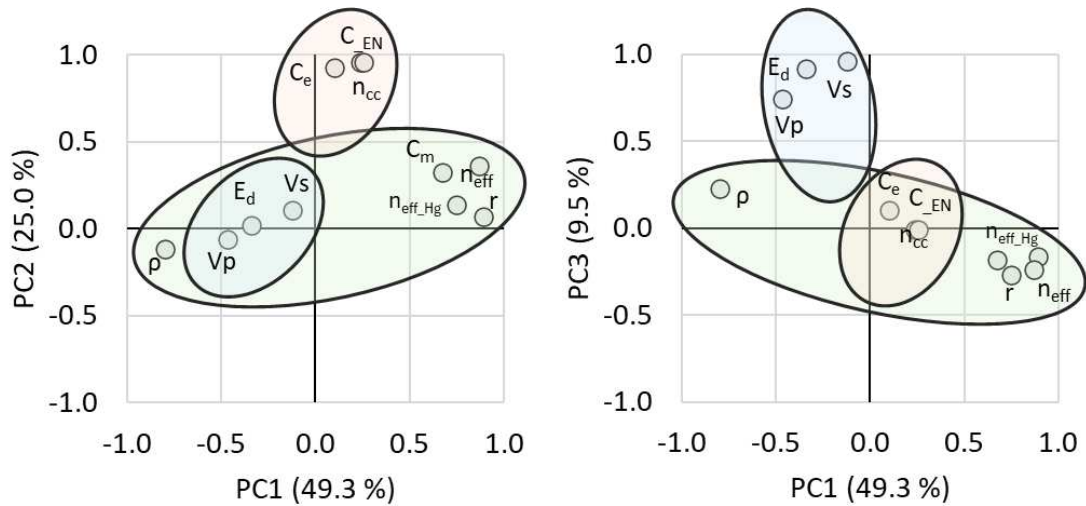


Fig. 6.10. Principal component analysis, including three principal components (PC) and the variance that they explain. Oval areas group the variables (blue – dynamic properties, pink – water transport properties; green – pore space-related properties). n_{eff} – open porosity; ρ – dry density; n_{eff_Hg} – mercury-accessible connected porosity; V_p – P-wave velocity; V_s – S-wave velocity ratio; E_d – dynamic Young's modulus; C_{EN} – capillary absorption coefficient; n_{cc} – capillary connected porosity; C_e – initial absorption coefficient; C_m – late absorption coefficient.

The relationships among n_{eff} , n_{eff_Hg} , and n_{cc} are illustrated in Fig. 6.11. These porosity metrics reflect the characteristics of the pore system, as well as methodological differences, including the pore size ranges captured by each technique and the applied pressures. For instance, MIP detects pores with radii smaller than 180 μm and, therefore, underrepresents vesicular lavas, which often contain pores larger than 1 mm.

n_{cc} is consistently lower than n_{eff} . For lavas with $n_{eff} < 16\%$ – similar to the n_{eff} threshold defined in Fig. 5.7 for lavas that have their strength controlled by microcracks and pores – n_{cc} increases with n_{eff} , suggesting that a greater proportion of connected pores participate in spontaneous imbibition. For example, for trachytes, n_{cc} accounts for 79 % of n_{eff} . BP25, despite one specimen having $n_{eff} = 17.40\%$, follows the trend observed in low-porosity lavas. In contrast, vesicular/high-porosity lavas with $n_{eff} > 16\%$ – within the cut-off defined in Fig. 5.7 for vesicular lavas that have their strength controlled by pore size – display decreasing n_{cc} values with increasing n_{eff} , and represent 25% of the n_{eff} , evidencing a reduced capillary transport efficiency due to the dominance of large pores. The weathered BF33 sample is an exception, where void infilling by secondary minerals likely reduces r and enhances spontaneous imbibition despite limited n_{eff} (n_{cc} is 92 % n_{eff}).

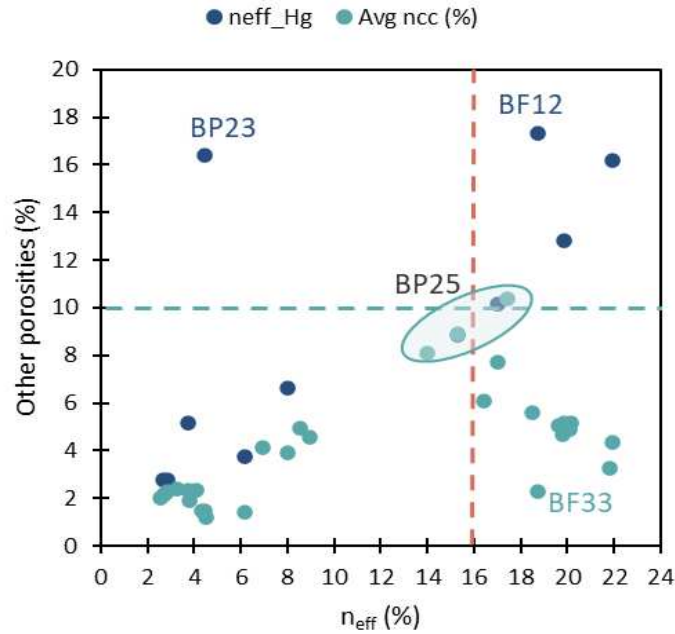


Fig. 6.11. Relation between n_{eff} (open porosity), n_{eff_Hg} (mercury-accessible connected porosity), and n_{cc} (capillary connected porosity). n_{cc} are primarily below 10 %. The cut-off of $n_{eff} = 16\%$ distinguishes massive (high-to-medium porosity) of vesicular (high-porosity) lavas, with BP25 (medium-porosity) in a transition stage.

These observations and capillary test results support the conventional view that large pores (radius > 1 mm) contribute minimally to capillary water absorption, suggesting that water transport in vesicular lavas is primarily driven by gravitational mechanisms. Although BF lavas contain several pores within the size range favourable for salt crystallisation. However, as noted by Benavente et al. (2011), large pores with openings above 10 μm may act as solution sinks where crystallisation occurs without generating sufficient stress to damage the rock.

The relationship between n_{eff_Hg} and n_{eff} is approximately positive linear ($R^2 > 0.87$) when excluding BP23, which has the highest r among the massive basalts. Further microstructural analysis would be required to verify if microcracks explain this exception.

6.3.5. Implications for volcanology and volcanic terrains

The Vp/Vs ratio is a common tool for seismic subsurface characterisation in volcanic settings (Vargas et al., 2017). Higher values typically indicate melt or water-saturated rocks, while lower values may suggest the presence of dry steam or gas phases (Bustos and Adam, 2023 and references therein). Although Vp and Vs are usually measured during field surveys, laboratory-based high-frequency methods improve the interpretation and prediction of large-scale seismic data (Lesage et al., 2018). Vairé et al. (2024) further argue that the preferred pore shape orientation should be considered when interpreting seismic data.

Results indicate that Vp/Vs increases with vesicularity, felsic composition, and porphyritic textures, in line with established findings for fractured and porous rocks. Vp is more sensitive to mineralogical and textural variations than Vs (Bustos and Adam, 2023). However, the ratio does not show significant directional variation, and no clear influence from elongated pores is observed. Also, the extent of variation between samples prevents a clear distinction based solely on composition or texture. For example, massive trachytes may display similar Vp/Vs ratios to vesicular intermediate lavas.

In massive lavas, such as trachytes and dense basalts, pore size characteristics suggest that fluid transport may occur via vapour adsorption and capillary condensation, depending on thermo-hygrometric conditions (Benavente, 2011). Studies have shown that increased water vapour pressure accelerates crack growth in andesites (Nara and Kaneko, 2005). At higher RH, capillary condensation around the crack tip originates a liquid condensed water that reduces crack growth resistance and creates a significant compressive stress around the tips (Nara et al., 2010; Nara et al., 2012). Crack-tip velocity may increase by two to four orders of magnitude in water-saturated conditions (Nara et al., 2009). Thus, RH and sorption mechanisms have a significant influence on subcritical crack growth and fracture toughness in volcanic rocks, both of which are associated with time-dependent fracturing (Atkinson, 1984), known to increase seismic activity preceding volcanic eruptions (Kilburn and Voight, 1998).

Capillary flow is the dominant water transport mechanism in rocks exposed to the atmosphere (Benavente et al., 2015), such as those found on volcanic slopes. Both permeability and capillarity are described as indicators of volcanic rock collapse potential

(Cueto et al., 2024a), relevant for hazard assessment and geotechnical planning. On São Miguel Island, capillary absorption is particularly significant due to intense rainfall and the occurrence of stagnant water, both of which contribute to slope instability (Heap et al., 2023 and references therein; Silva et al., 2023).

Massive lavas, especially those with porous bands, can reach moderate to high capillary absorption and, possibly, are susceptible to salt weathering through repeated wetting and drying cycles. Therefore, assessing capillary imbibition capacity is advisable for medium-porosity lavas where millimetric pores are either localised in porous bands or uniformly distributed in the entire specimen. These materials correspond to the lavas depicted in a transitional n_{eff} zone of Fig. 5.7.

Vesicular rocks (high porosity, with millimetric to centimetric pores) are weaker (Fig. 5.7) and have an intermediate capacity for water uptake by capillarity. In these rocks, water transport is primarily governed by permeability. Permeability also plays a primary role in processes such as outgassing (Collinson and Neuberg, 2012) and hydrothermal fluid migration (Todesco et al., 2003; Stimac et al., 2015). While pre-deformed vesicular lavas tend to be poorly permeable, brittle failure can significantly enhance permeability, particularly when the pore network is dense and distributed throughout the specimen. Unlike fractures, pores, even if elongated, are more likely to remain open under the higher confining pressures encountered at depth (Bustos and Adam, 2023; Vairé et al., 2024), thereby facilitating gravitational water transport.

Mechanical testing on ~8/13 mm diameter specimens suggests that strength is relatively scale-independent in intact samples if the L/D ratio is kept constant. However, in rock masses, discontinuities reduce overall stiffness and strength compared to laboratory specimens (Hudson and Harrison, 2000; see Chapter 2.2.2, Part A; Chapter 5).

The pore-scale heterogeneity of lava rocks can be evident even within a single specimen, and produce distinct physical, hydraulic, and mechanical properties. However, whether heterogeneity at the micro- to intact-rock scale should be considered in large-scale volcanic models, as posed by Vairé et al. (2024), remains a nontrivial question.

6.4. Conclusions

This chapter examined the heterogeneity of Azorean lava rocks through a combination of non-destructive techniques and 3D imaging, yielding a comprehensive dataset of physical and water transport properties.

- In general, individual specimens and lithological groups display homogeneity in ultrasonic wave velocity and capillary absorption. Conversely, intra-group variability reflects differences in microstructure.
- Physical properties, such as n_{eff} , ρ , and r , are mainly governed by pore system structure. At the same time, ultrasonic wave velocities and dynamic moduli also depend on mineralogical and textural features. Water transport properties mostly depend on the pore size distribution rather than mineralogy, and most samples had an incomplete saturation after 48 h. Furthermore, the coefficient of water absorption is underestimated when calculated using the NP-EN 1925:2000 standard, particularly for more porous materials, whose sorption process is better explained by the SF model.
- Massive basalts (BAf and BP) displayed a wide range of capillary behaviour, ranging from low to high. On the other hand, low-porosity trachytes have limited water uptake. The presence and distribution of capillary-sized pores in massive basalts suggest a susceptibility to deterioration via mechanisms activated through or associated to spontaneous imbibition. Lavas with a predominance of micropores (< 15 μm) are prone to vapour adsorption and capillary condensation processes that contribute to long-term mechanical weakening.
- For vesicular specimens, large pores (>1 mm) do not actively participate in spontaneous imbibition; instead, gravitational flow dominates. The mechanical behaviour, particularly UCS, is affected by pore size and the spatial distribution of large pores. Varying pore dips in these natural samples hinder the effects of directional elongation on pore strength.
- 3D microstructural analysis proved essential, providing pore network models that offer insights beyond what is possible through visual inspection or traditional porosimetry.

This study highlights the complex relationship between microstructure and mechanical and physical behaviour. The obtained results have important implications for volcanology, engineering geology, and hazard assessment, especially in volcanic regions such as São Miguel Island, by improving predictions of rock behaviour under variable environmental conditions and informing more accurate large-scale volcanic models. Future work should investigate the role of crystal orientation and develop empirical equations that link pore space and capillarity to mechanical strength.

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*Effects of hydrothermal
alteration*

Chapter

Hydrothermal alteration influence
on properties of rocks in a volcanic
environment: A critical analysis

Hydrothermal alteration influence on properties of rocks in a volcanic environment: A critical analysis

This chapter is based on the publication by Pereira et al. (2024a)¹, prepared within the scope of this doctoral thesis. An adaptation of the paper was pursued, with excerpts integrated throughout this chapter and properly cited, following Universidade dos Açores rules and aligning with the terms of the Creative Commons Attribution 4.0 International Licensed (CC BY 4.0).

7.1. Preliminary notes

Hydrothermal alteration influences the mechanical and physical properties of host rocks and regulates fluid circulation, ore deposit formation, fracture propagation, and the geotechnical performance of rock masses, such as slope and excavation stability. Most studies on hydrothermal alteration have been conducted for the characterisation of geothermal fields (Browne, 1970; Browne, 1978; Marini, 2000; Lagat, 2009), allowing to understand the main factors controlling hydrothermal alteration (temperature, pressure, fluid chemistry, permeability, subsurface geology, and time).

The prevalence of hydrothermal altered rocks, either in geothermal fields or volcanic settings (Wyering et al., 2015), and the variability regarding their mechanical and physical properties (e.g., Robb, 2005; Yıldız et al., 2010) has recently prompted more laboratory studies. As stated by Pereira et al. (2024a), the influence of hydrothermal alteration remains elusive, leading to contradictory findings in the literature. Higher degree of hydrothermal alteration does not always result in the weakening of the host rocks, nor the reduction of permeability and porosity (e.g. Wyering et al., 2014; Frolova et al., 2014; Marmoni et al., 2017; Heap et al., 2020c; Heap and Violay, 2021; Scott et al., 2023). Furthermore, the relation between the type of alteration and the properties of the rocks is complex since it depends on several features, including the host rocks, conditions of pressure and temperature (P-T),

¹ Pereira, M.L., Zanon, V., Fernandes, I., Pappalardo, L., and Viveiros, F., 2024a, Hydrothermal alteration and physical and mechanical properties of rocks in a volcanic environment: A review: Earth-Science Reviews, 104754, <https://doi.org/10.1016/j.earscirev.2024.104754>. Licensed under CC BY4.0.

chemical composition of the fluid, and duration of fluid-rock interaction (Frolova et al., 2010, 2011; Frolova et al., 2014 in Pereira et al., 2024a).

As a result, hydrothermal impacts the mechanical and petrophysical properties of rocks by changing mineralogy, texture, structure, stiffness, deformation, and overall stability. Understanding the underlying poro-chemo-mechanical processes involved in rock-fluid interaction is important in several fronts, as reviewed by Pereira et al. (2024a). It contributes to improved numerical models of geothermal reservoirs and heat transport, supports geophysical and log interpretations, optimising drilling and improving the exploitability of these fields (Ghassemi, 2012; Ochieng, 2013; Wyering et al., 2014; Frolova et al., 2014; Koros et al., 2015; Cant et al., 2018; Villeneuve et al., 2019; Bär et al., 2020; Heap et al., 2022a). Data can also be used to assess slope and excavation stability of altered rock masses (Reid et al., 2001; Coggan et al., 2013; Koros et al., 2015; Villeneuve et al., 2019; Heap et al., 2021b; Villeneuve and Heap, 2021; Darmawan et al., 2022; Kanakiya et al., 2022; Heap et al., 2022b; Mordensky et al., 2022) or the competence of altered rock foundations for construction (Rigopoulos et al., 2010; Frolova et al., 2014). Furthermore, new data can be considered to develop more accurate models on volcanic hazard (Heap et al., 2019; Kennedy et al., 2020), and complete pre-existing petrophysical global and regional databases (Bär et al., 2016; Bär et al., 2020; Weydt et al., 2021; Scott et al., 2022; Scott et al., 2023).

This review aims at establishing trends on how physical and mechanical properties vary with the degree and type of hydrothermal alteration, completing the available reviews on unaltered volcanic rocks (Heap and Violay, 2021; Lavallée and Kendrick, 2021). The available data provided by several authors and regarding different volcanoes and geothermal fields worldwide was compiled in a dataset. The obtained average values of density (ρ), porosity (n), permeability (k), P-wave velocity (V_p), S-wave velocity (V_s), unconfined compressive strength (UCS or σ_{c_UCS}), indirect tensile strength (ITS or σ_t), Young's modulus (E_d and E_s), Poisson's ratio (ν_d and ν_s), cohesion (c) and angle of internal friction (ϕ) show that both external and inherent conditions of the host rock dictate the development of hydrothermal alteration, contributing to a complex phenomenon.

7.2. Data compilation from the literature

7.2.1. Search strategy and data compilation

The following keywords were used in online search engines (Google Scholar, Elicit, Web of Science, and ResearchGate) to collect the literature: “volcanic rocks”, “mechanical properties”, “physical properties”, “rock mechanics”, “rock deformation”, “hydrothermal alteration”. 32 research papers written in English and covering the last 15 years was selected for the data set (Franzson and Tulinius, 1999; Ladygin et al., 2000; Nasimov et al., 2005; Pola et al., 2012, 2014; Frolova et al., 2014; Mayer et al., 2015; Heap et al., 2015b; Siratovich et al., 2014; Wyering et al., 2014; Mayer et al., 2016; Siratovich et al., 2016; Cant et al., 2018; Mordensky et al., 2018, 2019; Navelot et al., 2018; Durán et al., 2019; Farquharson et al., 2019; Heap et al., 2019, 2021b, 2020c, 2022b; Gibert et al., 2020; Kennedy et al., 2020; Nono et al., 2020; Kanakiya et al., 2021; Weydt et al., 2022; Scott et al., 2022; Kanakiya et al., 2022; Darmawan et al., 2022; Schaefer et al., 2023; Scott et al., 2023), covering the hydrothermal systems depicted in Fig. 7.1. The main physical and mechanical data on hydrothermally altered rocks comes from volcanic settings, which do not necessarily host geothermal systems.

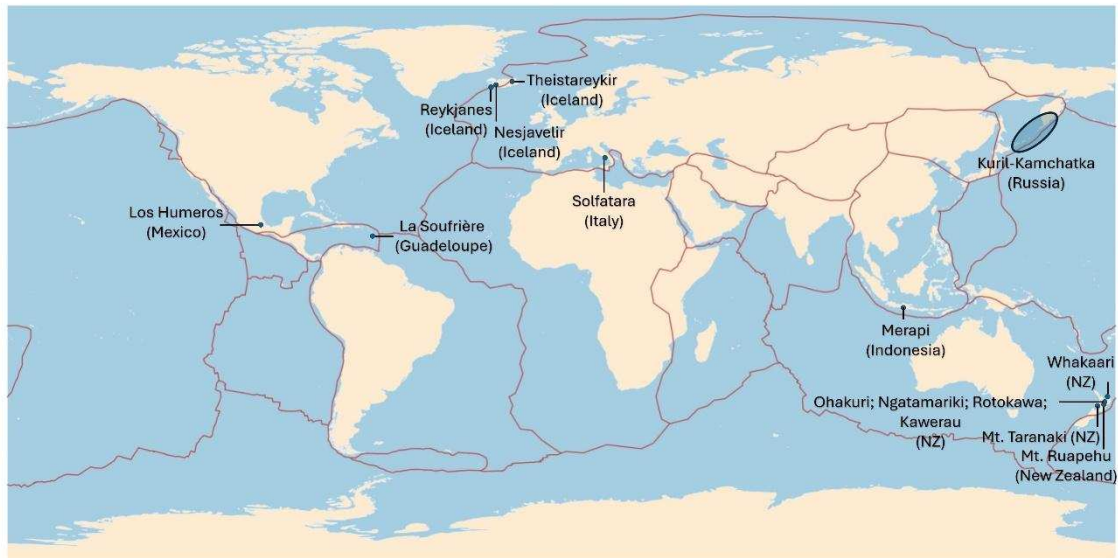


Fig. 7.1. World map, including the lithospheric plate boundaries in red; from Esri GIS Education, last updated in 2023, with the location of the materials covered by the dataset. The studied lithologies are present in geothermal regions (Kuril-Kamchatka; Los Humeros; Ngatamariki, Rotokawa, Kawerau, Ohakuri; Solfatara) and hydrothermal systems associated with volcanic environments (La Soufrière, Merapi, Mt. Ruapehu, Mt. Taranaki, and Whakaari volcanoes). Reproduced from Pereira et al. (2024a). Licensed under CC BY 4.0.

Properties are summarised as minimum (min), maximum (max), and average (avg) values. The data compilation is organised according to location, host rocks, secondary mineralisation, hydrothermal alteration facies, fluid pH, and degree of alteration (see Pereira et al., 2024a for Table S1 of the Supplementary Data and Appendix 7.1). The host rocks correspond to volcanic rocks, comprising lavas and pyroclastic materials, and other lithologies found in the hydrothermal systems of Fig. 7.1, such as intrusive rocks, marbles, skarns, and sedimentary rocks. Notably, data in the literature is not uniform, and not all the information is always provided. For example, some authors opted to present the rock types as groups (e.g., tuffs and tuffites) and others individually. Others only refer to pyroclastic rocks and lavas not specifying their nature (e.g., andesites, trachytes, etc). In this work, they are named as “lava (not specified)” and “pyroclastics”. The type of alteration was uniformised considering the main hydrothermal assemblages (e.g., “alunitic + silicic”), and the degree of alteration followed the classification of Gifkins et al. (2005), spanning from unaltered to fully altered. Despite some uniformisation, the compiled data was kept as close as possible to the original source.

7.2.2. Critical analysis organisation

Before establishing the results based on compiled data, this study presents the thermal stabilities and the Mohs’ hardness of several hydrothermal minerals that compose the alteration facies collected from the literature (Appendix 7.1). The main goal of this section is to complete the theoretical groundwork set in Chapter 2.1.4 (Part B) to better comprehend the results of the compiled literature.

Due to the multifaceted character of hydrothermal alteration, the compiled data are presented according to the degree and type of alteration. In the Results section, the main range of values for each property is first established. Then, correlations between several properties of altered rocks are addressed to verify whether the trends from fresh rocks (Fig. 2.12 and Fig. 2.17) are maintained.

Hydrothermal alteration is presented by the type of alteration. However, it is challenging to assess the influence of alteration solely based on its type, without considering the changes across different lithologies. As Wyering et al. (2014) noted, rocks from the same lithology can have distinct properties because of varying hydrothermal alteration. Andesites from different hydrothermal systems are an example, showing similar strength when altered by the same type of process, while those from the same system but belonging to a different

facies have pronounced strength differences. Thus, the degree of alteration is established for each rock type to assess this intricate effect better.

In each section, results are presented by rock type into two main groups: dense rocks, including lavas and intrusive rocks, and fragmental rocks, such as porous clastic deposits, following the approach of Stimac et al. (2015).

Results are discussed based on a summary compiled from the data, establishing the main controls on the changes in physical and mechanical properties resulting from hydrothermal alteration.

7.3. Thermal stability, hardness, and specific gravity of the main hydrothermal minerals

Hydrothermal alteration modifies the rock's microstructure, mechanical and physical properties, and its failure mode, depending on (Kolawole et al., 2021; Heap et al., 2022b):

1. whether the alteration leads to an increase or decrease in rock porosity, which depends on the interplay between mineral dissolution and precipitation.
2. whether secondary minerals are characterised by lower or higher values of physical and mechanical properties (e.g., strength/hardness) compared to the primary mineral assemblage.

Regarding the host rocks, it is generally assumed that high porosity and permeability, presence of fractures, weak cementation, high volcanic glass content and mafic composition favour alteration (Browne, 1984; Cathelineau et al., 1985; Lagat, 2009; Franzson et al., 2010; Frolova et al., 2010).

Pereira et al. (2024a) provides an update of the diagram from Henley and Ellis (1983) (Fig. 7.2), by relating thermal stabilities, hardness, and specific gravity of the several hydrothermal minerals (Deer et al., 2013), as these features can help to predict the strength and stiffness changes in the host rocks due to alteration. For instance, secondary soft minerals (hardness < 4; Brzovic and Villaescusa, 2007) in veins or replacing the groundmass are often assumed to reduce the rock's strength (Shang et al., 2016; Turichsev and Hadjigeorgiou, 2017). However, hardness is not the equivalent of strength, which also

depends on the heterogeneity of the mineral structure (cleavage, microcracks, inclusions - Kovaleva, 1974).

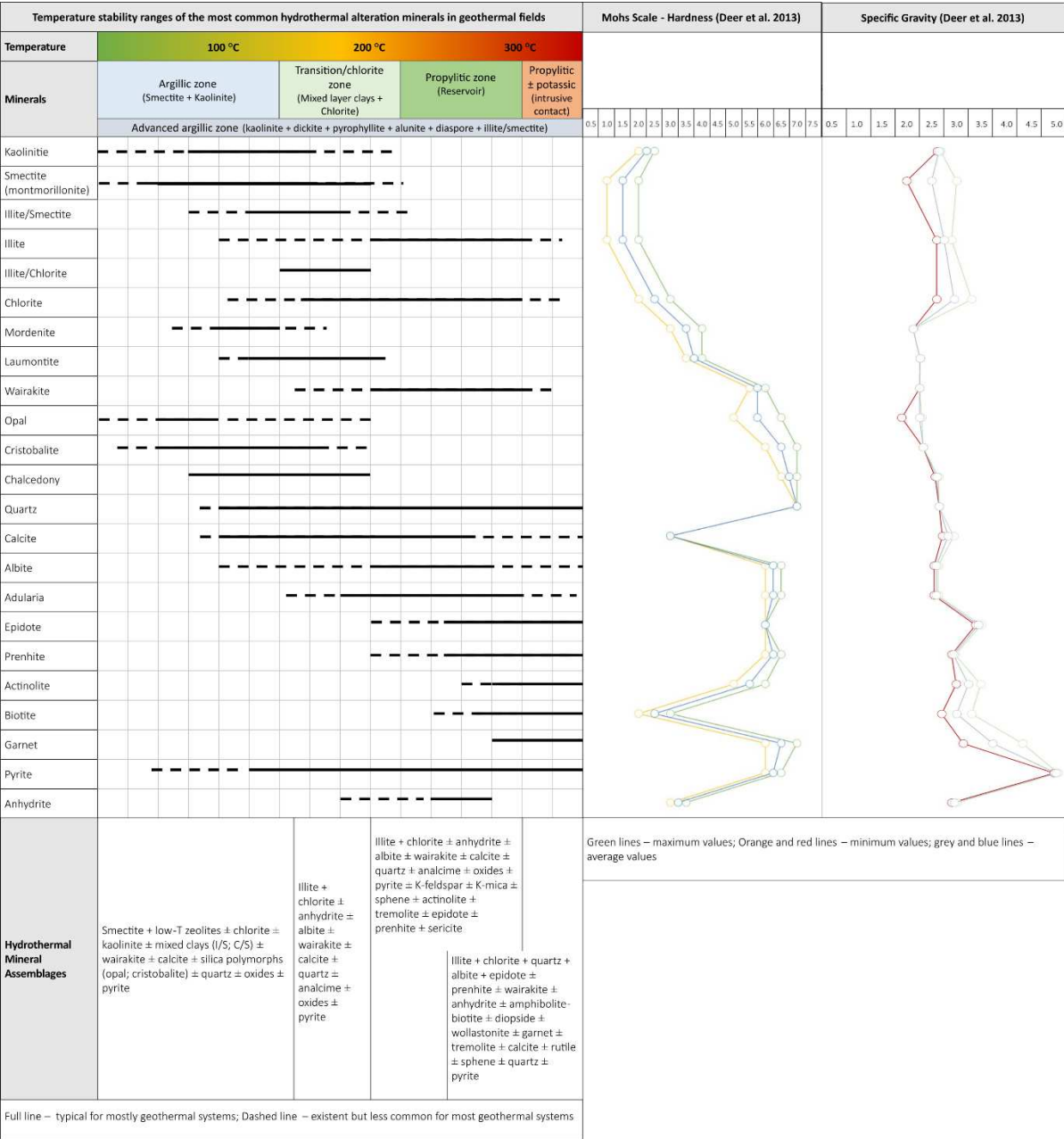


Fig. 7.2. Diagram with thermal stability, hardness (Mohs scale), and specific gravity of several hydrothermal minerals, also including the main hydrothermal mineral assemblages. Figure reproduced from Pereira et al. (2024a) (see references therein). Licensed under CC BY 4.0.

Fig. 7.2 shows that hardness varies more among minerals than specific gravity, which has its peaks for sulfide and oxide minerals. Furthermore, there is no relation between specific gravity and temperature, as denser minerals can exist at higher and lower temperatures and vice versa.

Regarding the typical facies that develop in intrusion-related geothermal systems (Fig. 2.8), it is generally considered that high-temperature propylitic and advanced silicic facies contribute to the strengthening, porosity and permeability reduction, by forming hard minerals, such as quartz, garnet, and epidote (Frolova et al., 2010, 2011; Nasimov et al., 2005; Frolova et al., 2014; in Pereira et al., 2024a; Fig. 7.2). Calcite and biotite, with a hardness of 3 and 2–3, respectively, are an exception among hard propylitic minerals, because of their mineral structure.

Advanced silicification minerals evolve through the following sequence with increasing temperature (Stimac et al., 2015): kaolinite (< 140 °C; 2–2.5 hardness), dickite ± kaolinite (~120–200 °C), dickite ± pyrophyllite (~200–260 °C), and pyrophyllite ± illite (~220–320 °C). Alunite and pyrite can be present along all these hydrothermal subzones, while diasporite and anhydrite are typical of higher temperatures (> 120 °C). High-temperature minerals likely contribute to the host rock's strengthening.

Clay minerals and zeolites are present at lower temperatures in the argillic/ zeolitic facies, deriving from the final stages of hydrothermal alteration (Frolova et al., 2014). These minerals are often regarded as weakening features due to their low hardness (e.g., Heap et al., 2012; Frolova et al., 2014).

Kaolinite (2–2.5 hardness) and smectites (1–2 hardness) result from the alteration of silicates under slightly acidic to sub-neutral pH conditions (e.g., Frolova et al., 2010, 2011; 2014; Fulignati, 2020), being part of the argillic facies. Kaolinite can also be formed in more acidic conditions (Pirjano, 2009; Table 2.1), and smectites swell in the presence of water or by thermal effects (e.g., Ladygin et al., 2000; del Potro and Hürlimann, 2009; Frolova et al., 2014; Nicolas et al., 2020; Heap et al., 2021b; Kanakiya et al., 2022).

Clays often evolve continuously or discontinuously with temperature into interlayered structures, also depending on the fluid flow (Utami and Browne, 1991). The mixed-layer chlorite/smectite is typical of the argillic and phyllic alteration facies (Fulignati, 2020), while mixed-layer illite/smectite marks the transition to phyllic/propylitic alteration facies, occurring from 120 to 240 °C (Fig. 7.2). These are typical of porous and weak horizons in hydrothermal systems (Ladygin et al., 2000).

Increasing temperature above 200/220 °C into the transition of the argillic-propylitic and propylitic facies, promotes the formation of illite (1–2 hardness) and chlorite (2–3 hardness), which are soft clay minerals that can swell in the presence of water and depending on the

temperature (Marini, 2000). Alongside zeolites, clays may explain rock weakening, particularly under saturation conditions (Heap et al., 2012; Heap et al., 2018b).

In the zeolitic facies, Si-rich zeolites (mordenite, clinoptilolite, and heulandite) have a hardness in the range of 3 and 4 and are found for $T < 150/200$ °C. Wairakite, is a high-temperature Ca-zeolite, with a hardness ranging from 5.5 to 6. Wairakite, together with quartz and adularia, are reported in boiling zones. Since all these minerals are hard (Fig. 7.2), they are considered as enhancers of the host rock strength (Pereira et al., 2024a).

Silica minerals vary their structure with temperature, with opal and cristobalite (5–7 hardness) transforming into chalcedony and quartz (6–7 hardness) with increasing temperatures and pressures (Keith et al., 1978; Keith and Muffler, 1978). However, quartz has a wide thermal stability and is ubiquitous in many geothermal fields (Pereira et al., 2024a and references therein), with silicification contributing to the overall strength and stiffness of the host rocks (e.g., Frolova et al., 2014; Mayer et al., 2016).

Secondary albite and adularia, which have a hardness from 6 to 6.5, coexist at $T > 140$ °C. While they have been found to weaken significantly saturated sandstones (Baud et al., 2000), they are hard minerals that may constitute vein networks.

Silicate minerals including epidote, prehnite, actinolite, garnet, and biotite, characterise high-temperature propylitic facies ($T > 250$ °C). These minerals are hard except for phyllosilicates like biotite.

Temperature and mineral hardness appear to be correlated (Fig. 7.2), despite other acting factors influencing their formation. Overall, despite some exceptions, hard minerals are typical of higher temperatures. These minerals are assumed to strengthen the rock, depending on their mineral structure and how they occur as hydrothermal minerals. For example, they may be fillings in voids decreasing permeability and porosity or constitute mineralised veins that contribute to the overall rock strength (Gudmundsson, 2011). Alternatively, they can also replace the primary minerals, mostly affecting the matrix (Lagat, 2009).

7.4. Results and discussion

7.4.1. General results per property

A summary of the range value of each property is presented in Table 7.1. The data is based on the dataset and was obtained by Pereira et al. (2024a).

Table 7.1. Value range of the properties - density (ρ), porosity (n), permeability (k), P-wave velocity (V_p), S-wave velocity (V_s), unconfined compressive strength (UCS or $\sigma_{c,UCS}$), indirect tensile strength (ITS or σ_t), Young's modulus (E_d and E_s), Poisson's ratio (ν_d and ν_s), cohesion (c) and angle of internal friction (ϕ) – compiled by Pereira et al., (2024a). Min – minimum; Max – maximum.

Property	Range	Rock Type / Context	Source
ρ (g/cm ³)	0.62-3.05	Min: unaltered pyroclastic rocks (La Soufrière, Guadeloupe) Max: propylitic intrusive rock (Reykjanes)	Navelot et al., 2018; Gibert et al., 2020
n (%)	0.3-76	Min: propylitic intrusive rock (Reykjanes) Max: vesicular lava, fresh to slightly altered (Whakaari)	Gibert et al., 2020; Kanakiya et al., 2021
k (m ²)	1×10^{-19} - 1×10^{-11}	Min: slightly/moderately argillic andesite (La Soufrière) Max: unaltered pyroclastic rock (La Soufrière)	Navelot et al., 2018
V_p (km/s)	0.50-6.23	Min: highly argillic andesite (La Soufrière) Max: fresh andesitic lava (La Soufrière)	Navelot et al., 2018
V_s (km/s)	0.82-6.69	Min: argillic rhyolitic ignimbrite (Ngatamariki/Rotokawa/Kawerau) Max: propylitic intrusive (Reykjanes)	Wyering et al., 2014; Gibert et al., 2020
UCS (MPa)	1-328	Min: unaltered tuff/tuffite (Kuril-Kamchatka) Max: propylitic tuff/tuffite (Kuril-Kamchatka)	Frolova et al., 2014
ITS (MPa)	0.2-25	Min: unaltered tuff/tuffite (Kuril-Kamchatka) Max: unaltered lava (Kuril-Kamchatka)	Frolova et al., 2014
E_d (GPa)	2-74	Min: argillic rhyolitic ignimbrite (Ngatamariki/Rotokawa/Kawerau) Max: propylitic tuff/tuffite (Kuril-Kamchatka)	Wyering et al., 2014; Frolova et al., 2014
E_s (GPa)	1-44	Min: rhyolitic pyroclastic rocks (Ohakuri) Max: unaltered andesitic lava (Mt. Ruapehu)	Heap et al., 2020c; Schaefer et al., 2023
ν_d	0.12-0.38	Min: slightly argillic intrusive rocks (Ngatamariki) Max: argillic rhyolitic ignimbrite (Ngatamariki/Rotokawa/Kawerau)	Cant et al., 2018; Wyering et al., 2014
ν_s	0.09-0.34	Min/Max: Andesitic lavas/breccias (Rotokawa)	Siratovich et al., 2016
c (MPa)	0.5-52	Min: unaltered tuff/tuffite (Kuril-Kamchatka) Max: unaltered andesitic lava (Mt. Ruapehu)	Frolova et al., 2020; Schaefer et al., 2023
ϕ (°)	35-57	Min: unaltered tuff/tuffite (Kuril-Kamchatka) Max: unaltered andesitic lava (Mt. Ruapehu)	Frolova et al., 2020; Schaefer et al., 2023

The geological setting has a limited effect on the variability of the measured parameters, as both the highest and lowest values are found in volcanic regions with and without

geothermal activity. In contrast, primary lithology, along with the type and degree of alteration, plays a more significant role. However, assessing the specific influence of hydrothermal alteration remains challenging and requires a more comprehensive evaluation.

7.4.2. Bivariate correlations for hydrothermally altered rocks

Fig. 7.3 illustrates the correlations between physical and mechanical properties in altered rocks. The correlations for unaltered rocks are established in Figs. 2.12 (Section 2.1.4., Part C) and 2.17 (Section 2.2.6, Part C). For altered rocks, the data are more scattered because of the varying influence of hydrothermal alteration, either in degree or type. The regression performance, assessed by R^2 , ranges from weak (< 0.50) to strong (> 0.80).

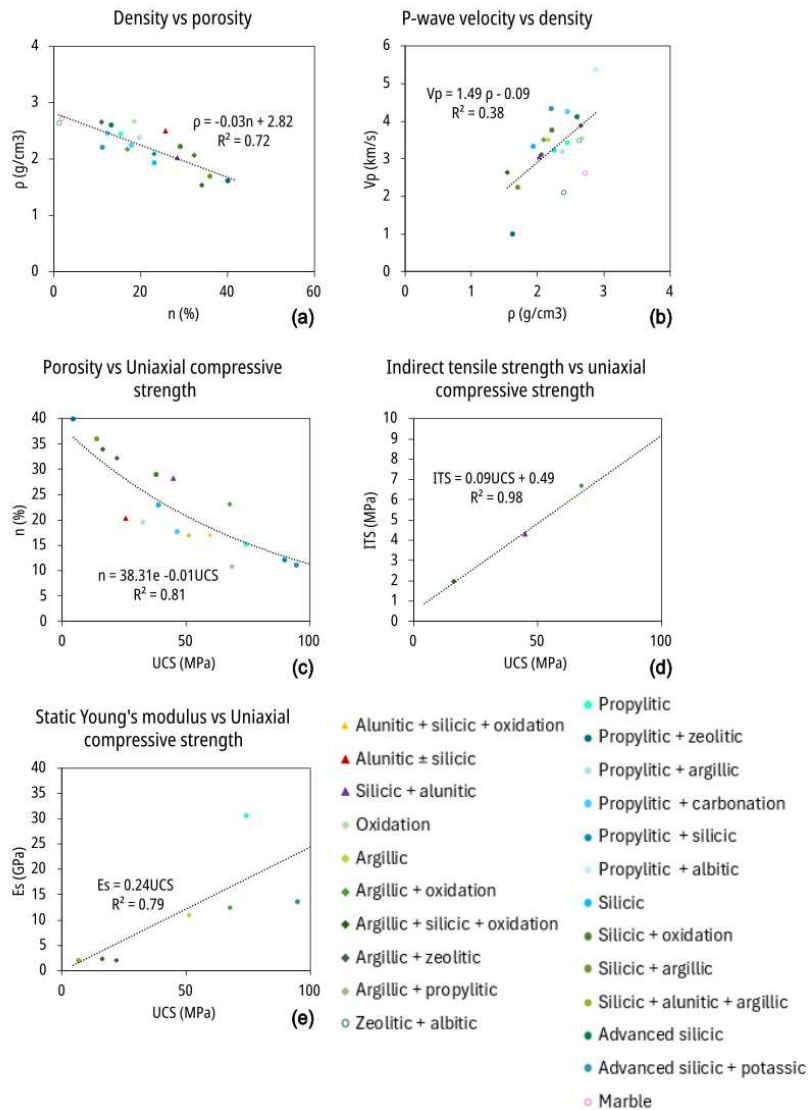


Fig. 7.3. Correlation between several physical and mechanical properties for different types of altered rocks. Figure reproduced from Pereira et al. (2024a). Licensed under CC-BY 4.0.

Despite the scattering, some trends between variables remain similar to unaltered rocks. For instance, n and ρ maintain their negative linear correlation, while V_p varies linearly and positively with ρ . The nonlinear relationship between n and UCS (or $\sigma_{c, UCS}$) is also preserved for altered rocks, albeit with a lower R^2 (0.81) compared to fresh rocks. Linear correlations between UCS and ITS (or σ_t), as well as between UCS and E_s , persist after alteration.

Wyering et al. (2014) noted that some relationships, such as n versus ρ and UCS versus E , remain stable regardless of hydrothermal alteration, which this review corroborates. Siratovich et al. (2014) and Weydt et al. (2022) argue that these properties are largely independent of alteration. The compiled data support the idea that variability across hydrothermal subfacies often erases clear trends, leading to weaker correlations compared to those of unaltered rocks. Additionally, the overlapping of the main hydrothermal facies (alunitic, argillic, and propylitic) makes it difficult to distinguish them.

7.4.3. Physical and mechanical properties of altered rocks

The main alteration types are depicted in Fig. 7.4, reproduced from Pereira et al. (2024a). The primary alteration facies of the dataset are divided into alunitic, argillic, propylitic, and silicic. Then, the subfacies are referred to after the “+” (e.g., argillic + oxidation). Fig. 7.4 indicates that the dataset is mostly influenced by the propylitic and argillic facies, with alunitic ± silicic facies also being well represented.

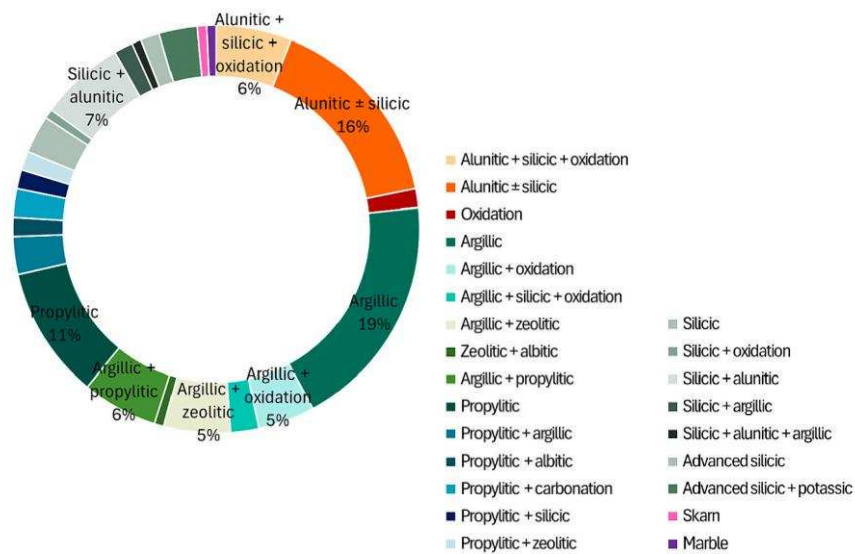


Fig. 7.4. Hydrothermal alteration facies and subfacies for the compiled dataset (see references in Pereira et al., 2024a). Figure reproduced from Pereira et al. (2024a). Licensed under CC-BY 4.0.

The influence of these facies and subfacies in the physical and mechanical properties is depicted in Fig. 7.5. The dashed polygons in Fig. 7.5 delineate the main facies (alunitic, argillic, propylitic, and silicic). The degree of hydrothermal alteration per rock type is presented for each main type of hydrothermal alteration, following Pereira et al. (2024a) approach and results.

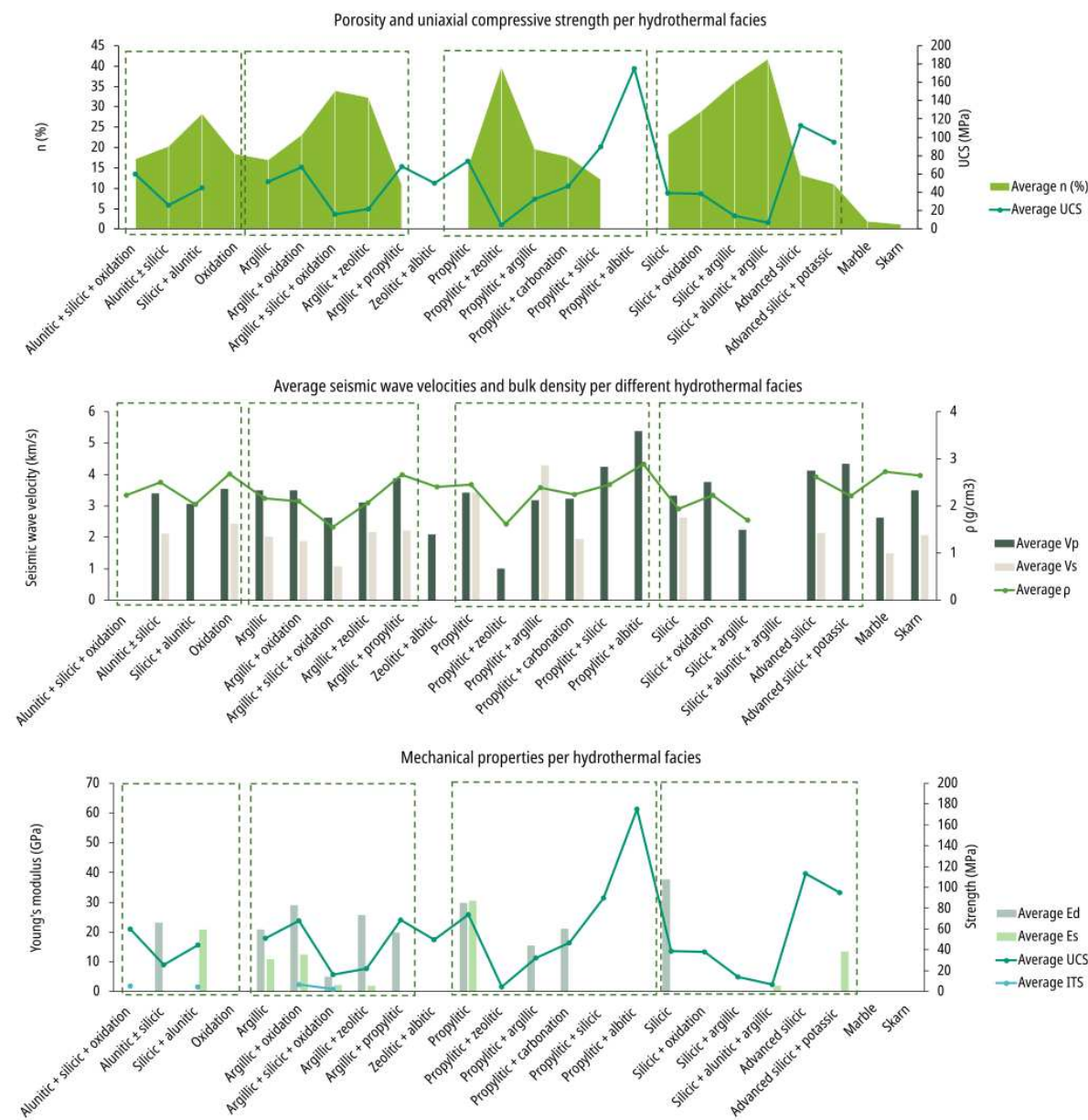


Fig. 7.5. Effect of hydrothermal alteration facies on physical and mechanical properties based on the compiled data (Appendix 7.1; Pereira et al., 2024a, see references therein). Figure reproduced from Pereira et al. (2024a). Licensed under CC-BY 4.0.

7.4.3.1. Alunitic alteration and oxidation

As explained in Chapter 2.1.4 (Part B) and in Table 2.1, the alunitic facies commonly develops under acidic conditions, typically associating with the formation of alunite, kaolinite, quartz, and oxides.

Fig. 7.5 shows that alunitic rocks have n between 17 % and 28 %, ρ between 2.03 and 2.50 g/cm³, V_p between 3.05 and 3.40 km/s, UCS between 26 and 60 MPa, and ITS between 4 and 5 MPa. n increase, and ρ , V_p , and UCS decrease within “silicic + alunitic” type, which include several rock types with varying degrees of alteration.

Oxidation (Fig. 7.5; Pereira et al., 2024a) leads to higher ρ (2.7 g/cm³) and ultrasonic wave velocities (V_p = 3.53 km/s and V_s = 2.43 km/s) than alunitic facies, despite the high porosity of the rocks (18 %). In oxidation, dense oxides and hydroxides tend to fill the rocks’ voids or replace the matrix (Abdel-Aal, 1978). Callahan et al. (2019) observed that the genesis of hematite, associating with chlorite and calcite, weakens a rock compared to its fresh counterpart.

Fig. 7.6 includes the effect of degree and rock type within alunitic alteration. In general, lavas show a 1.5- to 8-fold increase in porosity and a weakening factor of approximately 5.2 with progressive alunitic alteration. Breccias may exhibit up to a 9-fold increase in porosity, while tuffs show lower changes, with increases of about 1.3 times. Unlike lavas, modifications in the physical and mechanical properties of fragmental rocks are influenced by the dominant alteration process, whether dissolution or precipitation, during hydrothermal alteration (Mielke et al., 2015; Mordensky et al., 2018; Kanakiya et al., 2021; Weydt et al., 2022). Overall, lava rocks maintain higher stiffness and strength than fragmental rocks, regardless of the degree of alunitic alteration. However, this trend may not hold across all physical properties.

Data from slightly altered dense rocks (andesites and not specified lavas – Fig. 7.6) by alunitic alteration show that n (2–18 %) and k increases, with k reaching approximately 4 E-12 m². Both ρ (2.5–2.7 g/cm³) and ultrasonic wave velocities (V_p = 3.95–5.20 km/s; V_s = 2.21–3.09 km/s) decrease relative to their unaltered homologous (Fig. 2.11).

Alunitic andesites from Merapi Volcano (Heap et al., 2019) exhibit lower permeability, which decreases by up to four orders of magnitude, compared to the expected permeability based on porosity alone, which remained stable. The mineralised filling of throats connecting

pores reduced permeability, making a minimal contribution to total porosity (Heap et al., 2019).

In terms of mechanical properties, UCS of alunitic andesites declines to 94 MPa, whereas E either remains stable or increases ($E_d = 28\text{--}61\text{ GPa}$) compared to unaltered rocks. With advanced alunitic alteration, dense rocks typically display greater porosity and permeability, accompanied by reductions in density, wave velocity, mechanical strength, and stiffness. For instance, highly to fully alunitic lavas (andesitic or unspecified) show n varying from 16 to 24 %, k from $3\text{ E-}16$ to $4\text{ E-}12\text{ m}^2$, ρ of $2.08\text{--}2.47\text{ g/cm}^3$, V_p of 3.09 to 4.03 km/s , UCS values from 19 to 47 MPa, and E values from 16 to 28 GPa (Fig. 7.6).

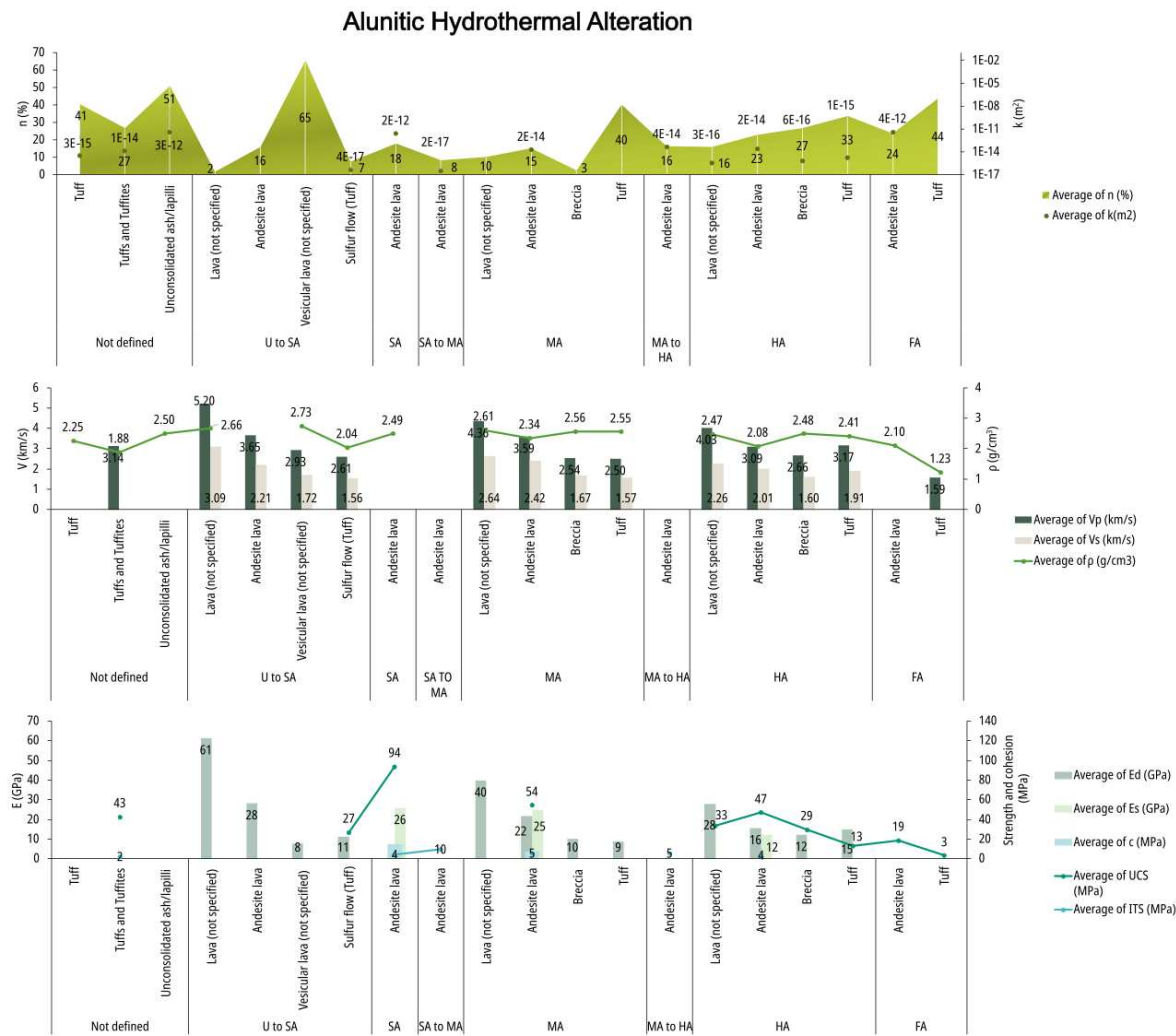


Fig. 7.6. Alunitic hydrothermal alteration influence on the physical and mechanical properties for different rock types with different degrees of alteration. U – unaltered; SA – slightly altered; MA – moderately altered; HA – highly altered; FA – fully altered). Figure reproduced from Pereira et al. (2024a; see references therein) and based on the compiled data (Appendix 7.1). Licensed under CC-BY-4.0.

Textural effects are evident at lower degrees of alteration and for vesicular rock materials. Slightly altered vesicular lavas, for example, present higher porosity (up to 65 %), lower wave velocities ($V_p = 2.93$ km/s; $V_s = 1.72$ km/s), and reduced stiffness (8 GPa) compared to their massive lava equivalents. This remains true for fragmental rocks, where unconsolidated pyroclasts display greater n (51 %) and k ($3E-12$ m²) than lithified pyroclastic rocks (Fig. 7.6; Pereira et al., 2024a). Compared to slightly alunitic massive lavas, tuffs within the same facies and exposed to sulfur are less permeable ($4E-17$ m²) and porous (7 %), despite also displaying reduced density (2.4 g/cm³), ultrasonic velocities ($V_p = 2.61$ km/s; $V_s = 1.56$ km/s), UCS (27 MPa), and E (11 GPa).

Breccias, observed at both moderate and high alteration levels, show variable trends. Moderately altered breccias demonstrate low n (3 %) because of mineral precipitation within their naturally fractured matrix. With increased alteration, n rises to 27 %, possibly due to dissolution, while density decreases. Despite these changes, E remains relatively constant across varying degrees of alteration.

Tuffs, when moderately altered to alunite, share comparable ρ and V_p with breccias but have markedly higher n (40 %). With more advanced alteration, n declines to 33 %, likely due to secondary mineral infilling. Strength is significantly low, with UCS values dropping to 13 MPa in highly altered tuffs and reaching as low as 3 MPa under complete alteration. Tuffs with unspecified degrees of alunitic alteration show similar physical behaviour to those moderately altered.

The slightly oxidised andesites and ignimbrites included in the dataset were compiled from Weydt et al. (2022). Ignimbrites are more porous (33 %) and have lower V_p (2.93 km/s) compared to oxidised andesites ($n = 4$ %; $V_p = 4.14$ km/s). When compared to their unaltered counterparts and the fresh group of ignimbrites and tuffs (Fig. 2.11), both lithologies become less porous, with oxidised andesites exhibiting the lowest value of n (4 %) and the highest ρ (2.7 g/cm³). Although oxidised ignimbrites have the highest n among the reviewed alteration types, they also maintain a relatively high ρ (2.6 g/cm³).

7.4.3.2. Argillic alteration

Fig. 7.5 also shows that argillic alteration impact on the rock's properties depend on the subfacies it associates with. Rocks in argillic facies have a n from 11 % to 34 %, ρ from 1.5 to 2.7 g/cm³, V_p from 2.62 to 3.87 km/s, UCS from 16 to 69 MPa, ITS from 2 to 7 MPa, and elastic properties from 5 to 29 GPa (E_d) and 2 to 12 GPa (E_s) (Pereira et al., 2024a).

When oxidation accompanies clay alteration (i.e., "argillic + oxidation" facies), there is an increase in UCS, E , and n relative to rocks altered by clay minerals alone. At the same time, ultrasonic velocities and ρ remain unchanged. More pronounced alteration occurs when silica minerals ("argillic + silicic + oxidation" subfacies) or zeolites ("argillic + zeolitic" subfacies) are present alongside argillic alteration. These combinations yield the lowest UCS (16–22 MPa) and the highest n (32–34 %) among argillic alteration, along with reduced E , ρ and wave velocities. In contrast, transitioning to the propylitic facies results in increased strength, ρ , and V_p , as well as reduced n , compared to rocks altered only by clay minerals.

The effects of the degree of alteration per rock type are present in Fig. 7.7 and explained in Pereira et al. (2024a). Regardless of the degree of alteration, dense lavas maintain their high strength and stiffness in comparison to argillic fragmental rocks.

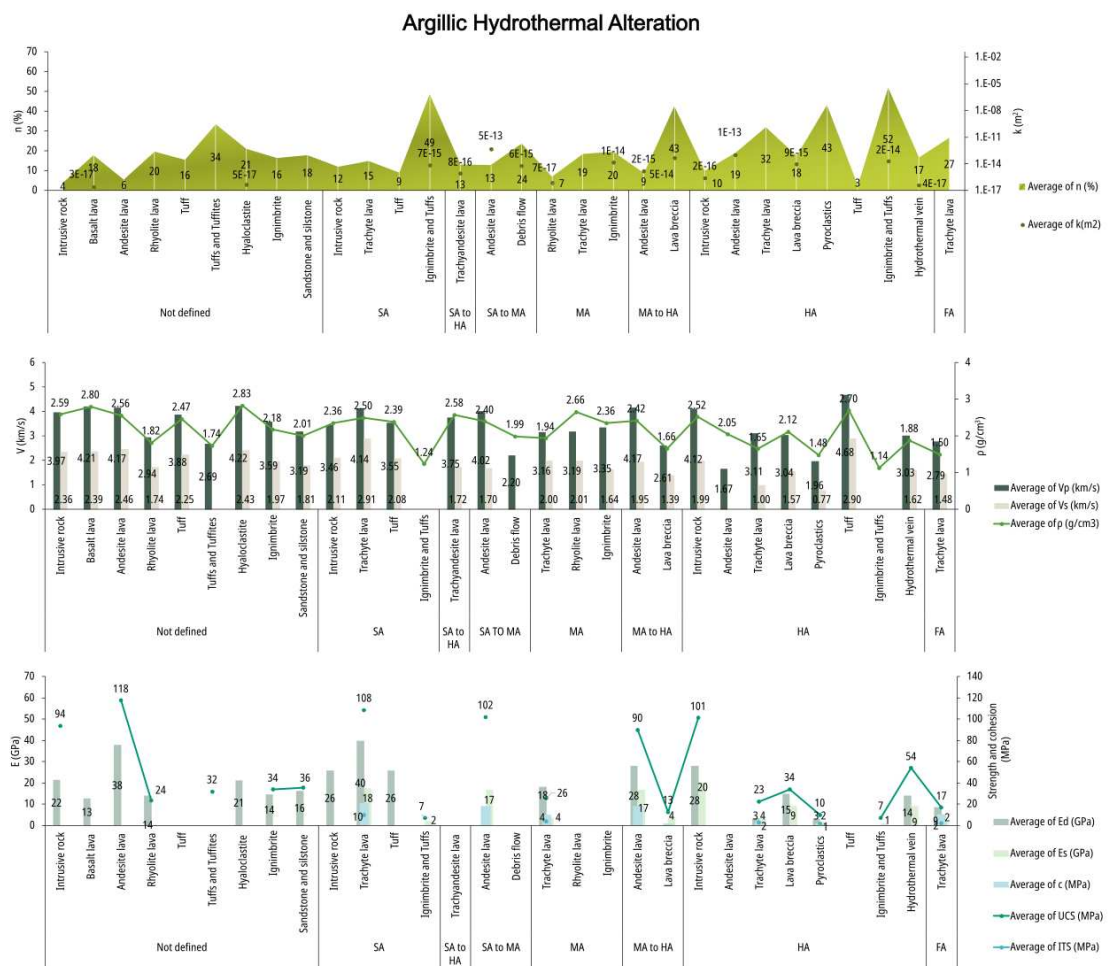


Fig. 7.7. Argillic hydrothermal alteration influence on the physical and mechanical properties for different rock types with different degrees of alteration. U – unaltered; SA – slightly altered; MA – moderately altered; HA – highly altered; FA – fully altered). Figure reproduced from Pereira et al. (2024a; see references therein) and based on the compiled data (Appendix 7.1). Licensed under CC-BY-4.0.

For dense intrusive rocks, slight argillic alteration results in minor increases in n (12 %) and k ($\sim 2\text{E-}16\text{ m}^2$), along with reductions in ρ (2.4 g/cm^3), V_p (3.46 km/s), and competence (UCS = 101 MPa ; $E_d = 26\text{ GPa}$). However, slightly altered intrusive rocks are weaker than highly altered one (Fig. 7.7) which suggests limited susceptibility to alteration.

From slight to high alteration, the n and k of andesites increase (up to 19 % and $1\text{E-}13\text{ m}^2$), while ρ (2.1 g/cm^3) and V_p (1.67 km/s) decrease progressively. Strength and cohesion also decrease, with UCS dropping to 90 MPa in moderately to highly altered cases. Regardless, the weakening effect was more prevalent in alunitic facies than in argillic facies for andesite lavas. Trachytes demonstrate a similar but more pronounced change than andesites concerning their unaltered terms. Increasing alteration (high to fully altered) results in higher n (32 %), lower ρ (1.7 g/cm^3), and reduced UCS (17 MPa), stiffness ($E_d = 3\text{ GPa}$), and c (3 MPa). Higher susceptibility to alteration may be attributed to their feldspar content, trachytic texture, and initially higher porosity (Pereira et al., 2024a).

Conversely, basaltic and rhyolitic lavas, despite the undefined degree of alteration, follow a similar weakening pattern with respect to their unaltered homologous (Fig. 7.7). In argillic basalts, n increases while ρ , E , and ultrasonic velocities decrease. The porosity of argillic basalts further increases by 7 % when transitioning into a propylitic facies and reaches 32 % when associated with zeolites. Argillic rhyolites exhibit the opposite trend of basalts, with a 7 % decrease in porosity compared to the unaltered rock. However, due to undefined alteration degrees, interpretations about the influence of silica content are not possible.

Lava breccias respond nonlinearly to increasing degree of argillic alteration. Moderate alteration increases porosity to 43 % and reduces UCS (13 MPa) regarding unaltered lava breccia (see Sections 2.1.4., 2.2.6, Part C); however, under higher degrees of alteration, n decreases to 18 %, while UCS increases to 34 MPa . This reversal is attributed to microstructural sealing, where secondary minerals or rock fragments infill voids (e.g., Browne, 1978; Farquharson et al., 2015; McNamara et al., 2016; Kendrick et al., 2016; Cant et al., 2018) more effectively than they replace the matrix. This sealing improves c despite the clay-rich alteration, a behaviour also noted in hydrothermal veins with argillic alteration and containing kaolinite, albite and minor smectite (Mordensky et al., 2018). Hydrothermal veins (Fig. 7.7), despite similar n and E , indicate higher UCS (54 MPa) compared to highly altered lava breccias.

Among fragmental lithologies (Fig. 7.7), tuffs show the most significant response to clay alteration. Porosity drops steeply from 54 % (unaltered) to 9 % with slight alteration, and

further to 3 % with advanced alteration. Simultaneously, ρ , V_p , and E_d increase, likely due to secondary mineral precipitation and compaction. Despite initial increases in permeability, further alteration intensity reduce k , suggesting that these altered rocks may develop flow barriers (Kanakiya et al., 2021).

Argillitic ignimbrites and tuffs follow a similar trend (Fig. 7.7). Compared to the unaltered terms, n initially decreases to 49 %, then increases to 52 % under higher alteration degrees, possibly due to microstructural changes. In contrast, pyroclastic rocks maintain n , ρ , V_p , and low competence (UCS = 10 MPa; E_d = 3 GPa; ITS = 1 MPa; c = 2 MPa), despite advanced alteration. Argillic tuffs and tuffites with undefined alteration levels retain the high n (34 %) observed in the unaltered counterparts but become slightly denser (1.7 g/cm³) and stronger (UCS = 32 MPa) with alteration.

In fact, some volcanoclastic units resist alteration and compaction better than others, due to their less-susceptible mineral assemblages (Stimac et al., 2015; Scott et al., 2023). Additionally, Franzson et al. (2010) suggested that the formation of micropores inside clay minerals may preserve overall porosity, even when macropores are sealed.

In hyaloclastites and the ignimbrite–tuff group, zeolitic alteration enhances porosity. However, this effect varies among lithotypes and cannot be generalised across all fragmental rocks. From unaltered to moderately argillic debris flows, n decreases by ~10 %, k is reduced to 6E-15 m², ρ increases (2.0 g/cm³), and V_p decreases to 2.20 km/s, reflecting the same pattern as tuffs.

Sandstones and siltstones (Fig 7.7; from Wyering et al., 2014), transitioning from argillic to propylitic facies, have an average n of 18 %, a V_p of 3.19 km/s, and a ρ of approximately 2.0 g/cm³. These rocks also exhibit moderate mechanical competence (UCS = 43 MPa; E_d = 22 GPa), comparable to other altered volcanoclastic rocks.

7.4.3.3. Propylitic alteration

Fig. 7.5 (and Pereira et al., 2024a) demonstrates that propylitic facies has a variable effect on the physical and mechanical properties of rocks, depending on whether it results in low-temperature propylites (soft minerals) or medium- to high-temperature propylites (hard minerals) due to the combination of different subfacies. UCS is significantly variable, reaching the highest and the lowest average values in the propylitic facies. For instance, a propylitic alteration combined with argillisation results in n = 20 %, while the strength are lower than those of propylitic facies alone (UCS = 74 MPa and highest values of E_d and E_s). A

similar trend becomes more pronounced when zeolites coexist with propylitic alteration, producing the highest n (40 %) and the lowest UCS (5 MPa), V_p , and ρ (1.6 g/cm³) amongst propylitic facies. Fig. 7.5 is in agreement with the literature, as zeolites and clays are considered weakening minerals in rocks (Heap et al., 2012; Frolova et al., 2014; Heap et al., 2018b).

Comparing “argillic + zeolitic” subfacies, which comprise tuffs, tuffites, hyaloclastites, and basalt lavas, with “propylitic + zeolitic” alteration, porosity increases by 10 %, and UCS reduces by 17 MPa. If only tuffs and tuffites are considered, then these fragmental rocks are weaker in the argillic facies than in propylitic alteration. It is stressed that thermally unstable zeolites are common in the matrix of tuffs (Heap et al., 2012), contributing to increased k and reduced ultrasonic wave velocity and E when thermally stressed (Heap et al., 2014c).

Carbonation is usually associated with calcite formation. Calcite, despite not dense nor hard, commonly fills open voids of the rock, explaining the intermediate values of n (18 %) and UCS (47 MPa), ρ (3.2 g/cm³), and V_p (3.23 km/s) of rocks in the “propylitic + carbonation” subfacies (Fig. 7.5). Conversely, albite in the propylitic facies leads to the highest UCS, V_p , and ρ within propylitic facies. On the contrary, for the group “zeolitic + albitic”, where zeolites predominate over albite, the UCS is in the same order of magnitude as argillic rocks. V_p is lower than V_p of argillic rocks, but still higher than rocks in the “propylitic+ zeolitic” group.

Fig. 7.8 (and Pereira et al., 2024a) shows that propylitic andesitic lavas display porosities comparable to their unaltered equivalents, reaching a maximum of 16 % in highly altered samples, slightly below the 19 % observed in highly argillic andesites. Despite a 1.2 times reduction in UCS compared to unaltered andesites, moderately to highly propylitic lavas still record the highest strength values among altered andesitic lithologies (UCS = 125 MPa). Stiffness remains unchanged across the alteration spectrum, maintaining the highest values within the propylitic facies. Compared to argillic equivalents, propylitic basalts are denser (3.0 g/cm³) and less porous (9 %), likely due to harder secondary minerals.

Propylitic intrusive rocks (undefined degree of alteration) retain physical properties similar to their unaltered homologous. They display a slight decrease in n (2 %), higher ρ (3.0g/cm³), and nearly unchanged V_p (4.17 km/s) and k (7E-17 m²). Conversely, E decreases significantly from 39 GPa to 15 GPa.

Dense rocks demonstrate that while physical properties are relatively preserved, mechanical integrity is compromised with increasing degree of alteration.

In the case of fragmental rocks (Fig. 7.8), tuffs within the “propylitic + carbonation” subfacies show increased n (14 %) with reduced ρ (2.3 g/cm³), V_p (3.21 km/s), and E_d (21 GPa) relative to their argillic counterparts. For propylitic tuffs and tuffites (degree not specified), albitic and silicic signatures increase strength, whereas argillic and zeolitic alteration and carbonation reduce it.

Highly altered propylitic debris flows display greater n but lower k than those altered under slightly to moderately argillic conditions. These changes show a predominant influence of intensity over the type of alteration and are related to pore geometry modifications (Navelot et al., 2018). For hyaloclastites (unspecified degree), physical and mechanical properties are broadly similar between the argillic and propylitic facies.

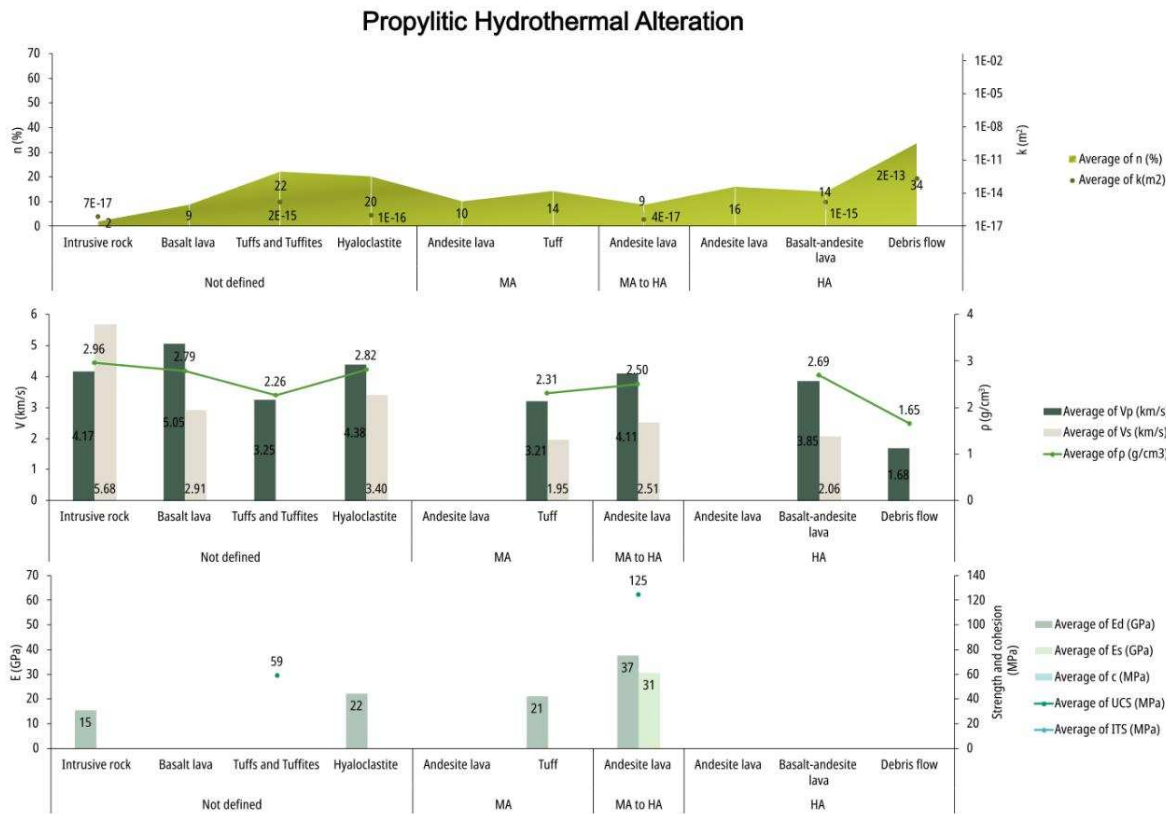


Fig. 7.8. Propylitic hydrothermal alteration influence on the physical and mechanical properties for different rock types with different degrees of alteration. U – unaltered; SA – slightly altered; MA – moderately altered; HA – highly altered; FA – fully altered). Figure reproduced from Pereira et al. (2024a; see references therein) and based on the compiled data (Appendix 7.1). Licensed under CC-BY-4.0.

7.4.3.4. Silicic alteration

According to Fig. 7.5 (and Pereira et al., 2024a), silicification of rocks results, in average: $n = 11\text{--}42\%$, $\rho = 1.7\text{--}2.6\text{ g/cm}^3$, $V_p = 2.24\text{--}4.33\text{ km/s}$, $\text{UCS} = 7\text{--}113\text{ MPa}$, and $E_s = 2\text{--}14\text{ GPa}$. Silicic alteration associates with the highest average value of n (*facies* “silicic+alunitic+argillic”), but intermediate values of ρ , UCS, and V_p in comparison to argillic and propylitic alterations. Moreover, silicic alteration can occur in low temperatures and high temperatures, commonly infilling voids and favouring the development of quartz vein networks. Silicic alteration of high temperature typically associates with crystalline (or recrystallised) quartz and adularia originating the “advanced potassic” facies (Frolova et al., 2014). Fig. 7.5 indicates that both advanced silicic “advanced + potassic” facies increase the strength, stiffness, and V_p , while reducing n to the lowest values among silicic facies.

Silicification occurs in various volcanic settings and affects different rock types (e.g., Browne, 1978; Farquharson et al., 2015; McNamara et al., 2016; Kendrick et al., 2016; Cant et al., 2018; Kennedy et al., 2020). Silicic lavas (Fig. 7.9 and Pereira et al., 2024a) have physical properties ($n = 15\%$; $k = 1\text{E-}15\text{ m}^2$; $\rho = 2.7\text{ g/cm}^3$; $V_p = 3.93\text{ km/s}$) similar to those of fresh lavas. Fully altered andesites in the “silicic + argillic + alunitic” subfacies display higher porosity and lower strength than fully alunitic andesite lavas, sustaining that clays and alunite produce the weakening of rocks when combined with silicification (Fig. 7.5).

Silicified ignimbrite and tuffs ($n = 34\%$; $k = 7\text{E-}16\text{ m}^2$; $\rho = 1.7\text{ g/cm}^3$; $\text{UCS} = 47\text{ MPa}$ – Fig. 7.9) are less porous and permeable, and denser than their unaltered equivalent (Fig. 7.5; Fig. 2.11), probably due to fracture-sealing and pore-filling, as previously suggested (Ladygin et al., 2000; Lutz et al., 2011; Nasimov et al., 2005; Frolova et al., 2014; Weydt et al., 2022). Moreover, according to Heap et al. (2020c) data on rhyolitic ignimbrite and tuffs from Taupo Volcanic Zone show that silicification, despite increasing n and k and reducing ρ , has a more evident effect on strength and stiffness, increasing them compared to the same argillic lithotype.

Highly silicified tuffs show reduced n (4 %) and higher E_d (38 GPa) compared to those altered by advanced alunitic processes. The tuff and tuffite group includes both silicic and advanced silicic alteration types (Frolova et al., 2014). Advanced silicification results in lower n and higher ρ , V_p , and UCS compared to tuffs altered under lower-temperature silicic conditions containing silica polymorphs. Tuffs and tuffites affected by either propylitic with albitic overprint or advanced silicification display UCS values comparable to those of unaltered dense rocks (Fig. 2.16).

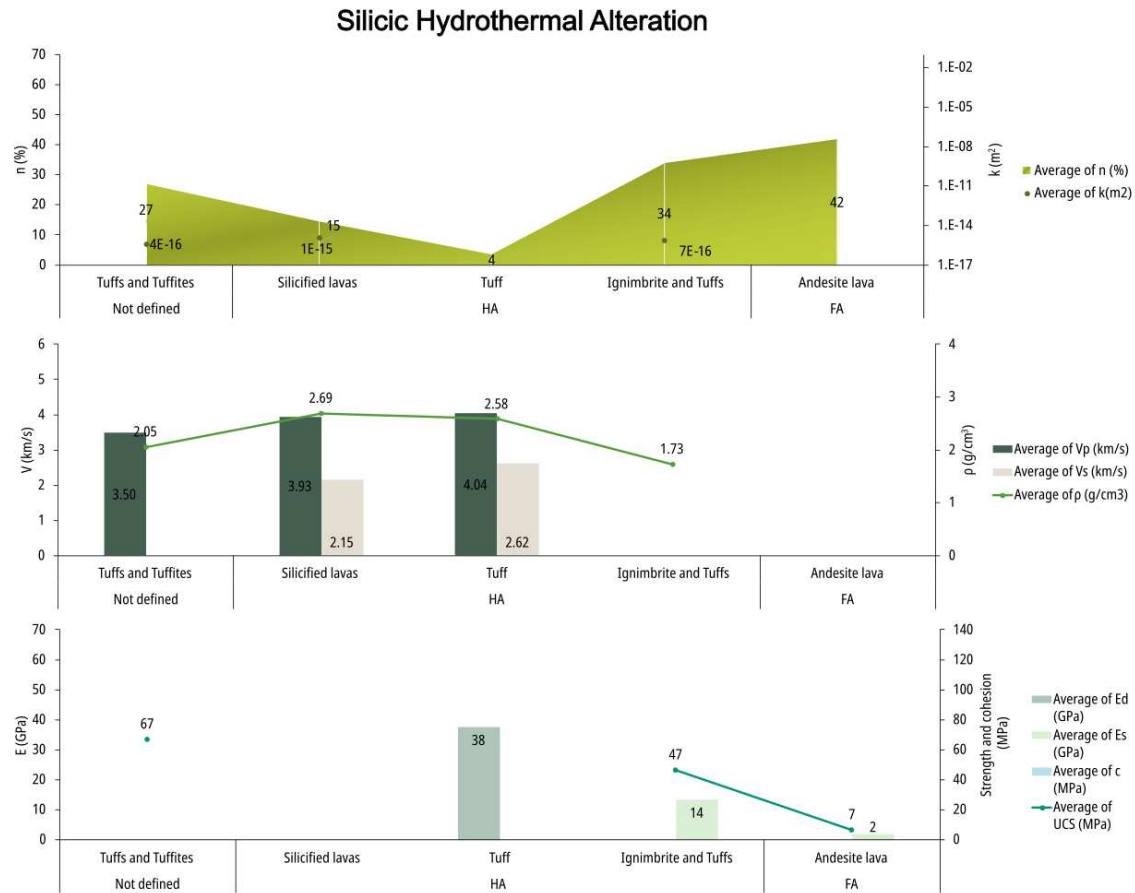


Fig. 7.9. Silicic hydrothermal alteration influence on the physical and mechanical properties for different rock types with different degrees of alteration. U – unaltered; SA – slightly altered; MA – moderately altered; HA – highly altered; FA – fully altered). Figure reproduced from Pereira et al. (2024a; see references therein) and based on the compiled data (Appendix 7.1). Licensed under CC-BY-4.0.

Metamorphic rocks, such as marbles and skarns (Fig. 7.9), studied by Weydt et al. (2022) in the Los Humeros geothermal field, display advanced alteration, with very low n (1–2 %) and intermediate ρ (2.6 g/cm³ for skarn, 2.7 g/cm³ for marble). These findings are consistent with earlier reports of altered metamorphic rocks showing porosity below 2 % and negligible permeability (Lutz et al., 2011).

7.4.4. Overview and discussion

Table 7.2 (from Pereira et al., 2024a) is a matrix that summarises the data differently and according to the effects of *degree of alteration* in the properties (n , ρ , k ; V_p , UCS, E_s) of well-documented *rock groups*. The colours express the lower (red), intermediate (yellow), or higher (green) value. The opposite stands for porosity and permeability, as low-porosity materials (green) are less prone to hydrothermal alteration.

Table 7.2. Matrix of the analysed compiled data, reproduced from Pereira et al. (2024a). U – unaltered; SA - slightly altered; HA - highly altered; FA - fully altered; arg - argillic; prop - propylitic; sil - silicic; adv. sil. - advanced silicic; oxi - oxidation; al – alunitic; zeo – zeolitic; pot – potassic; alb - albitic.

Host rock	Degree (min)	Degree (max)		Type	
Intrusive rock	U	SA	HA	Arg	Prop
n (%)	4	12	10	11	2
ρ (g/cm ³)	2.65	2.36	2.52	2.44	3.03 (prop + arg)
k (m ²)	4E-17		2E-16	2E-16	7E-17
Vp (km/s)	4.77	3.46	4.12	3.79	4.20
UCS (MPa)	170		101	94 (arg + prop)	
E _s (GPa)	39		20	20	
Lava rocks	U	U to SA	HA	Al ± sil	
n (%)	8	2	16	11	
ρ (g/cm ³)	2.69	2.66	2.47	2.58	
k (m ²)	3E-17		3E-16	3 E-16	
Vp (km/s)	4.76	5.20	4.03	4.53	
UCS (MPa)	121		33	33	
Andesite lava	U	HA to FA		Variable	Variable
n (%)	8	12 to 16		42 (sil + al + arg)	4 (oxi)
ρ (g/cm ³)	2.64	2.07		2.23 (al + sil + oxi)	2.71 (oxi)
k (m ²)	6E-15	4E-12		1E-12 (al + sil+ oxi)	4E-17 (prop)
Vp (km/s)	4.10	2.38		3.47 (al + sil)	4.32 (sil + al)
UCS (MPa)	161	13		7 (sil + al + arg)	125 (prop)
E _s (GPa)	30	12		2 (sil +al +arg)	31 (prop)
Trachyte lava	U	HA to FA		Arg + ox + sil	
n (%)	11	32		29	
ρ (g/cm ³)	2.38	1.50		1.58	
Vp (km/s)	4.39	2.79		2.95	
UCS (MPa)	117	17		20	
E _s (GPa)	18	2		3	
Basalt lava	U	-		Arg (± zeo)	Prop + arg
n (%)	10			26	9
ρ (g/cm ³)	2.95			2.78	2.79
k (m ²)				3E-17	
Vp (km/s)	4.31			3.96	5.05
Lava breccia	U	MA	HA	Arg	
n (%)	28	43	18	30	
ρ (g/cm ³)	1.95	1.66	2.12	1.89	
k (m ²)	5E-13	5E-14	9E-15	3E-14	
Vp (km/s)	2.87	2.61	3.04	2.83	
UCS (MPa)	25	13	34	23	
E _s (GPa)	7	4	9	6	

Table 7.2. (continued).

Host rock	Degree (min)	Degree (max)		Type	
Pyroclastics	U	HA		Arg + sil + oxi	
n (%)	38	43		43	
ρ (g/cm ³)	1.53	1.48		1.48	
Vp (km/s)	1.77	1.96		1.96	
k (m ²)	2E-12				
UCS (MPa)		10		10	
E _s (GPa)		2		2	
Breccia	SA	HA		Al $\pm$ sil	
n (%)	3	27		19	
ρ (g/cm ³)	2.56	2.48		2.52	
k (m ²)		6E-16		6E-16	
Vp (km/s)	2.54	2.66		2.60	
UCS (MPa)		29		29	
Ignimbrite + Tuff	U	HA		Arg ($\pm$ zeo)	Adv. sil + pot
n (%)	54	43		52	34
ρ (g/cm ³)	1.03	1.43		1.14	1.73
k (m ²)	2E-13	1E-14		2E-14	7E-16
UCS (MPa)		27		7	47
E _s (GPa)		7		1	14
Tuff $\pm$ Tuffite	U	HA	FA	Prop + zeo	Variable
n (%)	36	18	44	40	12 (adv. sil)
ρ (g/cm ³)	1.56	2.56	1.23	1.60	2.88 (prop + alb)
k (m ²)	2E-15	1E-15		4E-15	5E-16 (prop + arg)
Vp (km/s)	2.04	3.97	1.59	1.00	5.38 (prop + alb)
UCS (MPa)	15	13	3	5	175 (prop + alb)
Debris Flow	U	SA	HA	Prop	Prop + Alb
n (%)	33	24	34	34	24
ρ (g/cm ³)	1.74	1.99	1.65	1.65	1.99
k (m ²)	5E-13	6E-15	2E-13	2E-13	6E-15
Vp (km/s)	2.02	2.20	1.68	1.68	2.20

7.4.4.1. Influence of the lithology, degree and type of alteration

Results compiled by Pereira et al. (2024a) reaffirm that the rock type, combined with its porosity and microstructure, plays a major role in governing variations in physical and mechanical properties under differing alteration intensities and types, aligning with the findings in Mordensky et al. (2018). The influence of rock type is also more pronounced in low-temperature and near-surface environments (Browne, 1978). At depth and higher temperature, the effects of alteration tend to become more homogeneous, while the influence of lithology diminishes (Ladygin et al., 2010). Nevertheless, whether porosity or alteration is the dominant control on strength remains unsolved (Heap et al., 2022b).

Pereira et al. (2024a) also concluded that the degree of hydrothermal alteration determines whether dissolution, mineral replacement or mineral precipitation predominates, supporting prior research (Mielke et al., 2015; Cant et al., 2018; Mordensky et al., 2018; Kennedy et al., 2020; Kanakiya et al., 2021; Weydt et al., 2022). For instance, Mielke et al. (2015) reported that progressive alteration decreases porosity in both ash tuffs and sandstones, though it affects permeability in opposite ways—increasing it in ash tuffs while reducing it in sandstones. The progression of alteration is inherently linked to the type of hydrothermal alteration. Rock modifications in each alteration facies result from the combined effects of both lithology and the degree of alteration (Pereira et al., 2024a), differing between dense and fragmental rocks.

These observations explain the summary in Table 7.2. Dense rocks, such as lavas and intrusive rocks, tend to fracture and undergo mineral dissolution under stress (e.g., Kanakiya et al., 2021); yet their initially low porosity renders them less susceptible to hydrothermal alteration (e.g., Lagat, 2009; Cant et al., 2018). Increasing alteration typically increases the porosity of rocks, while reducing both density and ultrasonic wave velocities, as well as mechanical properties, especially in the presence of alunitic, argillic, or silicic alteration (Table 7.2). Conversely, propylitic alteration may mitigate these effects by decreasing porosity and enhancing strength.

Alteration-driven changes in porosity and permeability in dense rocks often correlate with reductions in other physical and mechanical parameters. However, the relationship between porosity and permeability is not always proportional, as it is governed by pore geometry, connectivity, and the nature of alteration (Bubeck et al., 2017; Kanakiya et al., 2022). For example, Scott et al. (2023) observed that even a minor decrease in porosity under low alteration intensity can rapidly decrease the permeability of lava flows, thereby limiting fluid flow and further alteration. Similarly, Farquharson et al. (2019) demonstrated that prolonged acid exposure in andesites from Mt. Ruapehu resulted in mineral dissolution and increased pore connectivity, while reducing the strength. However, alteration development differs within a lava flow, as the dense core lavas often feature well-connected pores due to microcracks, whereas isolated vesicles dominate marginal lavas (Scott et al., 2023 and references therein).

Although altered lavas may remain brittle, they reach lower peak stresses or undergo greater strain than their unaltered equivalents (Siratovich et al., 2016).

Intrusive rocks are characterised by microfractures but have low permeability due to limited pore connectivity, which further decreases under increased confining pressure (Cant et al., 2018). Table 7.2 evidences that alteration tends to increase porosity and reduce density in these rocks, likely due to progressive mineral dissolution. Mechanical degradation, particularly under argillic alteration, is pronounced, with even slightly altered intrusives displaying significant strength and stiffness losses. In contrast, propylitic alteration promotes the infilling of fractures with denser minerals, leading to increased rock density and improved mechanical properties.

In basalts (Table 7.2), physical properties differ according to the alteration type: propylitic alteration improves mechanical performance, while argillic alteration results in increased porosity and reduced density.

In andesitic lavas, advanced alteration typically reduces density and ultrasonic wave velocity (Table 7.2), though the extent of these changes depends more on alteration type than intensity (Pereira et al., 2024a). For instance, alunitic alteration, particularly when combined with silicification and oxidation, significantly increases porosity and permeability while reducing strength. Silicic alteration combined with argillic or alunitic alterations further compromises rock competence. On the other hand, propylitic alteration enhances the strength and stiffness of andesite lavas compared to argillic terms, and oxidation may increase density while decreasing porosity.

Argillic trachytes become more porous and substantially weaker than their unaltered counterparts, especially at advanced stages of alteration. These results suggest that susceptibility to argillic alteration depends on the original composition of the lava, in particular the content in feldspar.

Lava breccias, however, respond oppositely to trachytes (Table 7.2); higher degrees of argillic alteration in breccias are associated with lower porosity and greater strength, due to the extensive precipitation and sealing of fractures by secondary minerals.

Fragmental rocks show variable responses to hydrothermal alteration (Section 7.4.3 and Table 7.2). Pola et al. (2012, 2014) demonstrated the same for lavas and pyroclastic rocks, which displayed a general loss of strength with increasing alteration. In contrast, parameters such as friction angle and cohesion showed no systematic relationship with alteration intensity. Cant et al. (2018) studied tuffs from the Ngatamariki geothermal field, whose results showed that pore-dominated rocks had low permeability, whereas fracture-

dominated samples showed high connectivity. Mixed-type samples displayed wide porosity ranges and relatively high permeability and were only moderately affected by increasing confining pressure.

Compared to lavas, fragmental rocks are often associated with higher porosities, lower densities, slower ultrasonic velocities, and reduced strength, regardless of the type of alteration. However, their porosity and strength variations are overall less pronounced than in dense rocks, potentially due to microstructures that better resist mechanical compaction and chemical alteration (Stimac et al., 2015; Cant et al., 2018; Bustos and Adam, 2023). Rocks with initially high porosity also tend to maintain high permeability, even under high-temperature alteration conditions (Scott et al., 2023). On the other hand, pressure typically impacts the pore space of these rocks by reducing porosity more rapidly with burial than lavas and intrusive rocks (Stimac et al., 2015).

Argillic, alunitic, propylitic, and zeolitic alteration facies tend to reduce strength, density, and ultrasonic wave velocity while increasing both porosity and permeability (Section 7.4.3). In contrast, propylitic facies, either alone or in combination with albitic and advanced silicification, often decrease porosity and enhance rock strength (Section 7.4.3). In these cases, the formation of hard and resistant hydrothermal minerals dominates over dissolution processes, which are more prevalent in low-temperature and early-stage alteration environments. Nonetheless, under advanced alteration, even fragmental rocks can undergo significant reductions in porosity and permeability due to the complete filling of voids.

Breccias follow the same trend of other fragmental rocks, experiencing an increase in porosity of 24 % from slightly altered to highly altered terms, despite the similar V_p . According to Kennedy et al. (2020), breccias in volcanic conduits may undergo rapid shifts in effective pressure, partly because of hydrothermal alteration. Such phenomenon may contribute to episodic fluid flow, outgassing, and variations in the ground surface.

In the group of ignimbrites and tuffs, hydrothermal changes may either preserve or enhance strength and porosity, depending on the type of alteration. Strong silicification generally strengthens these rocks, whereas argillic alteration preserves their low strength and stiffness, regardless of the degree of alteration, aligning with previous observations (e.g., Franzson et al., 2010; Scott et al., 2023).

Tuffs are especially sensitive to the degree of alteration: samples with moderate alteration can become denser, stronger, and less porous, whereas fully altered samples tend to degrade their physical properties. Propylitic alteration coexisting with zeolites is associated with low rock quality, whereas silicification and albite-rich propylitic alteration can significantly improve the mechanical integrity of tuffs and tuffites.

In debris flow deposits, extensive propylitic alteration typically leads to increased porosity and considerable mechanical weakening. However, when propylitic processes are accompanied by albitic alteration, they contribute to improved strength and density, mirroring trends observed in other fragmental lithologies, such as tuffs and tuffites.

Beyond their variability under hydrothermal alteration, fragmental rocks are geologically important due to their potential to inhibit fluid migration and seal volcanic conduits (e.g., Kennedy et al., 2010; Mordensky et al., 2018; Kennedy et al., 2020). Moreover, pore pressure may increase and possibly trigger sudden explosive events (e.g., Heap et al., 2019). Additionally, their role in restricting fluid flow can facilitate the development of a shallow BDT zone (Kanakiya et al., 2021; Schaefer et al., 2023).

Cohesion is not included in Table 7.2, as it is less frequently collected compared to other strength parameters, such as UCS and E . Cohesion, like overall mechanical parameters, has higher values in lavas compared to lava breccias and pyroclastics, and decreases with increased alteration (Schaefer et al., 2023). Authors report that the angle of internal friction and the intact rock index, m_i (Villeneuve and Heap, 2021) have limited sensitivity to porosity and lack a clear link to structure, lithology, or degree of hydrothermal alteration (Schaefer et al., 2023).

7.4.4.2. Effect of structure and secondary mineral assemblage

Results in Section 7.4.3 and Table 7.2. evidence that microstructure, defined by the type of porosity (Cant et al., 2018), significantly impacts mechanical properties and alteration progress, as previously emphasised by Pola et al. (2012, 2014). Microstructural changes due to dissolution or precipitation primarily affect the rock's mechanical and physical properties with an increasing degree of alteration, although not linearly. Slightly altered rocks being more competent than highly altered ones is not a mandatory rule, as documented by Kanakiya et al. (2022).

Overall, most altered rocks retain their original microstructure, texture, and composition. However, their response to increased temperature and depth varies. Rocks from shallow,

low-temperature zones of geothermal systems, such as Ngatamariki, Rotokawa, and Kawerau in the Taupo Volcanic Zone, are generally more porous and, when saturated, show a significant reduction in density, ultrasonic velocities, and strength compared to their deeper, higher-temperature counterparts (Wyering et al., 2014)

Regarding the structure, the host rock behaviour in response to hydrothermal alteration generally depends on the accumulated damage and extent of healing (Callahan et al., 2019). In other words, the pre-existence and the subsequent infilling (partial or complete) of fractures significantly impact the rock's properties, regardless of the type of hydrothermal alteration. This observation aligns with prior studies (e.g., Gudmundsson, 2011; Siratovich et al., 2014). Fractures are chemically sensitive and tend to weaken under more acidic conditions. Mohtarami et al. (2017) demonstrated that acid exposure in porphyritic andesites and tuffaceous rocks acts selectively to dissolve reactive minerals, thereby altering fracture morphology. However, the integrity along fractures may still be preserved due to competing processes, such as pressure solution and free-face degradation, which can maintain cohesion and shear strength despite chemical dissolution.

On the other hand, the main type of alteration, and its dependence on the original rock type and on successive hydrothermal episodes (Weydt et al., 2022), as well as its combination with the several subfacies, that are driven by shifts in fluid pH and temperature, contribute to increased data scattering (Fig. 7.3) and weaken the correlations with respect to those established for unaltered rocks. Although several trends between physical and mechanical properties can be identified, there is also variability that is inherent within each rock type and across distinct observation scales.

The secondary minerals that form under a specific alteration type also dictate the rock's behaviour. Soft minerals, like clays and low-temperature zeolites that predominate in low-temperature environments under argillic alteration (Fig. 7.2), typically reduce the overall strength and stiffness of the host rock (e.g., Wyering et al., 2014; Frolova et al., 2014; Pola et al., 2014; Mordensky et al., 2018; Farquharson et al., 2019; Pereira et al., 2024a; Section 4.3). Alteration-driven changes in porosity and permeability, however, are not uniform (e.g., Mordensky et al., 2018; Villeneuve et al., 2019; Scott et al., 2023), as reduced mechanical properties do not always correspond to increased porosity, nor does higher permeability always result from higher porosity. For instance, Kanakiya et al. (2022) highlighted that lavas with similar porosity may exhibit significantly different permeabilities, while Cant et al. (2018) attributed this variability to differences in pore architecture. Alteration may also

compete with the infilling of voids by secondary minerals, through the creation of microporosity within the mineral's structure (Franzson et al., 2010).

Clay-rich alteration promotes ductile deformation (Siratovich et al., 2016; Mordensky et al., 2018, 2019), with altered rocks showing compaction and plasticity at lower confining pressures. However, this phenomenon remains dependent on porosity (Siratovich et al., 2016; Mordensky et al., 2022). At Mt. Ruapehu, unaltered lavas and fresh breccias are brittle under low confinement, whereas altered breccias exhibit ductile behaviour under comparable conditions (Schaefer et al., 2023).

Thus, the shift from dilatant to compactant behaviour depends on the rock type, texture, and structure, as well as the degree of hydrothermal alteration (Heap and Violay, 2021; Siratovich et al., 2016; Mordensky et al., 2018, 2022; Schaefer et al., 2023). Such phenomena have implications for better interpreting the evolution of volcanic systems, especially during eruptive phases (Kennedy et al., 2020).

High-temperature mineral assemblages, typical of propylitic facies, exert diverse effects on physical and mechanical rock properties, depending on the subfacies and the degree of alteration. Moreover, silicification has a complex relationship with porosity, either increasing it or reducing it through fracture sealing (advanced silicic and "propylitic + albitic" facies), which partially restores strength (Pereira et al., 2024a).

7.5. Conclusions

"Hydrothermal alteration is more influenced by local conditions rather than large-scale geodynamic processes, although the latter play a major role in maintaining the hydrothermal activity" (Pereira et al., 2024a). While the factors that control hydrothermal alteration are well established, the impact on the physical and mechanical behaviour of altered rocks remains less explored. To address this gap, a dataset was compiled to assess how rock properties change under various hydrothermal conditions, in particular *degree* and *type of hydrothermal alteration*.

The response of volcanic (and other materials present in volcanic settings) is significantly dictated by lithology, microstructure, and the presence of discontinuities (e.g., faults and fractures). Dense rocks like lavas and intrusive rocks are generally stiffer, less porous, and stronger than pyroclastic rocks, though these distinctions can blur due to welding,

compaction, and mineralised infilling in volcanoclastic units. Lavas are typically more prone to fracturing and developing permeability, while pyroclastics may retain porosity and permeability but remain mechanically weaker.

The review provides the following findings:

- In lavas and intrusive rocks, low-temperature facies such as argillic, alunitic, and shallow silicic drive mineral dissolution and replacement, reducing strength and increasing porosity. In contrast, propylitic alteration, especially at higher temperatures, often leads to strengthening due to mineral precipitation. The extent and nature of these effects are influenced by the chemical composition of the host rock, particularly alkali content.
- Altered dense rocks demonstrate larger variations in mechanical properties than altered fragmental rocks.
- Lava breccias are affected by the degree of alteration that, when higher, leads to pore and fracture infilling by secondary minerals, which contributes to the overall rock strength.
- Fragmental rocks display heterogeneous textures and different compaction degrees, making it difficult to discern the effects of type and degree of alteration. Typically, secondary mineral precipitation strengthens the rock, with argillic facies strengthening or maintaining the mechanical properties of the fragmental rocks, while physical properties degrade. Permeability may not increase proportionally with porosity, especially under high-temperature facies. Advanced silicic alteration, for instance, tends to reduce both porosity and permeability while increasing the competence of pyroclastic rocks.
- The physical and mechanical behaviour of rocks within the propylitic facies varies based on their combination with other subfacies. For example, coexistence with clays or zeolites can reduce the overall competence of a rock, which becomes more porous. Incorporating quartz and alunite, on the contrary, may yield more competent propylites.
- The inherent characteristics of the host rock, including the texture, structure, and chemical composition, govern how alteration manifests and progresses. While altered rocks generally follow the same correlation trends as their unaltered counterparts, the data become more scattered due to the added complexity of alteration processes.

Given the unpredictable and variable response of volcanic rocks to hydrothermal alteration, quantifying the degree of alteration is established as an important research practice. Geochemical proxies, such as whole-rock $\delta^{18}\text{O}$ (e.g., Darmawan et al., 2022; Heap et al., 2022c), provide accurate estimations of alteration intensity using minimal sample volumes. Chemical (or weathering) indices can also be used to identify the degree of alteration. Recent refinements to the Alteration Strength Index by Wyering et al. (2015) allowed for the prediction of mechanical properties, such as UCS, based on porosity, mineral hardness, and fracture density.

Future progress can consider controlled laboratory-induced alteration tests, such as those by Farquharson et al. (2019) and Nicolas et al. (2020), to be cross-referenced with geophysical and geochemical observations, thereby refining volcanic hazard assessments and improving our understanding of subsurface volcanic and hydrothermal processes.

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*Effects of hydrothermal
alteration*

Chapter

Alteration in Azorean volcanic rocks: Preliminary insights

Alteration in Azorean volcanic rocks: Preliminary insights

8.1. Preliminary notes

Hydrothermal alteration is ubiquitous in volcano-hydrothermal systems and geothermal fields, influencing the physical and mechanical properties of the volcanic host rocks as a function of the type and degree of alteration, as critically assessed by Pereira et al. (2024a) and in Chapter 7. In these geological contexts, altered materials prevail over fresh rocks, controlling the subsurface dynamics of fracturing, ductility, and porosity evolution over time and space. Hydrothermal alteration leads to unpredictable and heterogeneous behaviour of the host rocks, affecting geothermal exploitation, conditioning wellbore failure, and induced seismicity (Nicolas et al., 2020). Moreover, hydrothermal alteration affects volcanic terrains close to the surface with geotechnical implications (Pereira et al., 2024a; Section 7.1).

As noted by Heap and Violay (2021), “we do not fully understand the influence of alteration on the mechanical behaviour of volcanic rocks or the timescales required, despite its perceived importance in dictating volcano stability”. Thus, gaining a better understanding of these phenomena can improve volcano-hydrothermal mechanical models and field interpretations. Additionally, clarifying the properties of these materials can elucidate on their potential role in integrated geothermal-carbon capture and storage (CCS) operations (Sigfússon et al., 2018; Snæbjörnsdóttir et al., 2020; Cao et al., 2024), particularly as these options have yet to be studied in detail for São Miguel Island.

Obtaining altered blocks of a suitable size for specimen production to mechanical tests is difficult. As an alternative, induced alteration of cylinders has been conducted by Farquharson et al. (2019) and Nicolas et al. (2020). Farquharson et al. (2019) performed batch reaction experiments over a timescale ranging from one to four months on andesites collected in Mt. Ruapehu (New Zealand). The specimens were immersed in a batch reactor filled with sulfuric acid solution (initial pH = 0.64) at ambient temperature to mimic an acidic volcanic lake and induce alteration. The rock properties were measured periodically. Plagioclase and glass were dissolved, reducing the density and strength of the rock while increasing porosity, pore radius, and permeability. Nicolas et al. (2020) used a quarried block of andesite, from which three specimens were pre-heated and artificially altered using a brine under pressure (20 MPa) and different temperatures up to 280 °C. Artificial alteration was performed in an autoclave for one month using a fluid with seawater

composition. Triaxial tests were conducted to assess the elastic behaviour and failure, showing that the rocks became weaker and had decreased elastic compaction owing to the filling of microcracks by clay minerals (smectite). In both studies, a microstructural investigation was conducted to gain a deeper understanding of the modifications in rock properties.

In this research, only fresh blocks were collected from the surface. Samples altered by the existing hydrothermal system from the Fogo Volcano are limited to cuttings provided by EDA Renováveis, S.A (project HEATSTORE - Geothermica Era net), whose small and irregular shapes preclude mechanical testing. Therefore, it was explored the possibility of inducing hydrothermal alteration not in the laboratory, as in previous studies, but *in situ*, that is, in the field, in an fumarolic ground located the Caldeiras da Ribeira Grande, at Fogo Volcano. Specimens tested in the fresh state were buried in this area for four months, following the Farquharson et al. (2019) timescale. In *Part A*, the rocks were assessed for microstructure and chemically to look for signs of alteration.

Given the fact that several of the lava rocks were compact and the exploratory nature of this part of the work, cuttings from the Ribeira Grande geothermal system were selected for the physical characterisation of altered rocks to complement the chemical (X-ray diffraction; XRD) and petrographic data (via binocular microscopy) presented in Pereira et al. (2022). Unfortunately, it was not possible to obtain specimens for time-resolved uniaxial tests; however, for the first time, the physical properties and microstructure of these materials were assessed using rock digital physics, contributing to a better understanding of the subsurface geology of the Ribeira Grande geothermal field. The complementary part of this study is presented in *Part B*.

This research, although preliminary, aims to establish a local assessment of volcanic rock that can inform future studies. These studies provide a clearer definition of the conceptual model of the field. Additionally, the materials found in the area should be considered in the context of current climate demands to reduce CO₂ emissions by 2050 (IPCC, 2021), as they have the potential to be explored via the variation of the CarbFix concept (see Loschetter et al., 2025 and references therein).

Field induced alteration on lava rocks

8.2. Summary of materials and methods

8.2.1. Materials

Several disc and cylindrical specimens (45-51 mm in diameter) from the same samples tested as fresh materials (Fig. 3.6, and Chapter 5) were selected for the *in situ* induced alteration: 24 BP specimens (from BP15, BP18, BP23, BP25, BP30, and BP33), 15 BAF specimens (from BAF8, BAF9, and BAF12), 22 BF specimens (from BF2, BF8, BF10, BF33, and BF36), and 20 T specimens (from T12, T14, T17, T18, and T26). The samples used for the preliminary analysis (Chapter 4 - BP37, BP38, BAF18, BF3, BF13, BF15, T29, and T31) were considered to investigate the feasibility of the research plan. It is stressed that these samples were obtained from the same block, but are not the same specimens as those tested in Chapter 4.

The samples were buried ~50 cm below the soil surface in Caldeiras da Ribeira Grande, a fumarolic ground on the northern flank of the Fogo Volcano (Fig. 8.1). The main hydrothermal manifestations of Fogo occur in the Caldeiras da Ribeira Grande, Caldeira Velha, and Pico Vermelho areas, and correspond to low-temperature fumaroles and steaming ground (Caliro et al., 2015), thermal and cold CO₂-rich springs (Cruz and França, 2006; Ferreira et al., 2025), and soil diffuse degassing areas (Viveiros et al., 2015; 2023). New fumarolic areas around the Caldeiras da Ribeira Grande fumarolic field were created in 2010 during the drilling of a geothermal well. Fumaroles from the Fogo Volcano's northern flank (96-100 °C) have water vapour (H₂O), followed by CO₂ (3.1 vol%) as the main component, while minor gases (H₂S, H₂, CH₄, N₂, Ar, He, CO) have variable concentrations (Caliro et al., 2015; Pereira et al., 2022; Matias et al., 2024).

The samples were buried on July 30, 2024, and collected on December 6, 2024, intercepting both the rainy and relatively dry seasons in the Azores (Marques et al., 2007). The measured soil temperature, at the depth that samples were buried, was 98.6 °C, while the reservoir feeding Caldeiras da Ribeira fumaroles has an estimated temperature of 256 °C (Pereira et al., 2022). Soil CO₂ fluxes quantified during field campaigns in the area led to a minimum estimated flux of ~40 t d⁻¹ and CO₂ was determined to derive from biogenic and volcanic-

hydrothermal sources (Viveiros et al., 2023). Recent studies (Aiuppa et al., 2025) showed a fumarolic CO₂ flux of 87 tons/day.

Samples selected for field-induced alteration are referred to as *Reference_alt* (e.g., BP37_alt), while fresh specimens are referred to as in Pereira et al. (2025a) and Chapter 4 (e.g., BP37).

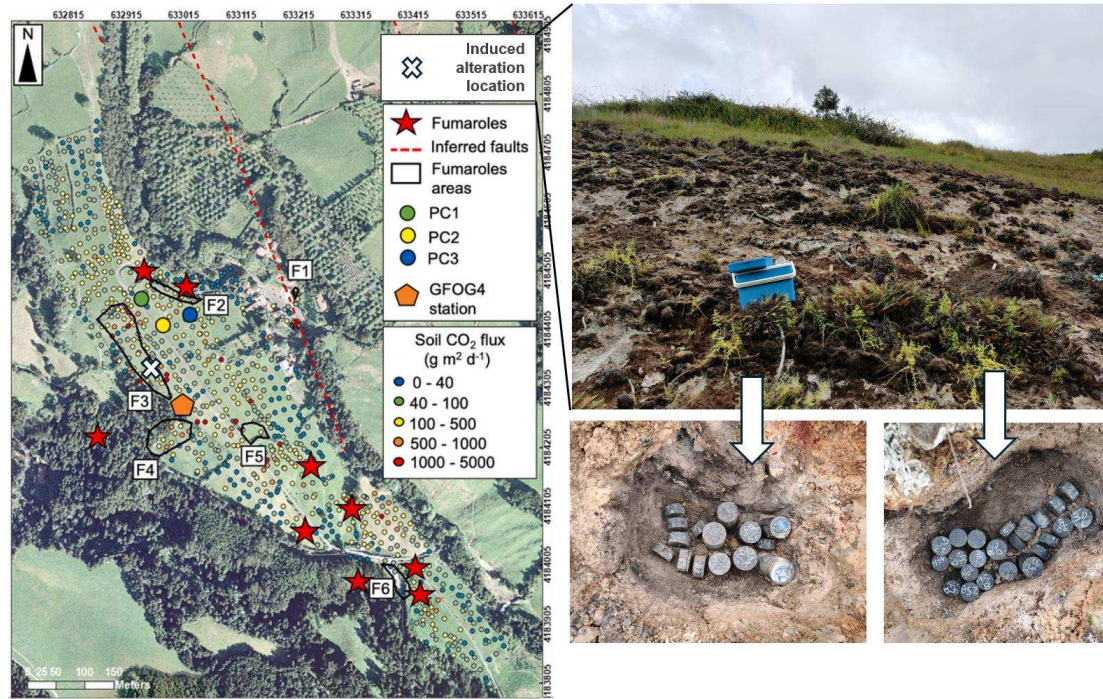


Fig. 8.1. Location of the induced alteration spot in the diffuse degassing area of Caldeiras da Ribeira Grande. The specimens were buried in the location marked with a white cross. Map representation reproduced from Viveiros et al. (2023), including the CO₂ flux measurement locations and the main fumarolic emissions (F1,2,3,4,5,6). Datum = World Geodetic System (WGS) 84. PC1, 2, and 3 correspond to the three control points. Original figure licensed under CC BY-NC-ND 4.0.

8.2.2. Research strategy and methods

To avoid time-consuming physical and mechanical tests, the alteration was first assessed in the “_alt” samples (Section 8.1.1, Part A). The investigation began with a macroscopic inspection complemented by SEM assessment of the rock surface. Internal microstructural research using μ CT (BP37, BAf18, BF3, BF13, and T31) and chemical analyses via whole-rock chemistry were performed. The results show that no evident alteration was developed and no further mechanical and physical tests were performed on the disc and cylinder specimens.

Prisms of $\sim 9\text{--}11 \times 16\text{--}19$ mm were cut from altered BP37, BAf18, BF3, BF13, and T31 samples (Table 3.3). SEM analysis (see Section 3.2.2.2) was conducted to obtain the surface morphology images, which were acquired in the secondary electron and mix modes with varying optical magnification.

X-ray imaging (Section 3.2.2.3) was performed in the absorption mode, acquiring 4001 2D radiographs (projections) over a 360° rotation. The selected conditions (air, 100–120 kV, 83–100 μ A, 0.4 $\times$) are presented in Table 3.3 and resulted in a voxel size of 14.68 μ m that is equal to that used by Pereira et al. (2025a; Chapter 4) for fresh homologous material.

The volume fraction of the pore space (total porosity – n_T and effective/open porosity – n_{eff}) and opaque minerals (Op), tortuosity (T), and absolute permeability (k) were computed using PerGeos® (Section 3.2.6.2).

Whole-rock chemical analyses were performed on “alt_” samples (BP37, BP38, BAF18, BF3, BF13, BF15, T29, and T31). TAS classification (Le Bas et al. 1986), described in Chapter 3.2.3, was obtained for comparison with data in Pereira et al. (2025a). As described in Section 3.2.3, alteration was assessed using sulfur content (S), LOI, Na₂O, the binary diagram of CaO+K₂O+Na₂O (felsic minerals) and Fe₂O₃^T+MnO+MgO (mafic minerals), and chemical weathering indices, following previous research strategies.

Increased S content can result from the formation of sulfur minerals because of increased temperature or acidic alteration (Bólos et al., 2019), while the LOI reflects the H₂O⁺ content in a sample heated at > 105 °C (Johnson and Maxwell, 1981), which increases because of the hydration of rocks (e.g., clay formation) due to alteration (Pandarinath, 2022 and references therein). Na₂O content might indicate Na depletion due to hydrothermal alteration, which has been reported to occur in lava rocks (Pandarinath et al., 2024 and references therein). The binary diagram was plotted to assess any enrichment or loss of these elements due to exposure to diffuse degassing. When applied to altered materials, binary diagrams indicate that points projected far from the origin are less altered than points projected closer to the origin (Pandarinath et al., 2024). Data were also projected in the FMW ternary diagram (Section 3.2.3; Ohta and Arai, 2007) to evaluate if the rocks plot closer to the W vertex.

The alteration indices were reviewed by Pandarinath (2022) and have been previously applied to altered volcanic materials (Weydt et al., 2022; Pandarinath et al., 2023; Pandarinath et al., 2024). The Chemical Index of Alteration (CIA; Nesbitt and Young, 1982; McLennan, 1993) and Chemical Weathering Index (CIW; Harnois, 1988) were calculated using Eq. 3.1 and Eq. 3.2, respectively. Both indices increase with an increasing degree of weathering (and/or alteration). Fresh rocks occur when CIA < 60 and CIW < 50, whereas altered rocks are defined above these thresholds (Nesbitt and Young, 1982; Harnois, 1988). Nevertheless, it is common to assume the same threshold (60) for both indices (Pandarinath, 2022).

8.3. Results and discussion

8.3.1. Assessment of the rock surfaces of the specimens

Macroscopic observations reveal that the alteration is superficial (Fig. 8.2), with reddish to brownish colour modifications due to the possible formation of clays and oxides. Most oxidation develops as a thin coating in the pores of vesicular (high-porosity) intermediate lavas and in low-porosity trachytes, while the compact basalts remain similar. SEM observations confirm an induced alteration limited to the rock surface.

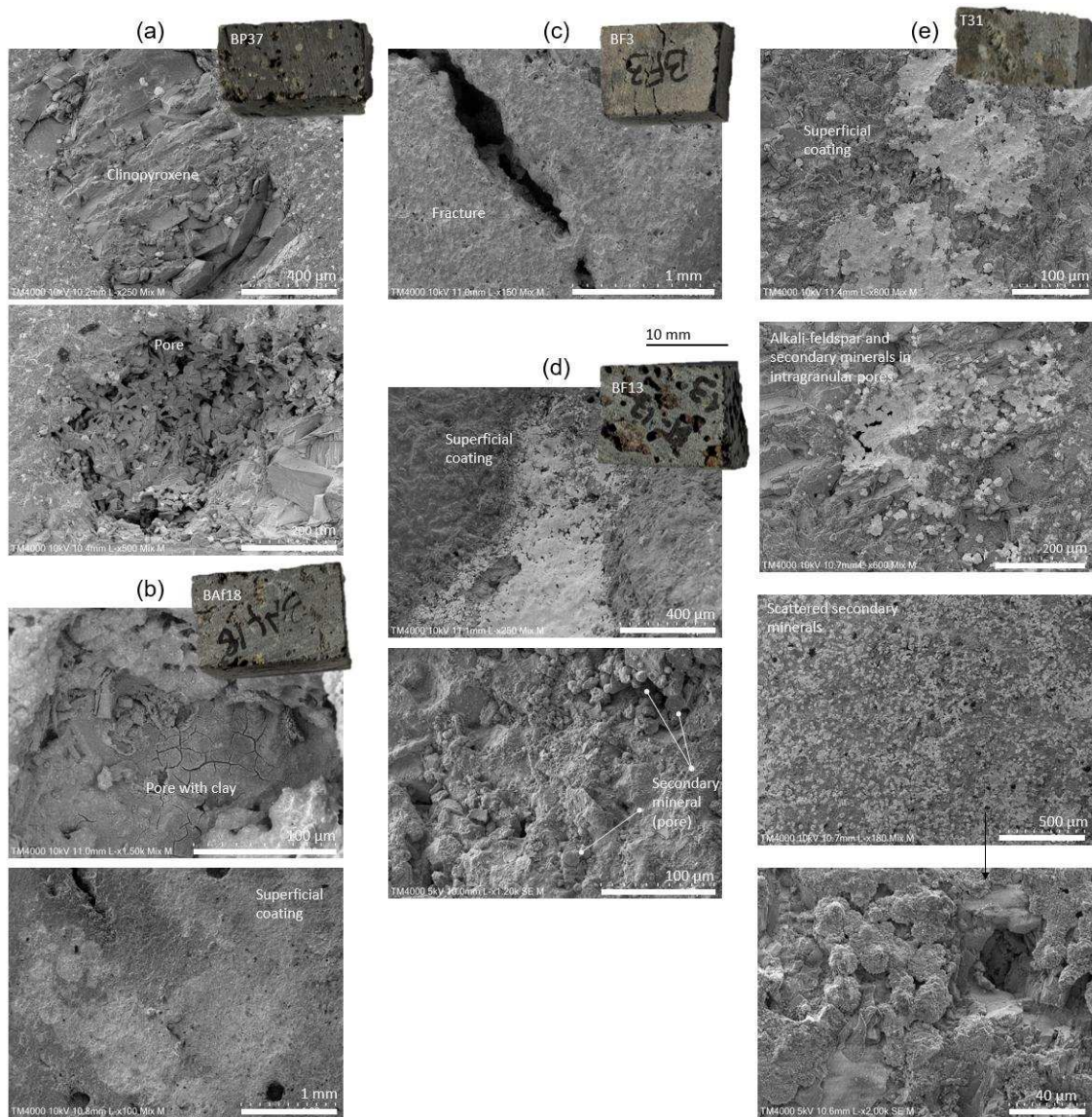


Fig. 8.2. Macroscopic appearance and scanning electron imaging (SE or mix mode) of the surfaces of the post-altered specimens. (a) BP37 and the primary minerals of the groundmass and in pores; (b) BAF18 with scarce pores containing clays (desiccation cracking) and surface with an alteration coating; (c) BF3 with fractures without secondary mineral fillings; (d) BF13 with secondary coating on the surface and incipient secondary minerals in the pores; and (e) T31 with secondary mineral coating on the surface along primary crystals and in the scarce pores.

Basalt BP37 (Fig. 8.2a) shows the primary minerals in the groundmass and pores not covered by secondary products. In contrast, basalt BAF18 (Fig. 8.2b) shows scarce clay presence inside pores, with desiccation cracking and a surficial coating in rare spots of the groundmass. BF3 (Fig. 8.2c) does not reveal precipitates along the fractures. Conversely, BF13 displays coatings of denser minerals than the groundmass (light grey colour), covering the pores or the groundmass. Inside the pores, secondary mineral phases are present with either a spheroidal or veneer morphology, possibly corresponding to oxides and/or clays (Welton, 1984). T31 (Fig. 8.2e) has more distributed alteration along its surface, with dispersed or concentrated surface coating in the groundmass or along the intragranular pores of the phenocrysts.

8.3.2. Microstructural analysis

The volume rendering (3D representation) of the five altered samples and their respective segmented pore spaces are shown in Fig. 8.3. Microphotograph cross-sections of the same materials are also presented in Fig. 8.4, with microstructural detailed features that were previously observed in 3D scans and thin-sections of the homologous samples before induced alteration (Pereira et al., 2025a; Chapter 4).

Basalt BP37 (Fig. 8.3a) preserves the phenocrysts of olivine and clinopyroxene. Quantification shows that the n_T of altered BP37 (4.04 %) is 2 % higher than that of fresh BP37 (2.07 %). Nevertheless, the pore space in both the fresh and altered samples maintained the same characteristics, including isolated rounded pores, intragranular pores, and coalescent pores (Fig. 8.4a). The amount of opaque minerals is similar (0.58 % for BP37 and 0.36 % for BP37_alt), corresponding to primary minerals. Oxidation, which forms mineral coatings, is not observed for BP37_alt. Olivine and clinopyroxene maintain their microstructure, with intragranular fractures that do not appear filled by secondary minerals. Reaction rims around ferromagnesian minerals are present in both altered and fresh BP37.

BAF18 basalt (Fig. 8.3b) has decreased total porosity and increased the number of opaques from BAF18 ($n_T = 2.20$ %; $Op = 0.20$ %) to BAF18_alt ($n_T = 1.19$ %; $Op = 0.80$ %). The porosity difference is not due to the filling of voids by secondary minerals but because the fresh prism has a network of transgranular microcracks, which represent approximately 1 % of the total porosity, combined with larger pores than BAF18_alt displays. Microphotographs show that in both BAF18 prisms, groundmass pores are round. Pores can also be intragranular or displayed along the borders of ferromagnesian minerals (Fig. 8.4b). Similar to BP37, opaque minerals in BAF18_alt are primary, bordering ferromagnesian minerals or as isolated

microphenocrysts in the groundmass in both fresh and post-altered rocks. The primary textures (e.g., reaction rims in olivine) are preserved in BAf18_alt (Fig. 8.4b).

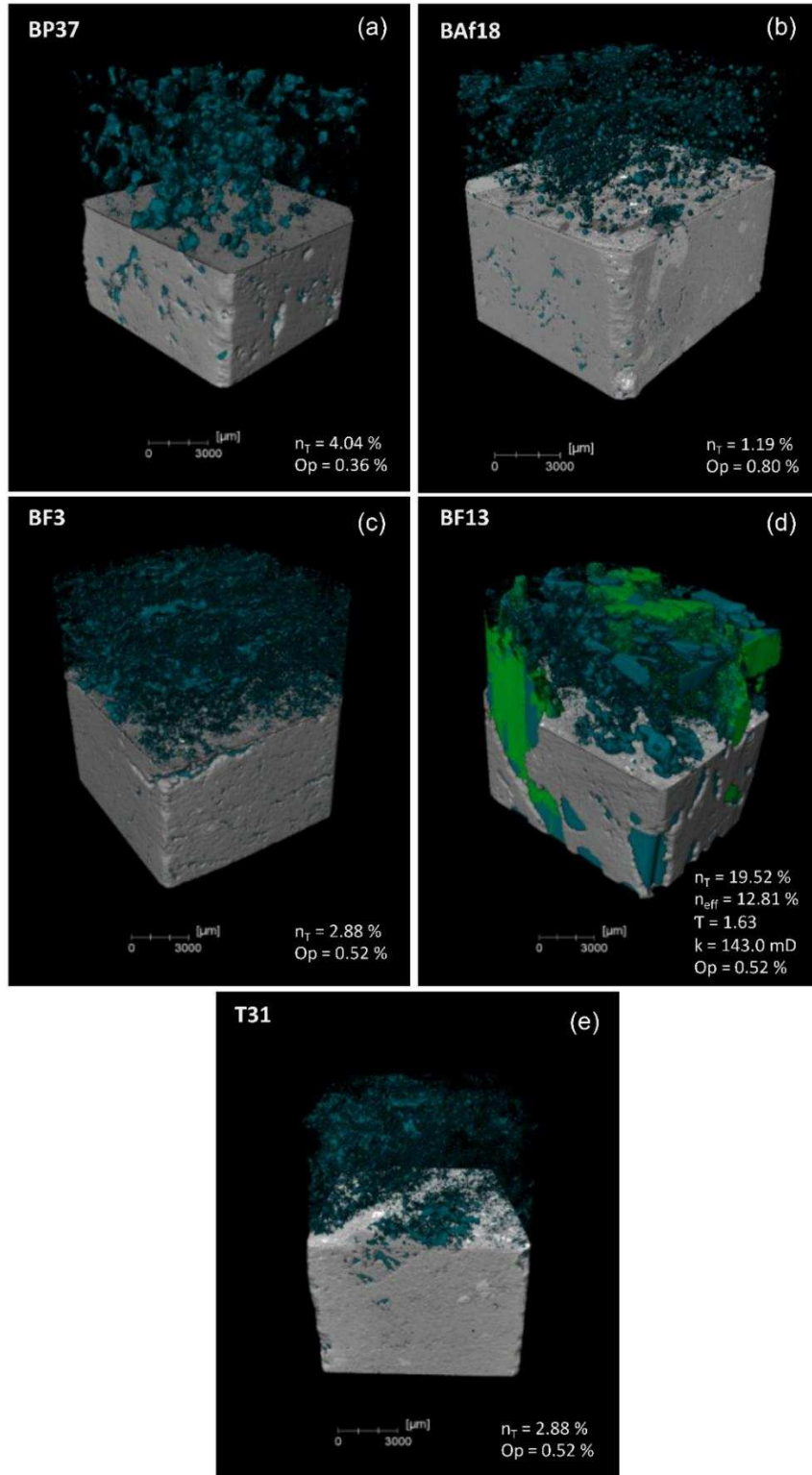


Fig. 8.3. Pore space segmentation and quantification of physical properties (total porosity – n_T : in blue; effective/ open porosity – n_{eff} , in green; tortuosity – T ; permeability - k) and opaque minerals (Op) for (a) BP37 – massive alkali basalt; (b) BAf18 – massive alkali basalt; (c) BF3 – massive intermediate lava rock; (d) BF13 – vesicular intermediate lava rock; (e) T31 – massive trachyte.

Regarding massive intermediate lavas from Fogo (Fig. 8.3c), the porosity is kept similar from BF3 ($n_T = 2.44\%$; $O_p = 0.19\%$) to BF3_alt ($n_T = 2.88\%$; $O_p = 0.52$). Both specimens include a network of irregular and open microcracks, without mineral fillings and typically limited to the phenocryst boundaries. Plagioclase maintains the disequilibrium textures observed in BF3. The opaque minerals are typically associated with ferromagnesian minerals, displaying a morphology in BF3_alt similar to BF3 (Fig. 8.4c).

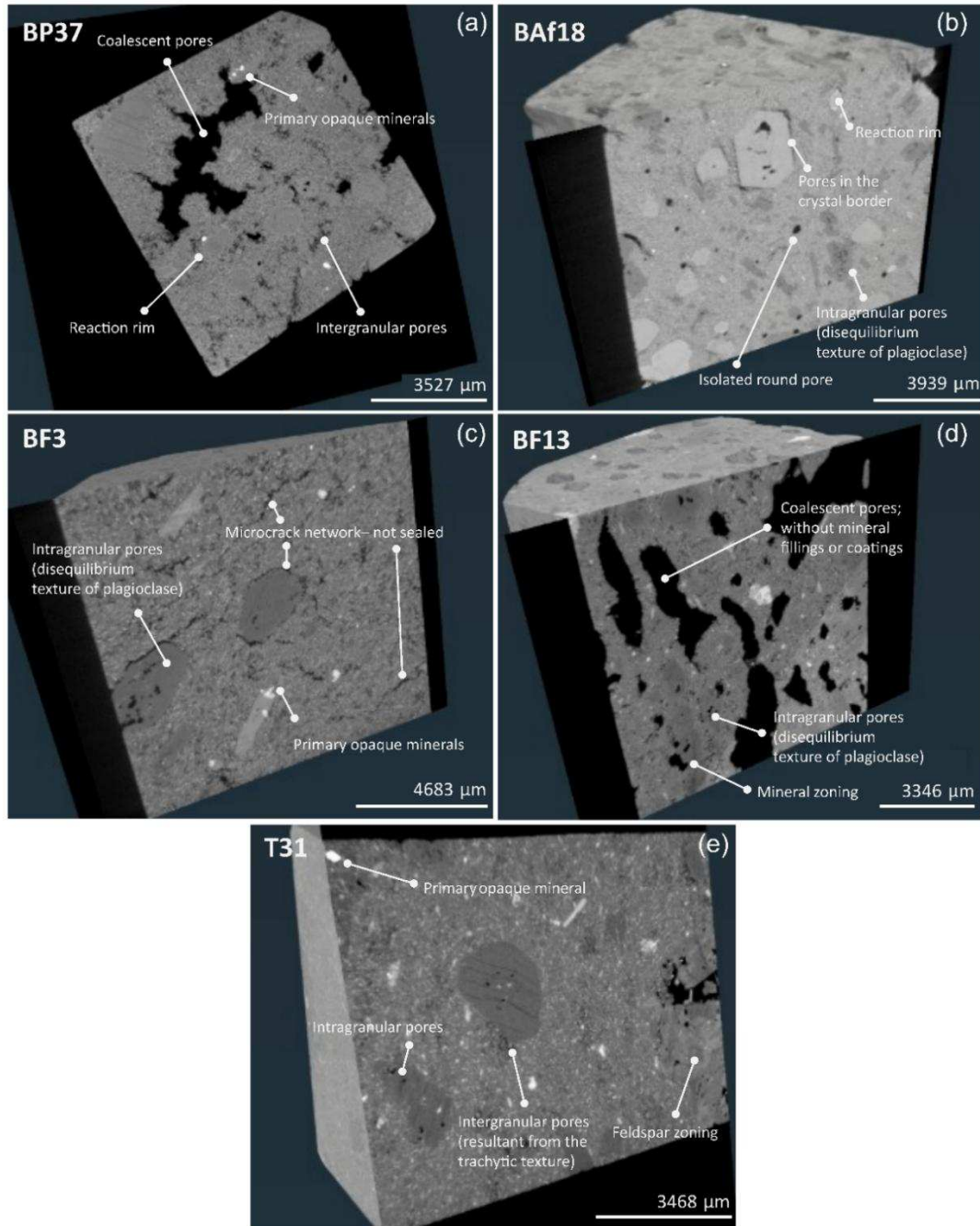


Fig. 8.4. Cross-sections of 3D scans, with microphotographs containing important microstructural features for post-altered (a) BP37 – massive alkali basalt; (b) BAf18 – massive alkali basalt; (c) BF3 – massive intermediate lava rock; (d) BF13 – vesicular intermediate lava rock; (e) T31 – massive trachyte.

In contrast to the low-porosity lavas, vesicular BF13_alt (Fig. 8.3d) has a connected void space resolved at $\sim 15\ \mu\text{m}$, similar to its fresh homologue. The several physical properties of BF13 ($n_T = 19.21\ \%$; $n_{eff} = 12.85\ \%$; $Op = 0.34\ \%$; $T = 2.59$; $k = 256\ \text{mD}$) and BF13_alt ($n_T = 19.52\ \%$; $n_{eff} = 12.81\ \%$; $Op = 0.45\ \%$; $T = 1.63$; $k = 143\ \text{mD}$) are proximate, indicating that alteration did not occur or is very incipient, despite the vesicular texture, which is considered to facilitate hydrothermal alteration (e.g., Pereira et al., 2024a; Table 7.1). BF13_alt pore space continues to be dominated by coalescent and elongated pores (Fig. 8.4d). BF13_alt vesicles differ only from fresh BF13 regarding the main orientation of the elongated pores, which defines the simulation of k along the x- and z-axes for BF13 and BF13_alt, respectively. BF13 has a more tortuous void space despite its higher k than BF13_alt. Minerals have similar morphologies, with opaque minerals mainly associated with ferromagnesian minerals. No secondary mineral fillings were observed in the interior pores of the BF13_alt despite the loss in k .

T31 sample internal microstructure confirms the absence or incipient-induced alteration (Fig. 8.3e). T31_alt ($n_T = 1.10\ \%$; $Op = 0.39\ \%$) has a slightly less porous groundmass than T31 ($n_T = 1.29\ \%$; $Op = 0.35\ \%$) but contains larger angular pores inside and near the feldspar minerals. Zoned feldspars and intragranular empty voids are observed in both the fresh and altered samples. Opaque minerals are present with similar morphology and in nearly identical quantities in both the fresh and post-altered trachytes (Fig. 8.4e).

The results from the digital physics analysis and microstructure investigation indicate that no alteration occurred in the internal regions of the various lava samples, with any changes remaining incipient and confined to the specimens' surface. The observed differences in porosity and the volume of opaque minerals can be attributed to sample heterogeneity rather than induced alteration, as the prisms were obtained from different sections of the same block.

8.3.3. Chemical analysis

The TAS diagram (Fig. 8.5) indicates that all rocks remain within the same classification field, with the exception of BAF18_alt and BAF_18, which represent a basalt and a trachybasalt, respectively. The induced alteration reduces the alkali content of all samples to varying degrees. Notably, T31 shows a broader variation from the fresh specimen, presenting lower levels of Si_2O and $\text{K}_2\text{O} + \text{Na}_2\text{O}$. In contrast to trachytes, trachyandesites, and basalts, altered basaltic trachyandesites show an increase in SiO_2 content, which is particularly pronounced in the vesicular variety. However, the overall variations remain relatively low.

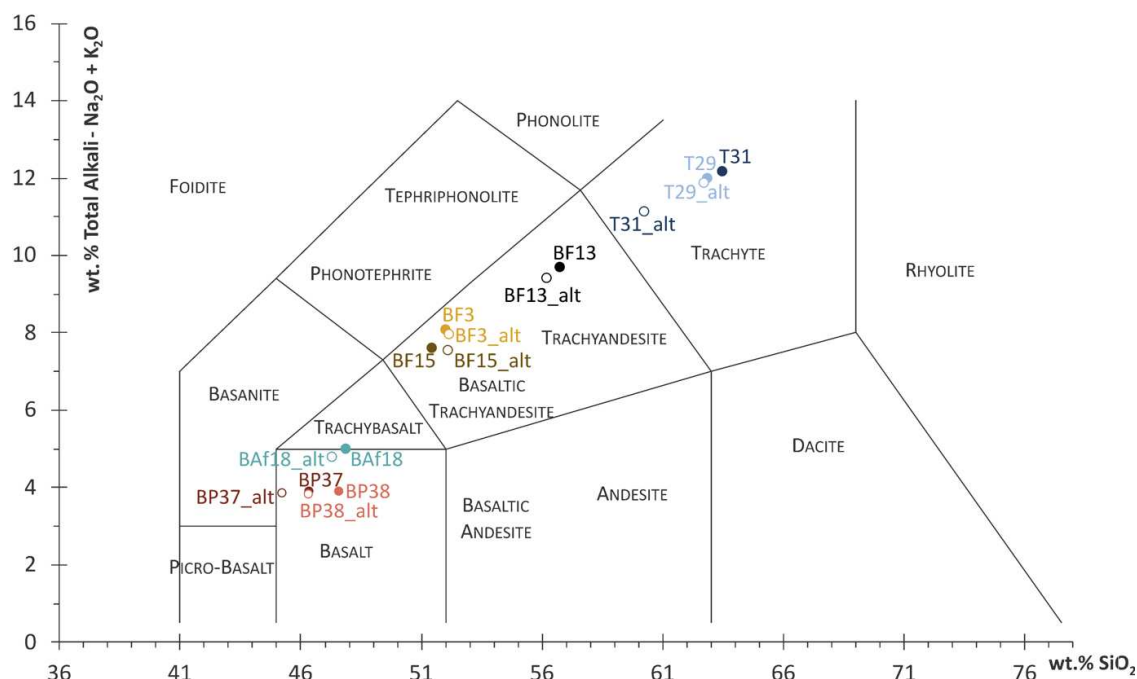


Fig. 8.5. The TAS diagram (Le Bas et al., 1986) comprises fresh lava rocks (Pereira et al., 2025a; BP37; BP38; BAf18; BF3; BF13; BF15; T29; T31 – full circles) and those subjected to *in situ* alteration (BP37_alt, BP38_alt, BAf18_alt, BF3_alt, BF13_alt, BF15_alt, T29_alt, and T31_alt – empty circles).

The binary diagram (Fig. 8.6a) shows that trachytes are plotted closer to the origin compared to basalts. Similar to the TAS diagram, T31_alt exhibits more chemical changes than the remaining samples. The altered trachytes display a slight increase along the y-axis, in contrast to other rock types, which show a decrease in the levels of $\text{Fe}_2\text{O}_3^{\text{T}} + \text{MnO} + \text{MgO}$. Trends in the x-axis are more variable. Altered basalts (BP37_alt, BP38_alt, and BAf18_alt) and vesicular basaltic trachyandesite (BF15_alt) display an increase in $\text{CaO} + \text{K}_2\text{O} + \text{Na}_2\text{O}$, while vesicular trachyandesite (BF13_alt) indicates a decrease in these oxides. Although BF13_alt shows a slight increase in CaO, the alkali content decreases with exposure to degassing.

T31_alt experiences an increment in CaO, leading to an overall rise in $\text{CaO} + \text{K}_2\text{O} + \text{Na}_2\text{O}$, despite a loss of $\text{K}_2\text{O} + \text{Na}_2\text{O}$. Fig. 8.6b, which focuses on the variation of Na_2O , provides evidence of Na depletion in T31_alt. Conversely, T29_alt presents a minor increase in CaO without decrease in the content of $\text{CaO} + \text{K}_2\text{O} + \text{Na}_2\text{O}$. Overall, the binary diagram indicates that trachytes tend to oxidise, whereas the competing loss in alkali content and gain in CaO leads to different trends along the x-axis. Nevertheless, the variations are less than 1.5 wt.%, which indicates an ineffective induced alteration.

The LOI of most altered samples (Fig. 8.7a) increases, apart from BP37_alt, BAf118_alt, and T29_alt, which maintain LOI levels similar to those of their fresh counterparts. Negative LOI

in both fresh and altered samples, particularly in basalts, is attributed to the oxidation of Fe^{2+} to Fe^{3+} , which increases the weight during heating. This phenomenon has been documented for various basalts worldwide (Zhong et al., 2017; Li et al., 2019; Zhong et al., 2019). A more significant increase in LOI occurs for BP38_alt (0.40 wt.%), BF13_alt (0.71 wt.%), BF15_alt (0.41 wt.%), and T31_alt (0.24 wt.%), suggesting that vesicular textures and the felsic nature of the samples favour an increase in the LOI. This may indicate the formation of clays or the further oxidation of Fe^{2+} in these materials. Nevertheless, the LOI values remain below 4 wt.%, which is the threshold suggested for altered volcanic rocks (Pandarinath et al., 2024).

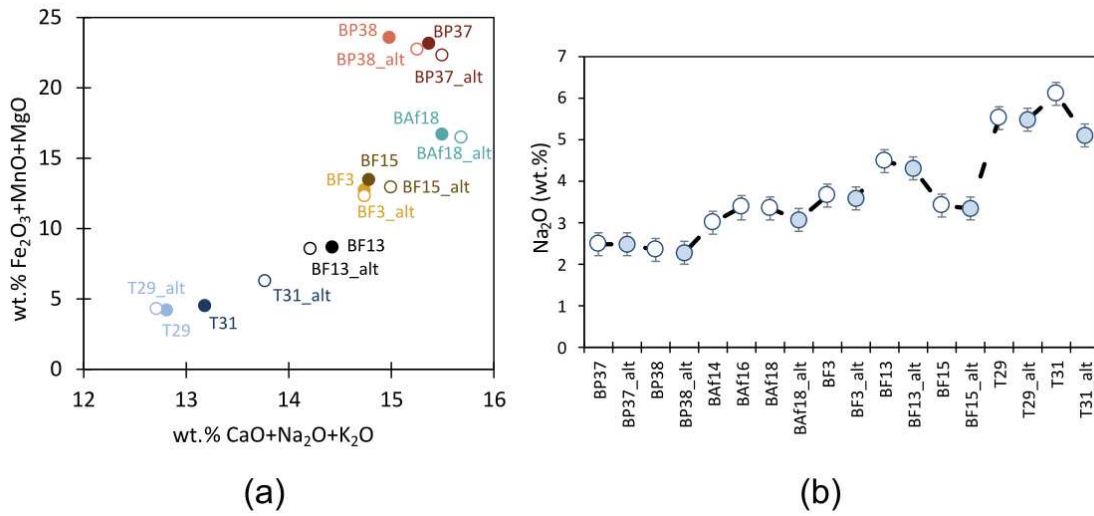


Fig. 8.6. (a) Binary diagram of wt.% CaO+K₂O+Na₂O (representing felsic minerals) and wt. % of Fe₂O₃+MnO+MgO (representing mafic minerals) for fresh samples (Pereira et al., 2025a; BP37; BP38; BAF18; BF3; BF13; BF15; T29; T31 – full circles) and those submitted to *in situ* alteration (BP37_alt; BP38_alt; BAF18_alt; BF3_alt; BF13_alt; BF15_alt; T29_alt; T31_alt – empty circles). (b) Na₂O content for the set of samples represented in Fig. 8.6a, comprising error bars that correspond to the standard error.

The LOI of most altered samples (Fig. 8.7a) increases, apart from BP37_alt, BAF118_alt, and T29_alt, which maintain LOI levels similar to those of their fresh counterparts. Negative LOI in both fresh and altered samples, particularly in basalts, is attributed to the oxidation of Fe^{2+} to Fe^{3+} , which increases the weight during heating. This phenomenon has been documented for various basalts worldwide (Zhong et al., 2017; Li et al., 2019; Zhong et al., 2019). A more significant increase in LOI occurs for BP38_alt (0.40 wt.%), BF13_alt (0.71 wt.%), BF15_alt (0.41 wt.%), and T31_alt (0.24 wt.%), suggesting that vesicular textures and the felsic nature of the samples favour an increase in the LOI. This may indicate the formation of clays or the further oxidation of Fe^{2+} in these materials. Nevertheless, the LOI values remain below 4 wt.%, which is the threshold suggested for altered volcanic rocks (Pandarinath et al., 2024).

The sulfur content of the altered samples (Fig. 8.7b) shows that both BP38_alt and BF13_alt contain high S, probably favoured by the degassing conditions and the structure of the specimens or by some contamination that may have also contributed to the prominent LOI increment. However, the values are significantly low and close to the detection limit (0.001 wt.%).

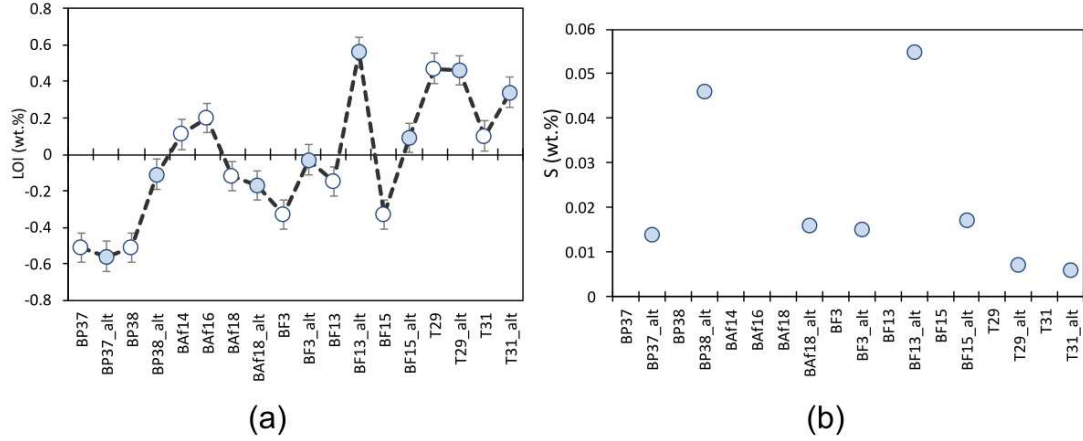


Fig. 8.7. Loss in Ignition (LOI –a) and sulfur content (S – b) of fresh and altered samples analysed in this study. S was obtained only for the altered samples (*reference_alt*).

The CIW (Fig. 8.8a) and CIA (Fig. 8.8b) evidence that both fresh and altered samples remain below the threshold of 60, differing from other altered (naturally) volcanic rock samples (Pandarinath et al., 2024).

Moreover, between the fresh and altered samples, variations in both CIA and CIW are minimal (~0.2 to 2). All basalts (s.l.) and T29 increase CIA and CIW values from fresh to altered members, in contrast to T31_alt, which displayed a reduction in CIA and CIW due to the accentuated increase in CaO, which is considered for both chemical alteration indices. Data projection in the FMW diagram (Fig. 8.8c) shows negligible variation between the fresh and altered members, with points close to the igneous rock trend (in bold; M-F join) and far from the W vertex. T31_alt increased in the mafic source but not along the W vertex.

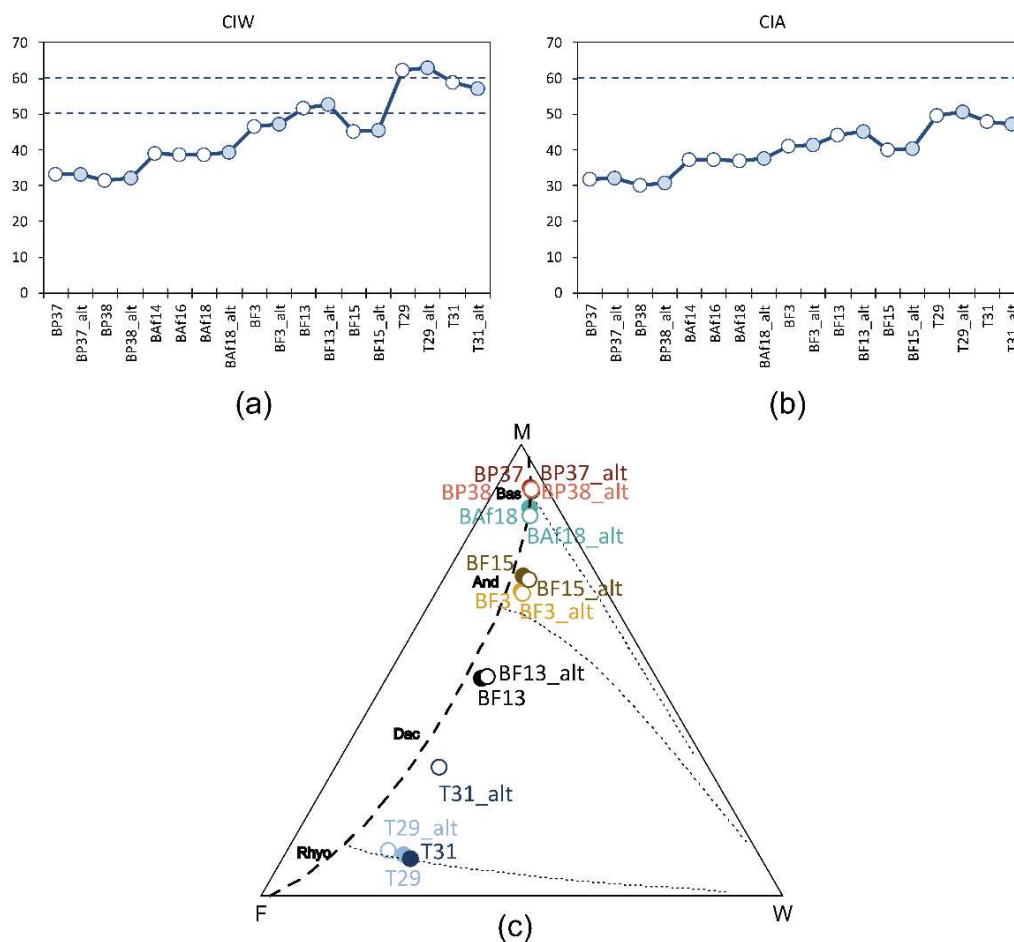


Fig. 8.8. Chemical alteration indices. (a) Chemical Index of Weathering (CIW) and (b) Chemical Index of Alteration (CIA). A threshold of 60 was used for both the indices. A threshold of 50 was also included in the CIW. These thresholds are considered to separate fresh (below the threshold) and altered (above the threshold) lava rocks. (c) FMW weathering index ternary plot (Ohta and Arai, 2007) comprising fresh lava rocks (Pereira et al., 2025; BP37; BP38; BAF18; BF3; BF13; BF15; T29; T31 – full circles) and those submitted to *in situ* alteration (BP37_alt; BP38_alt; BAF18_alt; BF3_alt; BF13_alt; BF15_alt; T29_alt; T31_alt – empty circles). Bas: basalt; And: andesite; Dac: dacite; Rhyo: rhyolite. The bold and dotted line represents the igneous rock trend, and the weathering profiles are displayed along the black dotted lines.

RG5 cuttings: *In situ* altered volcanic rocks from Ribeira Grande geothermal field (Fogo Volcano)

8.2. Summary of materials and methods

8.2.1. Materials

Given the absence/incipient induced alteration of the lava rocks analysed in Section 8.A, cuttings from the RG5 geothermal well were selected (Table 3.2) to investigate the physical properties of different volcanic rocks affected by hydrothermal alteration associated with the active and high-temperature Ribeira Grande geothermal field.

RG5 is an observation geothermal well drilled in 2009 in the Caldeiras sector (Fig. 3.7; see Chapter 3.2.1). RG5 reached a depth of 1343 m and displays a maximum measured temperature of 241 °C (Rangel, 2014). Table 8.1 includes the depth, number, and a brief description of the selected cuttings based on GeothermEx (2008) and Pereira et al. (2022).

The selection of rocks for μ CT considered the size of the cuttings, lithology (lava rock or pyroclastic rocks), degree (fresh or altered), and type (smectite and chlorite zones) of hydrothermal alteration (Pereira et al., 2022). The relationship of the rock type with the geothermal field structure (e.g., reservoir, caprock), as depicted in Fig. 8.9, was also taken into account. Eight μ CT samples were polished to a regular shape using a nail file. Due to the fragile nature of the lithic tuffs, the μ CT specimens were primarily extracted from the ash matrix.

Table 8.1. Selected cuttings from the RG5 well and brief cutting description (GeothermEX, 2008; Pereira et al., 2022). The dry density of all samples was assessed with a pycnometer, but only samples in grey-shaded rows were further analysed using X-ray microtomography. sm – smectite, chl – chlorite, ill – illite, N – number of fragments.

Selected cuttings	Depth (m)	N	Cuttings description per depth level
Lithic tuff	15	7	Moderately consolidated tan to grey lithic tuff. Ash matrix with lava lithics, hyaline crystals, and minor fine pumice. Alteration is weak, mostly clays. The μ CT specimen represents the ash matrix.
Trachyte lava lithics	25	2	Lithics of light grey lava, hard, aphanitic and fresh (slight presence of beige/white clays). Combined with ash matrix fragments (tan) and fine crystals (mostly feldspar).

Table 8.1.(continued).

Selected cuttings	Depth (m)	N	Cuttings description per depth level
Trachyte	41–43	4	Trachytic grey lava, hard, aphanitic to porphyritic. Fresh to weak alteration. Oxides and clays are a coating or pervasive in the groundmass of lavas. Scarce beige clays observed as fillings. The μ CT specimen represents a fresh trachyte.
Altered lithic tuff	79	5	Consolidated light brownish beige lithic tuff in the fresh-sm zones transition. Ash to sandy matrix combined with hyaline feldspar and lava lithics. Alteration is weak and mostly associated with beige/white clays, which correspond to smectite and kaolinite (Pereira et al., 2022). The μ CT specimen obtained from the ash matrix.
Trachyte sm	153–155	4	Grey and moderately hard lava, less vesicular. Weakly to moderately altered, with clay fillings, sometimes associated with silica and calcite crystals, possibly former veins. XRD data (Pereira et al., 2022) revealed discrete smectite, quartz, hematite, and calcite and the absence of chlorite and illite. The μ CT specimen represents a fresh compact trachyte.
Lithic tuff ill/sm	195	5	Light greenish or purplish grey lithic tuff consolidated. Light greenish to brownish grey ash matrix altered to clay. The presence of minor discrete illite and chlorite and interlayered smectite-illite clays (Pereira et al., 2022). Lava lithics mottled by white to green clays. Alteration is moderate (chl zone – ill/sm subzone), and the selected samples are from the ash matrix.
Lithic tuff ill/sm	199	3	Similar to the above. The μ CT specimen represents the ash matrix converted into greenish-light-grey clay.
Intermediate lava	237	5	Massive to vesicular, grey to brownish grey, hard lava, white to green fillings and coatings of clays (mostly discrete chlorite) and quartz, combined with calcite and minor oxidation.
Intermediate lava	269–271	7	As above, but with patchier calcite and quartz, also as fillings. Discrete chlorite prevails with minor interlayered smectite-illite (Pereira et al., 2022). Most investigated lavas were massive to vesicular in texture; the latter were selected for μ CT analysis.
Tuff breccia/caprock	305	7	Light greenish to brownish grey consolidated breccia, moderately hard, with rare calcite crystals and light green altered rock fragments. Significant amount of adularia and illite is the dominant clay (Pereira et al., 2022). Alteration is moderate to strong. The selected cuttings were breccia fragments.
Lava breccia	377–379	6	Weak to moderately altered lava breccia, with brownish/reddish-grey colour and moderately hard. Lava and clay fragments. Presence of hematite, quartz, and minor clays (Pereira et al., 2022).
Reservoir lava	407–411	9	Dark grey lava, hard, low-porosity and aphanitic. Sometimes patchy hematite and the presence of calcite and quartz, either along veinlets or in pores. Fresh to moderately altered, with minor discrete chlorite (Pereira et al., 2022) in pores and associated with titanite.
Reservoir lava	610	3	As mentioned above, with discrete illite (Pereira et al., 2022).
Altered rock	847	1	Altered pale green rock, sometimes brownish, moderately hard and compact, with strong alteration, displaying silicification and chloritisation (discrete illite and chlorite). Loose calcite and quartz are probably from veins.

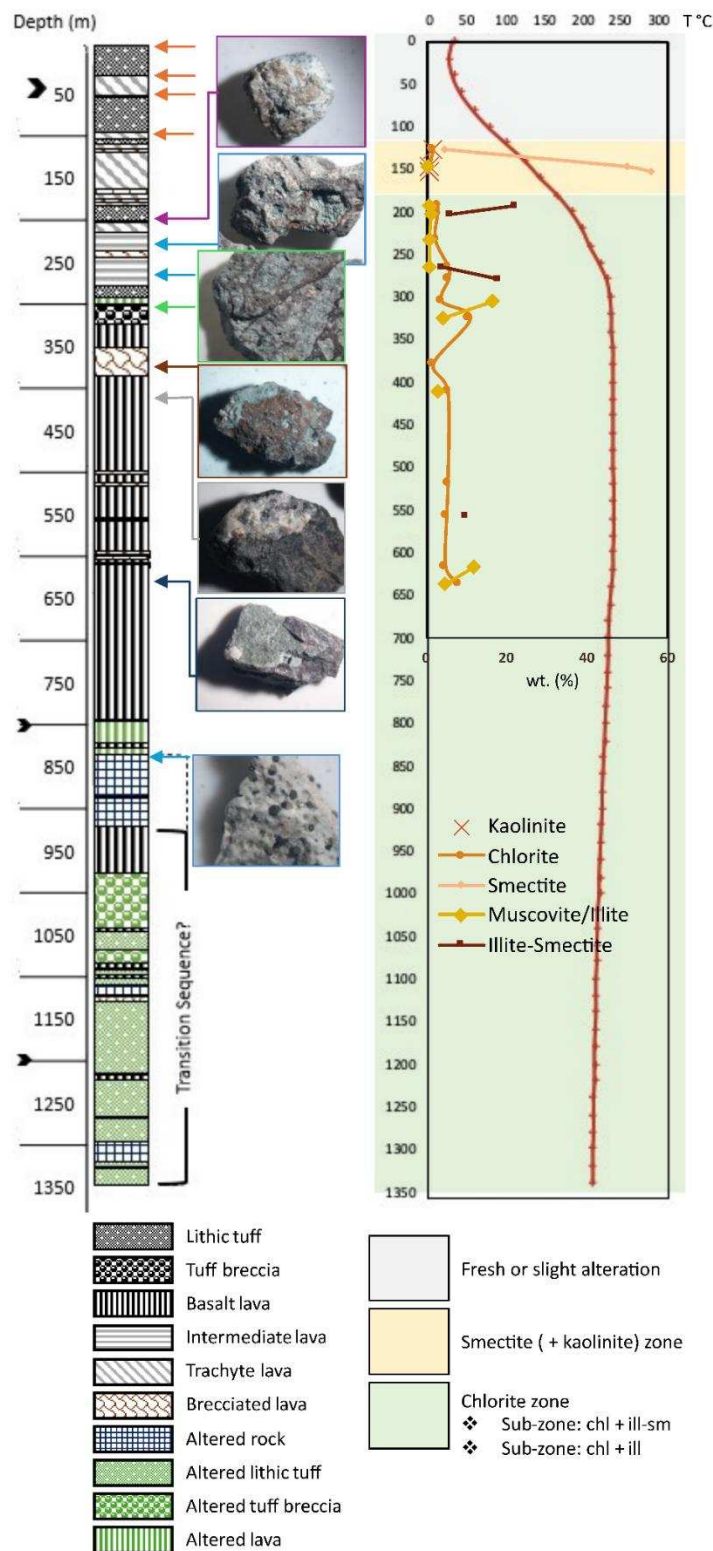


Fig. 8.9. RG5 well subsurface geology according to Pereira et al. (2022; licensed under CC BY-NC-ND 4.0) and binocular microscope photographs of some cuttings obtained from the selected depth levels (coloured arrows; microphotographs of the lithic tuff in the illite-smectite subzone; vesicular intermediate lava; caprock tuff breccia; lava breccia, reservoir lavas and altered rock – Table 8.1). The evolution of temperature (red line, T) and the amount of clay minerals (wt.%) throughout depth and along the main hydrothermal alteration zones (grey, beige, and light green) are presented.

8.2.2. Methods

The dry density (ρ_{dry_pyc}) of several cuttings (Table 8.1) followed the procedure of Section 3.2.4.1, using a pycnometer, and was calculated according to Eq. 3.6.

Similarly to Section 8.A., X-ray imaging of the regularised cuttings was obtained through μ CT (Section 3.2.2.3). Scans were performed in absorption mode, acquiring 2401 2D radiographs (projections) over a 360 °rotation and the conditions (air, 80 kV, 87 μ A, 4X) presented in Table 3.3. The nominal voxel size of 4.04 μ m was selected to better assess the void space of the massive lavas.

The digital volume of the samples allowed for the segmentation of the pore space and quantification of various physical properties (total porosity – n_T and effective/ open porosity – n_{eff}) and opaque minerals (Op), as described in Section 3.2.2.3. Clay mineral identification was difficult because of the similar grey-scale levels to other groundmass minerals (e.g., feldspars). Whenever the specimens displayed connected porosity, both T and k were computed (see Section 3.2.6.2).

8.3. Results and discussion

8.3.1. Density

The results for ρ_{dry_pyc} are presented in Fig. 8.10, corresponding to a total of 71 measurements. Fig. 8.10a depicts several rock types along the depth (x-axis). Fig. 8.10b concerns ρ_{dry_pyc} for lava rocks, while Fig. 8.10c regards pyroclastic rocks. Average values are shown in the plots.

Lavas are denser (average of 1.8 g/cm³) than pyroclastic materials (average of 1.4 g/cm³).

Fresh and superficial trachyte lavas are slightly denser than higher depth fresh and weakly altered trachytes (41–43 m and 153–155 m depth). Intermediate lavas are denser than trachyte lavas, with densities in the range of 1.6–2.3 g/cm³. Lower values occur for vesicular intermediate lavas, which are brownish/greenish grey with rock pores filled with silica and chlorite minerals (Table 8.1 and Fig. 8.9), while massive lavas are denser.

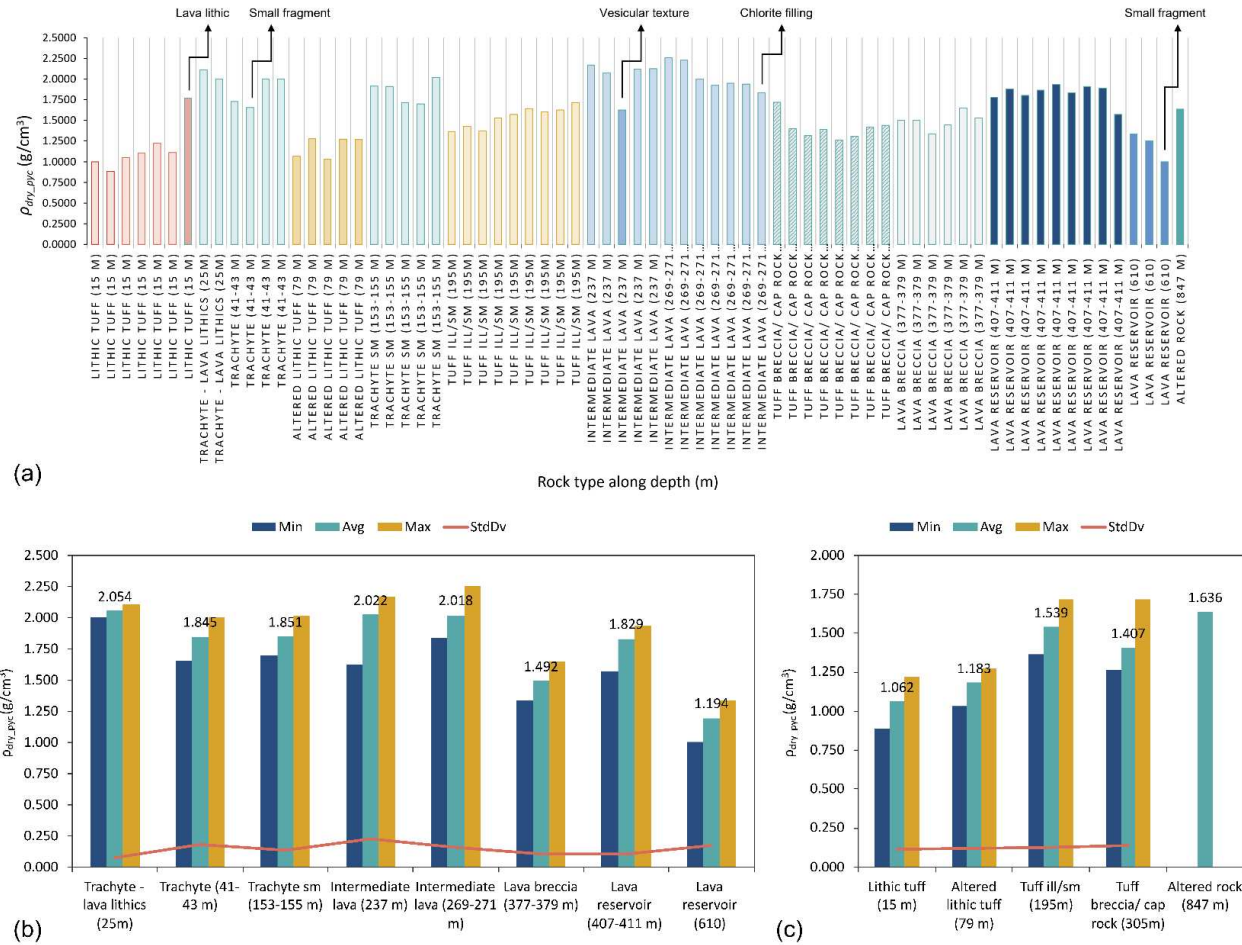


Fig. 8.10. Dry density of the investigated rocks measured using a pycnometer (ρ_{dry_pyc}). (a) ρ_{dry_pyc} measured for all investigated lithologies along the depth of RG5 well; (b) ρ_{dry_pyc} statistical metrics for lava rocks; and (c) ρ_{dry_pyc} statistical metrics for pyroclastic rocks. Min – minimum; Avg – average; Max – maximum; Std.Dv – standard deviation.

Lavas of the reservoir lavas decrease in density with depth, from 1.8 g/cm³ to 1.2 g/cm³ on average. Notwithstanding, this decrease may also be related to the fact that fragments collected from the end of the reservoir (610 m) were smaller and more prone to inaccurate density measurements using the pycnometer. Among the lavas, lava breccia is the least dense (excluding the lava reservoir from 610 m) due to its less consolidated and brecciated texture. This texture favours the filling and coatings by clay minerals and oxides, as well as the veining by quartz and calcite (Table 8.1).

RG5 trachytes and intermediate lavas, which show weak alteration, have densities that are either higher than or similar to those reported for highly altered to fully altered trachytes and andesites (Pereira et al., 2024a; Chapter 7). In contrast, the densities of reservoir lavas are lower than those of the altered lavas discussed by Pereira et al. (2024a). Additionally, the RG5 lava breccia is approximately 0.2 g/cm³ less dense than similar rocks that exhibit slight to high argillic alteration (Pereira et al., 20024a). These results indicate that trachytes can have densities comparable to those of reservoir lavas. This may be attributed to reservoir lavas belonging to the chlorite zone and being influenced by increasing alteration with depth.

The pyroclastic rocks appear to be more altered than the lavas, and their average ρ_{dry_pyc} increases with depth, except for the caprock (Fig. 8.10a and Fig. 8.10c). The superficial lithic tuff (15 m depth; ρ_{dry_pyc} = 0.9–1.2 g/cm³) is affected by weak acidic alteration, forming kaolinite coatings (Table 8.1). However, the extent of this alteration is less than that observed in the lithic tuff at a depth of 79 m, which is already transitioning from fresh material to the smectite zone (see Fig. 8.9). The average ρ_{dry_pyc} of the 79 m depth lithic tuff increases to 1.2 g/cm³, with a maximum value of 1.3 g/cm³. With increasing depth and alteration, the lithic tuff in the illite-smectite subzone of the chlorite facies (Fig. 8.10) has a higher density, ranging between 1.4 and 1.7 g/cm³. Because the three mentioned tuffs correspond to the same lithology, it can be stated that increasing the depth favours compaction and alteration, which promotes void infilling and the coating of the primary minerals, leading to increased dry density. Consequently, it can be inferred that hydrothermal alteration influences porosity, void space connectivity, and mechanical properties, as previously reported for other pyroclastic materials (Wyering et al., 2014; Stimac et al., 2015; Durán et al., 2019).

The tuff breccia has similar ρ_{dry_pyc} values to the lithic tuff found in the chlorite zone, with ρ_{dry_pyc} = 1.3–1.7 g/cm³. Despite its brecciated texture, the caprock is well-consolidated and has high content of adularia, illite, and chlorite (Table 8.1), which accounts for its density.

The more altered tuffs in RG5 (“tuff ill/sm” and the caprock) have densities similar to argillic tuffs or highly altered pyroclastics as reviewed by Pereira et al. (2024a).

Below the geothermal reservoir, the altered rock continues to demonstrate this density trend, recorded at $\rho_{dry,pyc} = 1.6 \text{ g/cm}^3$. This may be due to increased compaction and significant hydrothermal alteration manifested by mineral fillings and coatings.

8.3.2. Microstructural analysis

3D images were obtained for the four lava rocks (Fig. 8.11) and four pyroclastic rocks (Fig. 8.12), highlighted in grey in Table 8.1.

Regarding lava rocks, the superficial trachyte (41–43 m depth) in the fresh zone of the geothermal field has a structure similar to T31 (before and after induced alteration – Fig. 8.4e), with groundmass pores displayed between the feldspar laths. For the obtained nominal voxel size ($\sim 4 \mu\text{m}$), the trachyte from RG5 has a $n_T = 1.86 \%$ and $Op = 1.14 \%$, similar to values of T31 (Pereira et al., 2025a; Chapter 4) and T31_alt (Fig. 8.3e). The “trachyte sm” rock shows a significant decrease in porosity ($n_T = 0.09 \%$), while opaque minerals amount increases ($Op = 4.21 \%$). Based on microscope observations, this sample is more compact and has an intergranular void space filled by clay minerals (Table 8.1). At the selected voxel size, connected porosity is only observed at feldspar phenocrysts (Fig. 8.11; $n_T = 1.03 \%$; $n_{eff} = 0.77 \%$), which contain intragranular and tortuous cracks ($T = 2.35$) that contribute to minor fluid flow within the crystal ($k = 0.05 \text{ mD}$). The feldspar crystals also show an irregular light-grey shadow, which might correspond to an alteration coating. The decrease in porosity is attributed to the primary structure of the lava rock, as well as to increased clay content due to alteration, rather than mechanical compaction with depth, as lavas are less susceptible to such a phenomenon than tuffs (Stimac et al., 2015; Cant et al., 2018; Chapter 7).

The intermediate lava rock (269–271 m depth) contains pores dispersed in a low-porosity matrix with sparse opaque minerals ($n_T = 1.03 \%$; $Op = 5.65 \%$). Vesicles are filled with acicular and spheroidal minerals (Fig. 8.11), which may correspond to the silica/calcite associated with discrete chlorite, as observed under a binocular microscope (Table 8.1). It should be noted that despite the increased total porosity owing to the large pores, the connected porosity for a voxel size of $4 \mu\text{m}$ is null. This might be due to the precipitation of secondary minerals that fill the connections between vesicles (throats), which is a common phenomenon in hydrothermal systems (Chapter 7). The observations for RG5 intermediate lava contrast to what has been observed for BF13 (Section 8.3.2, Part A) and vesicular samples analysed in Pereira et al. (2025a) and Chapter 4. Moreover, specific textures are

observed in mafic minerals, probably pyroxene, which might correspond to primary exsolution lamellae (Fig. 8.11) that is not produced by alteration.

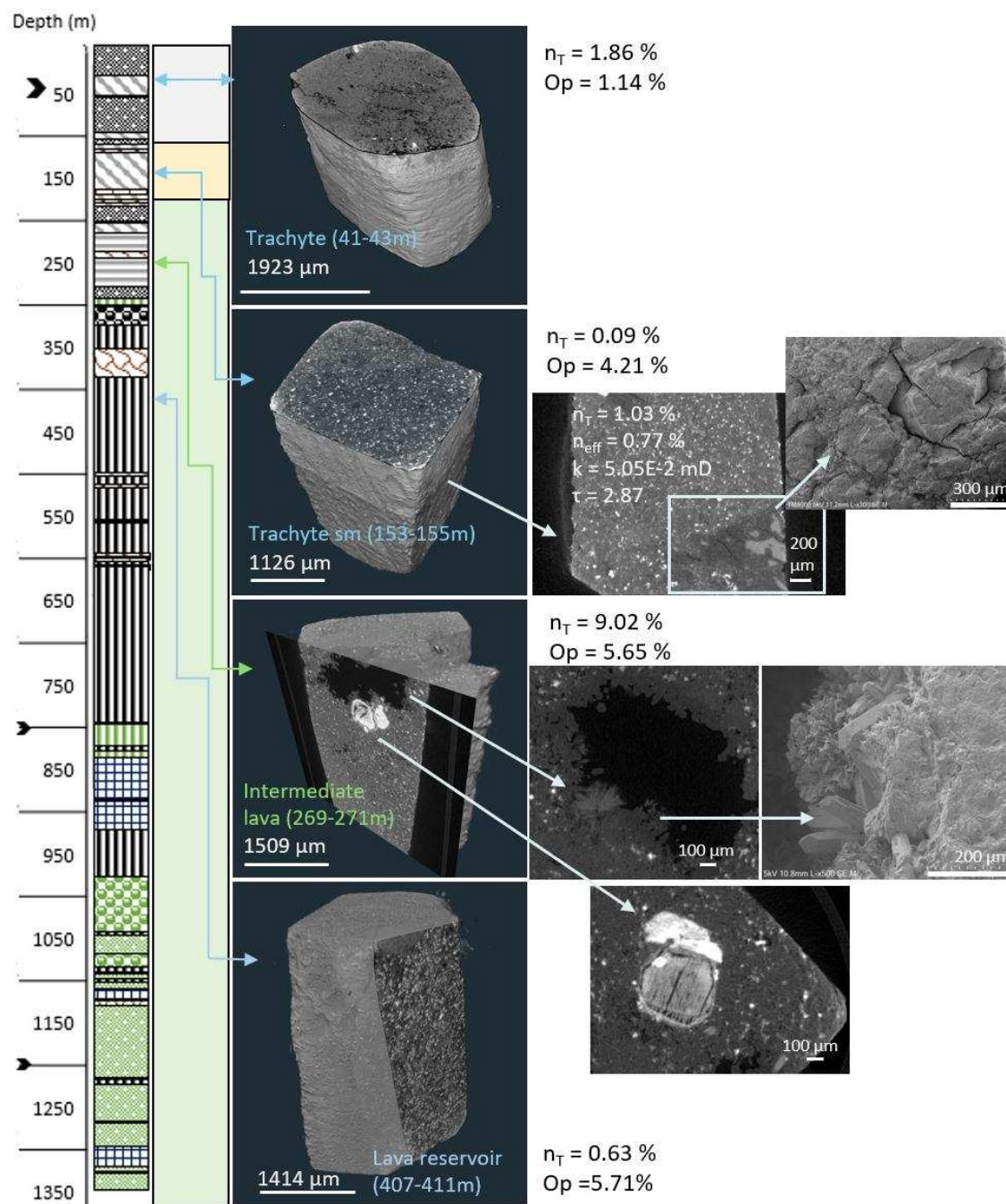


Fig. 8.11. 3D images of selected lava rocks obtained via X-ray microtomography (voxel size of $\sim 4 \mu\text{m}$). Quantification of physical properties - n_T – total porosity; n_{eff} – connected porosity; T – tortuosity; k – permeability; Op – content in opaque minerals – using image analysis. The representation includes the subsurface geology of RG5 well, the main hydrothermal zones (see Fig. 8.9), and some detailed features of the 3D scans. Scanning electron microscope imaging of the fractured alkali feldspar crystal and surficial pores of the intermediate lava containing secondary mineral fillings are also included.

The lava reservoir is a low-porosity ($n_T = 0.63 \%$) sample that keeps a similar amount of opaque minerals (5.71 %) to the intermediate lavas. It is assumed that part of these dense minerals may be formed by hydrothermal alteration. Furthermore, the lava rock itself does not contribute to the permeability of the system, as no connected porosity is defined for the used voxel size.

The pyroclastic minerals are visibly more porous than the lava rocks, particularly those occurring at lower depths (Fig. 8.12).

The ash matrix of the lithic tuff from 15 m depth ($n_T = 14.84 \%$; $n_{eff} = 10.39 \%$; $T = 2.35$; $k = 0.65$ mD; $Op = 1.68 \%$) contains irregular pores coated with acicular light-grey secondary minerals, while the matrix contains vermicular dark-grey minerals, which are probably secondary clays. The vesicular texture and high porosity of these rocks contributed to the connected but tortuous void space. However, the permeability is limited and much lower than that observed for vesicular lava rock BF13 (Fig. 8.3d). The ash matrix of the lithic tuff at 79 m depth (transition from weak alteration to smectite zone) has physical properties ($n_T = 15.08 \%$; $n_{eff} = 11.43 \%$; $T = 2.35$; $k = 0.90$ mD; $Op = 0.54 \%$) of similar values to the lithic tuff above, but the intergranular pores are smaller and distributed all over the rock (Fig. 8.12).

Variations become visible for the ash matrix of the lithic tuff from the illite-smectite subzone, which is more compact ($n_T = 1.57 \%$) and has no connected porosity for the $\sim 4 \mu\text{m}$ nominal voxel size. The 15 times reduction in porosity might be due to the primary structure of the tuff combined with more intense hydrothermal alteration (Table 8.1) and mechanical compaction due to increased depth.

The tuff breccia that constitutes the impermeable caprock above the reservoir shows an increased amount of opaque minerals (4.61 %) and pores ($n_T = 4.61 \%$). The pores are not connected between them, have polygonal/ angular shape and contain hydrothermal minerals of different morphologies (Fig. 8.12). For the selected resolution, no matrix permeability exists, sustaining that these rocks are impermeable. Furthermore, moderate to strong hydrothermal alteration favoured the precipitation of secondary minerals, as shown by the skeleton veinlets present in the tuff breccia (Fig. 8.12).

Overall, lavas and tuffs have lower values of porosity than altered lavas, pyroclastic rocks, and tuffs reviewed by Pereira et al. (2024a) because of the specimen size and chosen resolution for μCT .

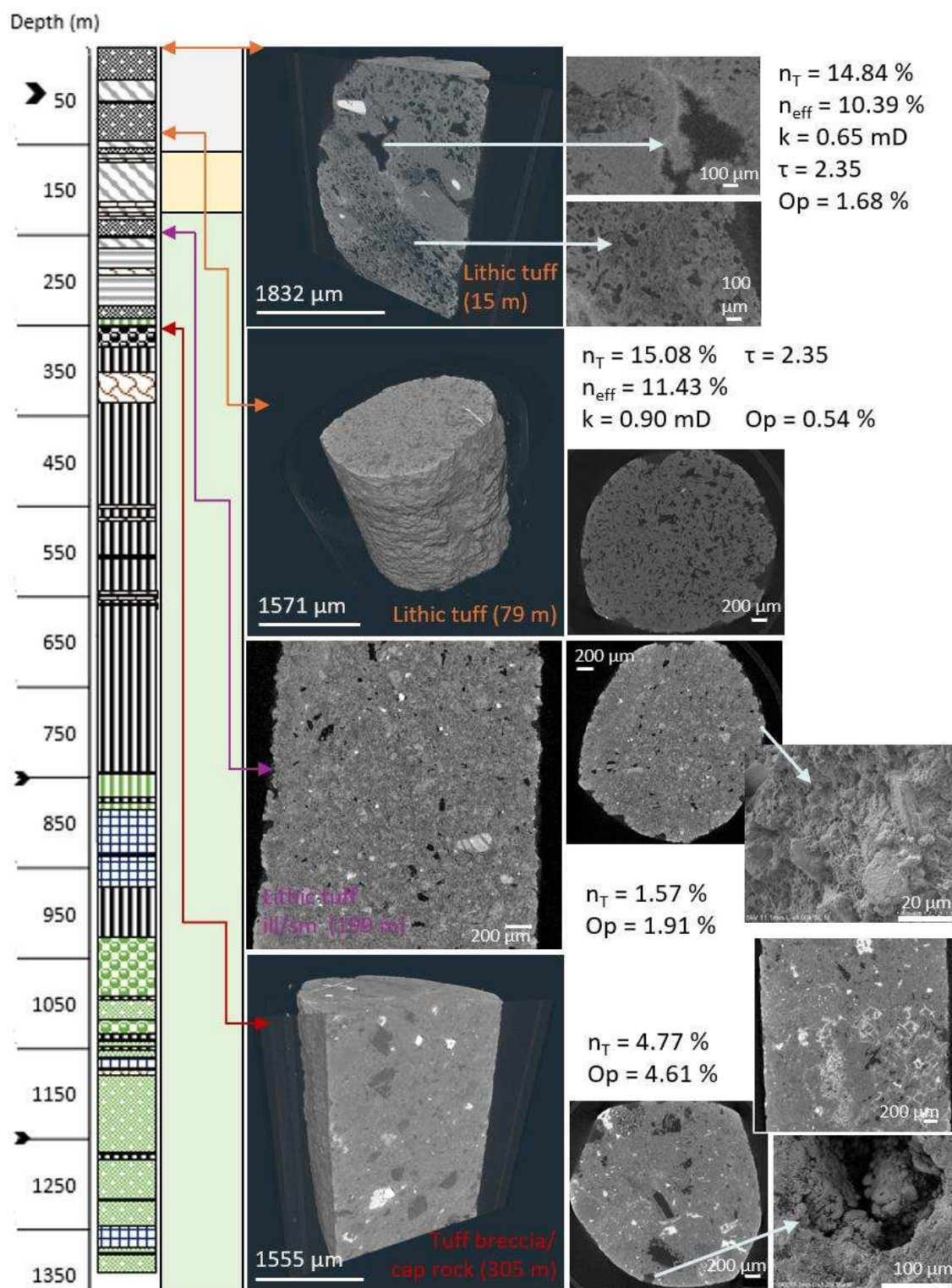


Fig. 8.12. 3D images of selected pyroclastic rocks obtained via X-ray microtomography (voxel size of $\sim 4 \mu\text{m}$). Quantification of physical properties - n_T - total porosity; n_{eff} - connected porosity; T - tortuosity; k - permeability; Op - content in opaque minerals - using image analysis. The representation includes the subsurface geology of RG5 well, the main hydrothermal zones (see Fig. 8.9), and some detailed features of the 3D scans. Scanning electron microscopy imaging of the surface matrix of the lithic tuff (illite-smectite subzone) and surficial pores of the caprock containing secondary mineral fillings are also included.

RG5 well is in the northeastern-most part of the Ribeira Grande geothermal field (Fig. 3.7), displaying a low initial reservoir pressure (~52.3 bar at 800 m), in contrast with the estimated high temperature (Rangel, 2014). The distribution patterns of both the temperature and pressure of the geothermal field depend on the fluid density, depth, and permeability of the feed zones of the field (Rangel, 2014). In other words, in the upflow zones, the high-temperature fluid with low density rises and becomes cooler and denser in the lateral flow areas, possibly increasing pressure. The conceptual model of the Ribeira Grande geothermal field considers a geothermal fluid (~250 °C) that enters the reservoir in an upflow zone located in the southeastern part of the field (east of the Cachaços-Lombadas sector – Fig. 3.7) and flows laterally at shallower levels to the northwest, forming an extensive and relatively shallow reservoir in the Pico Vermelho sector (GeothermEx, 2008). Thus, RG5 is located in a peripheral hot zone and might be weakly connected to the remaining part of the field because of the existence of structures (faults or fractures) that restrict fluid flow, or due to restricted feed zones.

The obtained results reveal a low-porosity matrix of the volcanic rocks present in RG5 well, making them impermeable and probably more resistant to mechanical failure, despite increasing hydrothermal alteration with depth. Thus, the permeability in the system is sustained via major structures (fracture-dominated permeability), probably vertically, as the host rocks have poor connectivity and the well has low reservoir pressure (Rangel, 2014). The physical properties established in this study support the idea of a fracture-fed RG5 well that is hydraulically isolated. Despite connecting to zones that supply high temperature fluids, RG5 well low pressure and low-porosity rocks might limit sustainable fluid rates and storage capacity, decreasing their geothermal and carbon mineralisation potential.

8.3.3 Physical data versus the XRD data from Pereira et al. (2022)

Fig. 8.13a completes the XRD data from Pereira et al. (2022), including new findings regarding the density and total porosity of volcanic rocks from RG5. Variations along the depth are focused for both the physical properties (Fig. 8.13b and Fig. 8.13c) given the intercalation of lavas, which are denser and less porous, with pyroclastic materials, less dense, and more porous. Exceptions occur in the lava breccia (Fig. 8.13b), that has densities close to the tuffs, and for the intermediate lava (Fig. 8.13c), with significant porosity due to the vesicular texture.

Crossing the total porosity and density data with the amount of minerals (clays, quartz, and calcite – XRD data from Pereira et al., 2022) resulted in scattered data (Fig. 8.13b and Fig. 8.13c), which indicates the lack of dependence between the variables. Discrete chlorite

remains constant and independent of porosity, density, and rock type (Fig. 8.13b and Fig. 8.13c), confirming its stability over a wide range of temperatures and hydrothermal settings (Fig. 7.2). Discrete illite reaches its peak in the tuff breccia (caprock) with relatively low porosity and moderate density. This is indicative of zones of former high permeability that are presently sealed (e.g., Reyes, 1990). Interlayered clays occur in the low-porosity lithic tuff in the chlorite zone and are scarce or non-existent in lava rocks. This is due to a combination of increased depth and temperature, with diffuse fluid flow, that is typical in tuffs and favourable to interlayered clays precipitation (Harvey and Browne, 1991; Utami and Browne, 1999; Pandarinath et al., 2006).

Higher levels of calcite are obtained for lava rocks of variable density, that is, for less dense lava breccia and for denser rocks, such as low-porosity reservoir lavas or vesicular intermediate lavas. The pyroclastic rocks have lower calcification. On the other hand, intense silicification affects both the lava rock and tuffs at various depths, confirming the frequent occurrence of this type of alteration. Both the low-porosity lava reservoir and “tuff ill/sm” have high content in secondary quartz, as well as the caprock, lava breccia, and vesicular intermediate rock. While quartz is formed for different lithologies that allow for distinct fluid flow types (diffuse and channelled), calcite formation is limited to lavas, where the percolation of fluids is controlled by fractures. Both minerals, together with chlorite and illite, indicate that former zones of high permeability are now sealed (e.g., Reyes, 1990; Lagat, 2009).

Fig. 8.13. (Next page) New physical data on cuttings and previous findings by Pereira et al. (2022; licensed under CC BY-NC-ND 4.0). (a) Minerals determined by XRD analysis (in wt.%) conducted by Pereira et al. (2022), complemented with values of the average dry density (g/cm^3) and total porosity (%) with depth. The temperature of the RG5 well is represented by the red full line. (b) Variation of average dry density with depth for pyroclastic and lava rocks and its correlation with the amount of minerals (clays, quart, and calcite). (c) Variation of total porosity with depth for pyroclastic and lava rocks and its correlation with the amount of minerals (clays, quart, and calcite).

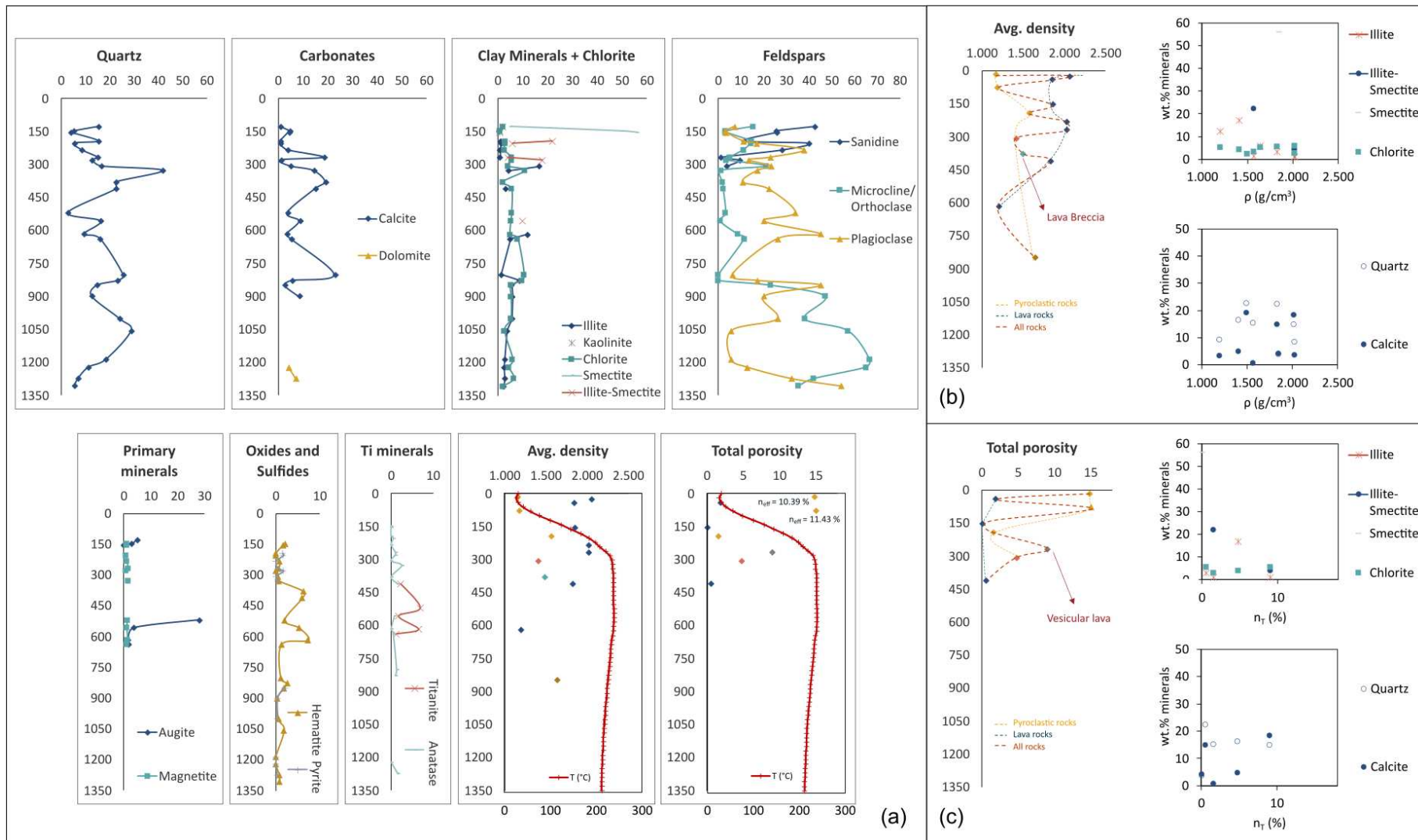


Fig. 8.13. Caption in the previous page.

8.4. Conclusions

The microstructure and hydrothermal alteration of volcanic rocks from São Miguel Island have been studied by focusing on induced alteration in the field and analysis of cuttings from a geothermal well. The research establishes that structure, particularly the porosity of the rocks, is a key controller in the development of hydrothermal alteration, either close to the surface or at depth.

For the induced alteration experiment (*Part A*), lava rock specimens were buried at a fumarolic ground for four months. Results showed only superficial alteration, with minimal changes in microstructure, physical properties, and chemical composition. Thus, this experiment showed that the chosen timeframe for the environmental conditions was insufficient to produce significant hydrothermal alteration in the samples, especially the ones with a more massive texture, rendering further mechanical and physical testing invalid.

Analysis of cuttings from the RG5 geothermal well (*Part B*) provided insights into naturally altered volcanic rocks at various depths. For the first time, rock digital physics was applied to these materials, allowing for the determination of several physical properties and complementing previous petrographic and X-ray diffraction findings. The main conclusions include:

- Lavas generally showed higher density and lower porosity compared to pyroclastic rocks.
- Hydrothermal alteration and compaction increased with depth, leading to higher dry densities in pyroclastic materials.
- Microstructural analysis revealed that alteration infilled void space, covering the interior of pores and reducing the overall porosity and permeability. Volcanic rocks with high porosity can have their connected porosity significantly limited.
- The geothermal reservoir rocks showed low porosity and permeability, suggesting that the system's permeability is primarily fracture-dominated. On the other hand, the tuff breccia, despite its texture, is impermeable, sustaining its role as a caprock in the system.
- No clear correlation was found between physical properties (porosity and density) and the abundance of secondary minerals.

The obtained data contribute to understanding the characteristics of the Ribeira Grande geothermal field, particularly in the RG5 well area (Caldeiras sector, north flank of Fogo Volcano). The low-porosity matrix of volcanic rocks implies limited fluid storage capacity

and sustainable flow rates, which may impact the geothermal potential of some wells and carbon mineralisation capabilities. This research is preliminary but lays the groundwork for future studies on Azorean volcanic rocks, which could refine conceptual models of the geothermal field. Further investigation is needed to fully understand the influence of hydrothermal alteration on the mechanical behaviour of these rocks and their potential role in integrated geothermal-carbon capture and storage operations.

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Chapter

Results integration and final discussion

Results integration and final discussion

9.1. Preliminary note

The following chapter summarises the main findings from Chapters 4 to 8, relating and positioning them within a broader theoretical context. The general discussion is framed around the aims outlined in Chapter 1, complemented with a critical review of the significance and limitations of the obtained results.

9.2. Integration and contextualisation of the main findings

The main findings are consolidated and discussed in this section from a micro- to intact rock scale. Most results align with existing literature, reinforcing established concepts while further extending current knowledge, contributing to a deeper understanding of lava rock behaviour across scales.

9.2.1. Microscale

The analysed lava samples, collected from Sete Cidades and Fogo volcanoes, range in composition from basalts (s.l.) to trachytes and show diverse textures, from massive (low to medium macroscopic porosity, with scarce to millimetric pores) to vesicular (high porosity, with pores reaching centimetric sizes) at the hand-sample scale. Petrographic observations, supported by whole-rock geochemical data, allowed the classification of the collected lava types, all of them with a holocrystalline porphyritic texture. Basalts include alkali basalts and trachybasalts, while intermediate lavas comprise basaltic trachyandesites (mugearites) to trachyandesites (benmoreites). Vesicular textures were sampled in intermediate lavas, whereas trachytes and basalts are massive, with sparse microcracks and porous bands.

Lava rocks are structurally complex, shaped by a variety of tectonic and eruptive processes (Kennedy et al., 2010; Lamur et al., 2017; Colombier et al., 2017). They present significant variability in chemical, mineralogical, and microstructural characteristics, which are not always evident macroscopically (Mogi, 2006; Heap and Violay, 2021). Given the critical influence of microstructure on the physical and mechanical properties of rocks, its characterisation is essential for understanding intact rock behaviour.

The adopted multi-method, multi-scale approach proved effective for investigating the micro- to intact-scale features of the lava rocks. While the employed techniques are complementary, their differing analytical conditions and resolutions preclude direct data comparisons. Conventional laboratory methods remain practical and cost-effective for basic characterisation, whereas advanced imaging techniques provide high-resolution insights into the microstructure.

To achieve a more complete microstructural characterisation, both 2D and 3D imaging techniques were employed. Thin-section photomicrographs and SEM-BSE images enabled quantitative analysis of phenocryst and pore content in 2D. μ CT offered 3D visualisation of both pores and crystals ($> 15 \mu\text{m}$ resolution), particularly valuable for assessing pore connectivity, which influences rock behaviour. μ CT effectively captured vesicular and fractured textures, while SEM-BSE imaging provided the resolution needed to characterise microporosity.

MIP was employed to characterise the pore size distribution and mean pore radius for pores smaller than $180 \mu\text{m}$. The results reveal that lava rocks, regardless of composition, have unimodal, bimodal, or polymodal PSD, and the n_{eff} generally increases with r . Most analysed lavas have a massive texture dominated by micropores (radius $< 15 \mu\text{m}$). Pore size intervals, linked to fluid transport mechanisms (Fig. 2.9), suggest that these massive lavas, irrespective of type, are prone to vapour adsorption and capillary condensation. In contrast, vesicular and medium-porosity lavas have a greater proportion of macropores and larger mean radii, suggesting that other transport mechanisms may prevail.

Microstructural observations in both 2D and 3D support prior classifications in the literature, which show that porosity in lava rocks spans from pore-dominated to microcrack-dominated microstructures, with intermediate forms displaying a combination of both (Cant et al., 2018). MIP data, when combined with pore network modelling (PNM), yield critical insights into vesicular lavas, which have a significant number of pores with an equivalent pore radius $> 700 \mu\text{m}$, often due to pore coalescence. Sphericity quantification resulted in average of .59 to 0.65 combined with a higher elongation. Internal 3D imagery further reveals that pore-linking fractures connect most pores. Permeability simulations and pore throat size analyses indicate that in vesicular samples, permeability is primarily governed by pore size rather than by total porosity. Conversely, in fractured lavas, characterised by smaller equivalent pore radii ($< 620 \mu\text{m}$) and a denser network of narrow throats, fluid flow appears more dependent on porosity.

The pore structure of lava rocks cannot be directly characterised using the carbonate rock classification proposed by Lucia (2007). In the studied lava rocks, intra- and intergranular porosity is typically composed of isolated, regularly shaped pores, often round, with connectivity facilitated by microcracks. Pores in the groundmass can also be angular when limited by feldspar laths. Vesicular lavas, by contrast, are pore-dominated and contain a variety of pore sizes and geometries, ranging from isolated with high sphericity (~ 0.80) to elongated due to coalescence. Pore-linking fractures and coalescence enhance connectivity in these rocks, as mentioned, and reduce the sphericity of the connected pores. Shape metrics, like sphericity and aspect ratio, are significantly influenced by pore coalescence and the presence of pore-linking microcracks, offering indirect indicators of the pore space system.

As previously suggested (Heap et al., 2014a; Heap et al., 2014b; Cant et al., 2018), the architecture of the void space, comprising the connectivity, size distribution, and r , plays a primary role in both mechanical behaviour and fluid flow dynamics. Time-resolved mechanical testing combined with μ CT confirm that all lavas are brittle under unconfined compression, developing multiple tensile fractures (splitting) aligned parallel with the loading direction. Both phenocryst and pores, especially those elongated and of significant size, acted as stress concentrators at their tips and edges, influencing crack propagation paths. These observations align with results from Brazilian disc tests and numerical modelling studies (Heap et al., 2014b; Bubeck et al., 2017). Real-time microstructural observations confirm that microcracks act as precursors to macroscopic fractures, by growing into visible joints and eventually into open fractures, as established for rock failure (Hencher, 2015).

Massive, low-porosity basalts (s.l.) show higher strength and lower deformation than trachyte, likely due to the texture and preferred crystal orientation, as pointed out before (Heap et al., 2016). At the same time, large pores (average equivalent radius $> 950 \mu\text{m}$) in vesicular lavas, especially those located near specimen edges and occupying a significant portion of the sample length, reduced $\sigma_{c,UCS}$ to half and led to more irregular fracture patterns. Additionally, the high n_{eff} in vesicular lavas is considered an overall weakening factor. No definitive conclusions could be drawn regarding the influence of pore orientation on mechanical behaviour, as the pores displayed different inclinations relative to the loading axis, with their size and spatial distribution inducing variability in strength.

$\sigma_{c,UCS}$ remained relatively consistent from microscale specimens to intact rock samples, despite the smaller diameters used in time-resolved tests. This finding suggests that

maintaining a consistent L/D ratio is essential, reiterating the results from limestone studies by Van Stappen et al. (2019) to lava rocks. However, in vesicular specimens, the spatial distribution of large pores with respect to the specimen length impacts the strength, as mentioned above. Contrary to UCS, stiffness comparison between scales was limited by differences in the strain measurement techniques. Even for the intact rock study (Chapter 5), variations between measurements obtained using SG and LVDT introduced discrepancies in the derived stiffness values.

9.2.2. Intact rock

General view of the used methods and sample organisation

This research reinforces that the concept of intact rock integrates both geotechnical and geological meanings. Lava rocks show significant variability, with microstructural features (defects) strongly influencing their physical and mechanical behaviour. A comprehensive assessment of anisotropy would require testing across multiple orientations, which was not possible. Nevertheless, the defects present in lavas introduced heterogeneity within the same block, reflected by spatial variations in properties (e.g., strength, capillary absorption, and ultrasonic wave velocity), that may be transposed to the rock mass. In turn, individual specimens have consistent ultrasonic wave velocities and capillary absorption that contrasts with the inter-group variability, reflecting differences in structure, texture, and mineralogy between samples.

The defined subgroups (Fig. 3.6) for the collected samples effectively captured the main structural and textural controls in the physical and mechanical properties. Grouping by subfacies presents a practical approach, especially when sufficient specimens from a single block are unavailable. In addition, the specimen sizes adopted for laboratory testing proved adequate for capturing natural heterogeneities of lava rocks, and standardised testing methods remain cost-effective and accessible, allowing inter-laboratory comparison of rock mechanics data.

Modifications to conventional procedures, such as the use of millimetric sized prisms compatible with μ CT and MIP techniques, produced comparable density and n_{eff} . However, fractured or massive samples with higher microcrack density ($n_{eff} > \sim 10\%$) are better represented by irregular lumps or larger, regular-shaped specimens. Pycnometric density measures were also useful for friable samples, such as cuttings. In general, pycnometer-

based densities were slightly lower, possibly due to the small size and alteration of the tested cuttings.

Density, open porosity, and ultrasonic wave velocities

The physical property data reveal that lava rocks can have a wide range of porosities, reaching similar values to the average ones established for pyroclastic materials by Pereira et al. (2024a). ρ and n_{eff} are inversely correlated, regardless of rock type, specimen size, or alteration state, which is consistent with patterns reported in the literature and the review by Pereira et al. (2024a). Principal component analysis (PCA) indicates that ρ and n_{eff} are primarily governed by void space characteristics, including PSD and connectivity. However, the data also suggest that, unlike n_{eff} , ρ is influenced by mineralogical composition, decreasing from mafic to felsic lithologies and aligned with established trends in the literature (González de Vallejo and Ferrer, 2011; Schön, 2015; Pereira et al., 2024a).

Differences between n_{eff_Hg} and n_{eff} can be attributed to the contrasting accessibility of fine pore and throats, which are more easily reached by mercury than water for the used testing pressures. Capillary-connected porosity (n_{cc}) is consistently lower than n_{eff} , and differences are amplified for vesicular samples, where only a fraction of the connected pore space contributes to capillary water absorption.

The combined influence of mineralogy, porosity, and microstructure observed in ρ is more evident for ultrasonic wave velocities, as indicated by PCA. However, the heterogeneity of lavas induces V_p scattering, a phenomenon previously reported for other volcanic rocks and attributed to the variable microstructures (Pappalardo et al., 2017; Bustos and Adam, 2023), which limits the use of V_p as a reliable predictor of rock strength. The determination of V_s proved more challenging, affecting the reproducibility of dynamic elastic moduli and Poisson's ratio. Nonetheless, the V_p/V_s ratios fall within the range reported for other volcanic rocks (Japsen and Mavko, 2006; Lesage et al., 2018).

Crack thresholds, strength, and stiffness

Connected porosity is a critical parameter in the characterisation of lava rocks. Higher n_{eff} generally correlates with lower strength, E , ρ , and ultrasonic wave velocities. The σ_{c_UCS} and E decreases nonlinearly with increasing n_{eff} , aligning with trends reported by González de Vallejo and Ferrer (2011), Heap and Violay (2021), and Pereira et al. (2024a).

n_{eff} appears to control the mechanical behaviour of lava rocks, particularly their peak stress. Strength values discrepancy becomes more evident in lavas with low porosity and smaller pore sizes, whereas vesicular specimens tend to display a more consistent strength. However, the ratios of crack initiation (σ_{ci}) and damage stress (σ_{cd}) to peak strength appear unaffected by initial porosity and texture, i.e, vesicular or massive. However, fresh to slightly altered low-porosity trachytes display crack initiation and damage at lower stress levels, despite reaching high σ_p . It was also verified that crack damage inherits the already accumulated damage but also depends on newly formed fractures.

Contrary to n_{eff} , mineral composition plays a secondary role in determining strength. More felsic lavas with higher alkali content, such as trachytes, display lower ρ , E , and ultrasonic velocities, alongside higher v . Trachytes show greater strain accommodation and a wide strength range (mr ~ 312), achieving both high and low peak stress levels depending on their texture and degree of alteration. Low-porosity trachytes reached high σ_c and remained brittle up to a confinement of 15 MPa. In turn, basalts (s.l.) have medium to high strength (mr ~ 473), influenced by their plagioclase and ferromagnesian mineral content. Basalts remained brittle under 30 MPa confinement but show limited post-yield plasticity and reduced c when n_{eff} exceeded 12.5 %. These findings underscore the significant role of microstructure in governing strength progress.

Despite compositional differences, distinguishing lava rock types based solely on strength (tensile or compressive) or E remains challenging due to the overriding influence of microstructural and mineralogical characteristics, as emphasised by Heap and Violay (2021). For instance, a trachyte may present similar stiffness and strength as a vesicular basalt.

Indirect tensile strength followed the general trend of unconfined compressive strength, with vesicular basalts less resistant to tension. Brazilian test results for intact rock support numerical models by Heap et al. (2021), indicating that microstructural features, particularly connected pore space and pore size, dictate σ_t .

The stress–strain curves obtained in this study closely follow the theoretical trends (Fig. 2.13). The brittle behaviour of the samples is evident, marked by a clear stress drop following the peak stress and the development of macroscopic fractures at failure. These fracture patterns are consistent with those observed at the microscale and resemble those reported for other brittle rocks (Paterson and Wong, 2005; Jaeger et al., 2007; Basu et al., 2013). Triaxial tests confirm that lava rocks remain brittle under confining pressures below

40 MPa, which corresponds to the lower limit of BDT defined for similar lithologies (Section 2.2.2, Part C; Fig. 2.14).

In terms of deformation of lava rocks, the E_{avg} appears as the most representative E across both micro- and intact rock scales. E depends on the void space characteristics and porosity, while appearing more sensitive to mineralogical composition than strength, corroborating findings from prior studies (e.g., Coats et al., 2018; Zorn et al., 2018). For instance, felsic rocks such as trachytes accommodate more strain, show lower E values, and present higher ν .

c and ϕ also vary across specimens, with significant reductions in medium-porosity and fissured lava rocks. Consequently, standard values commonly used in geotechnical design or volcanic systems modelling may overestimate the shear strength parameters of lava rocks.

- Effect of pores and fissures

Macroscopic fissures and microcracks are suggested as the primary source of variability in V_p , mechanical strength (tensile, unconfined, and confined compressive), and E of lava rocks, particularly in low-porosity ones ($n_{eff} < 8 \pm 2\%$). For the studied massive lavas, mechanical competence appears to be predominantly governed by the extent and distribution of fissures and, possibly, microcracks.

Due to the variable abundance of microcracks, strength heterogeneity is more pronounced in massive lava rocks than in vesicular ones (Fig. 5.7). This observation supports numerical models indicating that strength variability is reduced in rocks containing subspherical pores compared to those with microcracks, which represent voids with lower aspect ratios (Bubeck et al., 2017). Additionally, triaxial tests evidence that microcracks are more susceptible to closure under stress than vesicles, implying that at larger depths and scales, such fractures may close (Nara et al., 2011; Cant et al., 2018), potentially reducing the porosity and permeability of the host rocks.

Lavas with medium porosity values ($n_{eff} \sim 12.5 \pm 2.5\%$) may contain fissures, microcracks, pores of millimetric size distributed in the whole specimen, and localised porous bands that dictate their strength. High-porosity specimens ($n_{eff} > 18 \pm 3$) have an overall reduced strength and E compared to massive lavas. However, the values of V_p , strength, and E occur within a narrower range than those of massive lavas. Vesicular specimens also display greater homogeneity when tested for ultrasonic wave velocity and capillary water absorption along the three orthogonal directions, resulting in anisotropy indices, calculated

as Benavente et al. (2018), higher than 0.70. The presence of pores, mostly with a radii > 1 mm, facilitates earlier crack initiation and propagation, as well as lower peak stress values, maintaining the ratios of the crack thresholds to the σ_p .

Under confined conditions, vesicular lavas display plasticity (strain accommodation after yielding) at confining pressures as low as 10 MPa. Yet, they remain dilatant and are not fully ductile, with brittle failure materialised by the formation of macroscopic fractures. The stress–strain curves often show a strain plateau, consistent with observations in other porous volcanic rocks, and supporting the interpretation that pore-dominated lavas are more susceptible to strain softening (Marmoni et al., 2017).

- Effect of weathering: A glimpse

The partial infilling of voids with secondary mineral products marks the weathering of vesicular rocks (WG_{III}; BF.AIII). r and n_{eff} are decreased with respect to other vesicular lavas, and n_{cc} represents a significant proportion of the n_{eff} , despite the low capillary water absorption of these samples. Additionally, weathered specimens demonstrate plasticity when confined at 5 MPa, often accompanied by a less distinct post-peak stress drop and stress recovery.

Saturation and water transport mechanisms

Capillary tests are more accurately explained by the Sharp Front model for lavas with $n_{eff} > 6\%$, showing that C_{EN} frequently underestimates the rock's capacity to absorb water via capillarity. The SF model better captures the combined effects of anomalous imbibition due to aeration pores, in addition to the conventional capillary uptake through groundmass pores.

Medium-porosity massive lavas have moderate to high capillary water absorption capacity. In contrast, low-porosity massive lavas did not reach a constant water absorption after 48 h and showed low capillary absorption. Vesicular lavas with approximately $n_{eff} > 16\%$, demonstrate only moderate capillary absorption, with their pores minimally participating in spontaneous imbibition. This observation is supported by the relatively low n_{cc} in proportion to n_{eff} , reinforcing the widely accepted idea that pores larger than 1 mm exert negligible influence on capillary processes. Instead, fluid movement in vesicular rocks is primarily dictated by gravitational forces, in line with Fig. 2.9.

Building on prior studies (Nara et al., 2010, 2011, 2012), it is inferred that various water transport mechanisms, spanning from vapour adsorption to spontaneous imbibition, contribute to rock weakening and facilitate earlier failure. The current research on intact rock specimens confirms that water saturation under vacuum reduces tensile strength. These reductions are consistent with values reported for saturated tuffs (Wedekind et al., 2013) and suggest that water-induced weakening in lava rocks is not necessarily more severe under tensile than compressive loading, contrary to previous suggestions (Hashiba and Fukui, 2015). In fact, the magnitude of strength loss due to saturation is comparable to the reductions observed in UCS for lava rocks (Heap and Violay, 2021).

Fitting parameters of the Hoek-Brown criterion to São Miguel lavas: A preliminary “upscaling”

Triaxial test results on intact rock confirm that, at P_{conf} up to 30 MPa, relevant to the volcanic systems of São Miguel, fresh lava rocks are brittle. This brittle failure mode is conducive to the development of fractures, including hydrofractures, which play a critical role in facilitating the percolation of hydrothermal fluids and magma. Time-dependent rock fracturing has been linked to increased seismicity preceding volcanic eruptions (Kilburn and Voight, 1998), and several geomechanical parameters are integral to volcano numerical models. For example, E is frequently used in models of dyke emplacement and hydrofracture propagation (Gudmundsson, 2011), while rock strength parameters are essential for assessing the role of discontinuities and hydrofractures in volcano flank stability (e.g., Voight, 2000).

Structural and mechanical transformations at the scale of the volcanic edifice contribute to overall instability and influence the propagation of magma-filled fractures (Pinel and Jaupart, 2000; Gudmundsson, 2006; 2020; Heap et al., 2015). Hydrothermal fluids exacerbate this process by weakening fractured rock and inducing mineralogical alterations. Although micropores may contribute to unsaturated flow depending on their size distribution (Benavente, 2011), effective fluid transport is primarily governed by larger-scale discontinuities in the rock mass.

Using the HB failure criterion and the Hoek and Diederichs (2006) equation, rock mass strength and deformation parameters were estimated, assuming a GSI of 55 and a slope height of 500 m, representative of the northern flank of Fogo Volcano, in the Cachaços–Lombadas sector. The derived rock mass values highlight significant reductions in strength (92 %), E (21 %), and c due to the effect of discontinuities, which indicate possible instabilisation of lava rock slopes. Although the considered lavas are often classified as

“hard” geotechnical units, their stability is further compromised by natural fracturing, intense rainfall, volcano-tectonic activity, and deformation associated with magmatic intrusions, likely to occur in São Miguel Island. These processes collectively increase pore pressure, reduce rock strength, and intensify both static and dynamic loading (van Wyk de Vries and Francis, 1997; van Wyk de Vries and Davies, 2015), making these geological units susceptible to instability, particularly rockfalls, as observed on multiple volcanic islands (Whitchurch, 2012; Darmawan et al., 2020; González de Vallejo et al., 2020; Massaro et al., 2024).

The thesis did not focus on magma transport and emplacement models, but the HB model calibration to the triaxial test data underscores a significant mechanical weakening in the rock mass. This observation warrants further investigation in future volcano stability and hazard models.

Hydrothermal Alteration

The petrophysical and mechanical properties of hydrothermally altered rocks has been critically assessed in Chapter 7 through the compilation of a literature dataset, that uniformises the available data regarding rock type, alteration intensity, and alteration type. Although the progression and effects of hydrothermal alteration are dependent on local geological conditions, resulting in seemingly contradictory results, this analysis provides a foundational reference for evaluating altered lava rocks on São Miguel Island. In addition, the critical analysis address a gap in the literature that prior reviews (e.g., Heap and Violay, 2021; Lavallée and Kendrick, 2021) only partially covered, as well as it expands on existing petrophysical and geotechnical databases (e.g., Zhang et al., 2012; Bär et al., 2019, 2020; Scott et al., 2022, 2023), supporting new research on altered rocks.

The impact and progression of alteration are significantly variable worldwide and depend on the initial structure and texture of volcanic materials, namely porosity, fracture networks, and pore geometry. Depending on the external conditions, fragmental rocks are more prone to alteration than lavas due their initial high porosity and permeability. The review of Pereira et al. (2024a) shows that these materials remain porous and permeable compared to lava rocks, despite common void infill and compaction. On the other hand, alteration impacts are more pronounced in dense rocks, such as lavas, compared to fragmental rocks. Overall, lava rocks become more fractured, porous, and mechanically weaker as the alteration intensity increases, depending on their structure and texture. For example, lava breccias and vesicular lavas respond differently to alteration than massive lavas.

Most productive geothermal systems comprise zones of argillic (<140 °C), transitional (140–220 °C), and propylitic (>220 °C) alteration, as is also present in the Ribeira Grande geothermal field. Typically, argillic and transitional facies affect the low-permeability caprocks, while the underlying permeable reservoir is characterised by propylitic alteration. Despite the main zones being found predominantly worldwide, effects on the host rocks remain variable. Compiled data on high-temperature propylitic facies shows that this alteration type generally increase rock strength, c , and E due to the formation of harder hydrothermal minerals. In contrast, low temperature propylitic, argillic, zeolitic, and silicic alterations typically reduce these properties, due to the formation of soft minerals and increased porosity (competing dissolution vs. precipitation). Variations of these general trends are produced by the subfacies combined with the principal alteration zones.

In the RG5 well, the selected hydrothermally altered volcanic rocks from the unaltered, smectite-altered, and chlorite/transitional zones vary from lightly to moderately altered lavas of distinct compositions, whereas pyroclastic rocks (lithic tuffs and tuff breccias) range from slightly to highly altered (Table 8.1). The results indicate that increasing alteration with depth and temperature promotes the precipitation of hydrothermal minerals, which either occur in microcracks and pores or appear as coatings on primary minerals. Notwithstanding, the original pore structure of the studied volcanic rocks is preserved and primarily governs the porosity evolution of these rocks.

Lava rocks generally retain their compact nature and show low porosity across all hydrothermal zones. In vesicular lavas, microcrack sealing significantly reduces connectivity. Despite secondary mineral infill and the formation of more opaque phases, the dry density tends to decrease with increasing alteration, particularly with depth, due to the formation of low-density alteration minerals.

At the surface, lithic tuffs are relatively porous; however, their matrix becomes progressively less porous with depth and within the chlorite zone. This reduction may result from initial porosity, secondary mineral infill, or compaction. Tuff breccias, in particular, are extensively filled by secondary minerals, sustaining their classification as impermeable units.

When compared with XRD data (Pereira et al., 2022), the obtained results confirm the formation of soft, low-density hydrothermal minerals that contribute to reduced dry densities compared to unaltered similar lithologies described in Chapter 4. This mineralogical transformation is expected to lower the mechanical competence of volcanic rocks, even in cases of initially low porosity, by promoting increased deformation, early

failure, and plasticity. Furthermore, due to the complex interplay between original rock structure, hydrothermal alteration, and compaction, variations in physical and mechanical properties across samples are irregular and non-systematic, as previously noted in studies on altered volcanic rocks (Wyering et al., 2014; Cant et al., 2018; Durán et al., 2019).

9.3. Limitations of the thesis

This thesis presents a comprehensive microstructural, physical, and mechanical characterisation of lava rocks from São Miguel Island. Nevertheless, several limitations must be acknowledged to contextualise the findings and guide future research, presented in Chapter 10.

Firstly, petrographic analysis was not uniformly applied across all lava subfacies identified in Fig. 3.6. Furthermore, the inherent limitations of thin-section analysis are evident when not capturing megacrysts, like those seen in the BP group. Point counting in porphyritic rocks remains a methodological challenge due to the heterogeneous size distribution of crystals. Similarly, both 2D and 3D image segmentation are affected by resolution limitations and grey-level similarities between phenocrysts and the groundmass, which complicate accurate mineral and pore identification, in particular for massive lava rocks, where micropores predominate. Using texture-supervised classification partly solves the problem, but it needs further improvement.

A further constraint lies in the variability within samples, which hinders definitive interpretations. For example, a definitive evaluation of the effects of pore size and shape on mechanical strength is hampered by the inherent microstructural variability. Microscopic analysis showed important pore orientation variability even in samples with apparent preferential pore alignment. Furthermore, even though they are effective, methods like MIP and μ CT remain expensive.

The thesis focused on micro- to intact rock-scale observations. Although the results obtained are valuable for the characterisation of volcanic rocks, they provide only a partial understanding of rock mass behaviour in larger, more complex volcano-hydrothermal systems. For instance, the conceptual model developed for the Ribeira Grande geothermal system does not account for hydrothermal alteration, which has been shown to impact rock strength significantly.

Attempts to induce hydrothermal alteration *in situ*, in an active diffuse degassing area, were unsuccessful for the selected timeframe. This research outcome suggests that such approaches may not be viable for short- to medium-term investigations when considering such compact materials and that alternative approaches should be considered. In parallel, the cuttings from the RG5 well were too small for mechanical testing, despite characterised physically.

In summary, the methodology applied in this thesis establishes a robust framework for microstructural and geomechanical analysis. However, research integrating field observations, experimental alteration studies, and multi-scale geophysical and geochemical datasets is lacking. It could improve the characterisation and modelling of volcanic rock behaviour in natural and engineered volcanic settings.

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“O que é verdadeiramente tradicional é a invenção do futuro” *(in Portuguese)*

“What is truly traditional, is the invention of the future” *(in English)*

Agostinho da Silva

Though not Azorean, Agostinho da Silva is one of the most important Portuguese thinkers of the XX century. This aphorism marked the very beginning of my PhD journey, finding its place in my application to the “la Caixa” Foundation. And now, as every cycle must, it returns to its starting point.

To create, to innovate, to pursue science: these do not oppose tradition, but define it. No tradition survives without invention, just as no future can emerge without the roots of the past. And this PhD is like one of the many lava flows that adds itself to an ancient volcanic edifice.

Yet, the future we shape is not solely of scientific discovery. It is also a slow transformation into a more rooted self, shaped by time and space. It is this restlessness that sustains our questions, our solutions, and our prospects of what may come.

Chapter

Conclusions



This thesis set out to explore the physical and mechanical properties of volcanic rocks, with particular emphasis on fresh lava rocks from São Miguel Island, with varying composition and texture. Hydrothermal alteration effects are also explored through an extensive data collection that enabled the drawing of a critical analysis considering altered rocks worldwide. At the same time, this feature was assessed in Azorean volcanic rocks.

The main findings are presented in each “publication” chapter, containing the results and their discussion. The main contributions and their integration are discussed in Chapter 9. This Conclusions chapter focuses on the fundamental implications of the results, their impact, and how future research can further advance the current knowledge.

10.1. Findings and the objectives of the thesis

1. *Does the mineral composition and porosity influence the density of lavas to the same extent?*

Pore space characteristics, namely the connected porosity and the pore size, have a larger influence on the dry density of lava rocks. Mineralogy also has an influence, supporting the conventional findings in the literature, yet, to a lesser extent. The interplay between porosity and mineralogy also influences ultrasonic wave velocities, which reflect the presence of pores and cracks in the test specimens.

2. *How can void space be characterised at the microscale? What is the influence of the porous system in the intact rock?*

The multi-method and multi-scale research effectively characterised the pore size distribution, mean pore radius, and the connected porosity at a microscale, complementing the open porosity results obtained using conventional laboratory methods. Results show that massive lavas of different composition have a predominance of micropores, but scarce microcracks can promote connectivity within the rocks. Vesicular lavas have millimetric and centimetric pores connected by fractures, and the size of the vesicles influence several properties, such as strength and capillary water absorption. The microscopic observations

and the advanced imaging techniques enable the characterisation of lava rocks in detail and provide a better understanding of the intact rock behaviour.

3. *What is the water capillary absorption in Azorean lavas? How do capillarity and other water transport mechanisms relate to the pore size distribution of the analysed lavas?*

Low-porosity lavas, independent of the rock type, have low capillary water absorption capacity. Exceptions occur when these lavas have medium-porosity distributed in the whole specimen or localised in porous bands, contributing to a high capillary water absorption. On the contrary, high-porosity vesicular lavas, with pores often exceeding 1 mm in size, only have a moderate capillary water absorption, with water transport governed by gravitational forces.

4. *Can P-wave velocity (V_p) be used as an indirect precursor measure to predict mechanical properties and the results of destructive techniques?*

V_p measurement has the advantage of being non-destructive. However, the resulting data show considerable scatter, and V_p values do not infallibly distinguish between different lava textures. Unexpectedly, lower V_p values were obtained in specimens with higher strength, and vice versa. This counterintuitive trend suggests that V_p measurements are influenced by pre-existing microcracks, whose effects on compressive strength vary according to their orientation relative to the loading axis.

5. *What are the crack initiation and damage stress thresholds in lava rocks, and how do these relate to peak strength for distinct Azorean lava rocks?*

σ_{ci} is on average 45 % of the peak stress in the entire dataset. σ_{cd} is controlled by the already accumulated damage and newly formed fractures, and is, on average, 73 % of the peak stress. In both ratios, the average was lower for trachytes (33 % and 58 %) compared to basalts (s.l.), whereas massive and vesicular textures produced minor differences in basalts (s.l.). The obtained ratios are aligned with those established in the literature for intrusive igneous rocks.

6. *What are the connected porosity thresholds that define unconfined compressive strength and water absorption capillarity of the several lava rocks?*

Lavas with $n_{eff} < 8 \pm 2\%$ have strength variability due to microcracks and have low capillary water absorption. Lava rocks exceeding 12.5 % of n_{eff} can reach high capillary water

absorption coefficients, and have a transitional behaviour, where strength appears to be dependent on both porosity type and pore size. The macropores visible in these rocks are smaller than the pores observed in the BF sample group ($n_{eff} > 15/18\%$), which have their strength defined by the pore size, alongside a moderate water absorption capacity. The Sharp Front model more accurately explains capillary tests for lavas with $n_{eff} > 6\%$.

7. *How do pre-existing microstructural defects, such as pores and phenocrysts, affect the mechanical strength of volcanic rocks?*

The tips and edges of both phenocrysts and pores acted as stress concentrators. These microstructural features control the development of the crack pattern. The analysed lava rocks are brittle and develop fractures parallel to the loading axis, which often deviate due to phenocrysts and pores of significant size.

8. *Are the selected lavas brittle under confining pressures that are representative of the depth of the Azorean volcanic system?*

All lavas, independent of their texture and composition, remained brittle at confining pressures representative of the Fogo Volcano (Cachaços-Lombas sector). Massive basalts are brittle up to 30 MPa, whereas brittle vesicular intermediate rocks start to show plasticity after yielding at confining pressures of 10 MPa.

9. *How does saturation influence the indirect tensile strength (σ_t) of lava rocks? Is it similar to sedimentary rocks?*

Water saturation reduced the tensile strength by 33% in the tested lavas, a reduction consistent with decreases found for saturated tuffs but lower than the ones for sandstones and limestones, possibly due to the absence of clays in the studied rocks.

10. *What is the effect of hydrothermal alteration on the physical and mechanical behaviour of volcanic rocks?*

The effect of hydrothermal alteration on the physical and mechanical properties is variable. It depends on the initial structure of the rock (dense vs. fragmental rocks) and the intensity and type of hydrothermal alteration. Dense rocks tend to become weaker and more porous and permeable, whereas fragmental rocks are more prone to void infill by secondary minerals. The type of alteration is complex and typically associates with a subtype of alteration that defines the major variations. Zeolitic and argillic alterations promote a weakening of the rock, contrary to advanced silicic alteration or high temperature propylitic mineral assemblages.

11. Can the collected Azorean lavas be altered in situ in a place of diffuse degassing?

Attempts to induce hydrothermal alteration *in situ*, in a diffuse degassing area, were unsuccessful for the selected timeframe and the massive structure of the rocks, suggesting longer time periods of exposure or alternative laboratory methods are required. Chemical and microstructural evidence prove that the alteration was not effective.

12. What are the properties of distinct volcanic rocks affected by the hydrothermal alteration produced in the Ribeira Grande geothermal field (Fogo Volcano) with increasing depth?

Pycnometric dry density shows the greatest decreases in cuttings from greater depths, where alteration is moderate to high. Superficial massive lavas are only slightly altered, in contrast to vesicular lavas, which have more evident alteration due to secondary mineral infill, reducing the pores' connectivity. Reservoir lavas have a low-porosity matrix and high opaque mineral content, suggesting that permeability is due to large discontinuities at the rock mass scale of the geothermal field. The caprock tuff is impermeable, with microstructural analysis confirming low connected porosity and the sealing of formerly more permeable zones by secondary minerals.

10.2. Impact of the findings and their relationship with the aims of the thesis

The findings of the thesis demonstrate that lava rocks are complex materials, with microstructural and compositional variability arising from their wide volcanic origin. The geological nature of these lavas influences their geotechnical performance. In this sense, the thesis intended to bridge the disciplines of rock mechanics and volcanology. This interdisciplinary approach fosters the development of safer and more resilient geotechnical practices in volcanic environments. On the other hand, it contributes to a better understanding of lava rocks as a geotechnical and volcanological material, while defining parameters that can be used in several volcanic-hydrothermal models or volcanic slope potential instability analysis.

Within the scope of the first aim of the thesis, the microstructural characterisation of lava rocks from São Miguel Island is presented, integrating microscale data with a comprehensive laboratory campaign to assess their physical and mechanical properties. The scale-integrated analysis effectively frames the intact rock behaviour, indicating that mechanical performance is linked to microstructure and physical properties, such as n_{eff} . n_{eff}

thresholds defined for strength and unsaturated water flow show that these can be used to predict the geomechanical response of intact lava rocks. Furthermore, by characterising volcanic rocks across different scales, i.e., from the micro- to the intact rock scale, the conducted research enhances the current understanding of complex pore networks and their influence on lava rocks behaviour.

Although microstructural investigations provide valuable insight into rock behaviour, conventional intact rock tests remain indispensable for producing results that are comparable across laboratories. These tests are also the standard methods used by organisations performing rock mechanics characterisations in the Azores. In addition, this study highlights that intact rock blocks of lavas are not homogeneous and contain defects that should be considered to generate more reliable input data for both volcanological and geotechnical applications. Locally, in São Miguel, the results may contribute to the selection of lava rocks for aggregates and building stone, aiming at more resilient infrastructures in volcanic regions.

The combined dataset offers a solid and novel foundation for future studies on the mechanical performance of intact lava rocks, with potential contributions in refining models of rock behaviour under different loading and environmental conditions comprising volcanic terrains. Furthermore, the proposed empirical equations for estimating uniaxial $\sigma_{c,UCS}$, c , and ϕ serve as practical tools for engineers and geoscientists, helping in volcanic slope and excavations stability assessments and enhancing the prediction of rock behaviour in geotechnical applications in São Miguel and other volcanic islands.

The thesis also makes a novel contribution by defining water transport properties for different lava rocks, showing that massive lavas with distributed small pores along porous bands are prone to significant spontaneous imbibition. Conversely, vesicular textures in lavas contribute to a moderate capillary water absorption but may compromise the mechanical resistance of the rock due to pore size. Such findings are particularly important in assessing the vulnerability of the building environment and volcanic slopes on São Miguel Island, frequently affected by heavy rainfall, seismic activity, and volcanic unrest, that may compromise the stability of such "hard" lava units.

A further contribution of this thesis, within the second aim of the thesis, is the critical analysis focused on the effects of hydrothermal alteration on the properties of volcanic rocks, which synthesises global data on the mineralogical, physical, and mechanical properties of altered volcanic rocks. The developed critical analysis was intended to serve

as groundwork for the research developed on the effects of hydrothermal alteration on Azorean lava rocks. Although induced alteration was limited in these samples, the characterisation of drill cuttings from the Ribeira Grande geothermal field (RG5 well; Fogo Volcano) complement the available chemical data. Microstructural characterisation shows that many of the altered samples pertain to a low-porosity matrix, which may reduce fluid storage and flow capacity in the absence of structural pathways, which further contributes to refining conceptual models of the geothermal system in the study.

10.3. Future research

Based on the limitations of the thesis (Section 9.3) future research is suggested as follows:

- Assess microstructurally and petrographically all subfacies to cover the mineralogical variability and sample-to-sample heterogeneity.
- Increase the number of tested specimens, particularly for ρ , n_{eff} , and time-resolved tests to improve the reliability of the results for small-scale samples analysed via MIP and μ CT.
- Conduct a post-deformation microstructural observation of the intact rocks to investigate the micromechanisms associated with the deformation of the various lavas. Such venue of research would also facilitate direct comparison with SEM-BSE images from other deformed lava rocks, advancing fundamental research on brittle failure mechanisms.
- Incorporate detailed field characterisation of the slopes of São Miguel Island. For example, defining the GSI in available volcanic outcrops would enhance the “upscaling” of laboratory results to the rock mass scale and validate the heterogeneity of the volcanic sequences. Outcomes from such an assessment would support future numerical models for volcanology, thereby improving hazard assessments and predictive scenarios. These models would have relevance not only for the Azorean Archipelago but also for other active volcanic islands with nearby populations.
- Induce alteration under controlled laboratory conditions, combined with thermal stressing, to enable later triaxial testing to constrain the brittle-ductile transition in altered Azorean lava rocks. Results of such an experiment would provide reliable values to improve schematic models of the Ribeira Grande geothermal field and similar systems worldwide.



Appendices

Brazilian Test

Table 3.1. (Appendix). Size and specimen description for the Brazilian test. D – diameter; L – length (or height); Sat – saturated. Calliper uncertainty: $\pm 0,01$ mm.

BP	D1	D2	D3	D avg (mm)	L1	L2	L3	L avg (mm)	Specimen description	Test	Ratio D/L
1A	50.61	50.68	50.69	50.66	25.25	25.36	25.25	25.29	A1, A5, B3, C1, D2, E1, F1,	Unaltered	2.0
2A	50.03	50.38	50.46	50.29	24.32	24.38	24.04	24.25	A1, A5, B3, C1, D1, E1, F1,	Unaltered	2.1
2D	50.4	50.51	50.47	50.46	25.23	25.41	25.43	25.36	A1, A5, B3, C1, D1, E1, F1,	Unaltered	2.0
4A	45.09	44.77	45.1	44.99	24.63	25	24.85	24.83	A1, A5, B3, C1, D1, E1, E3	Unaltered	1.8
4C	45.17	44.89	45.54	45.20	23.9	23.77	23.53	23.73	A1, A5, B3, C1, D1, E1, E3, E12	Unaltered	1.9
4E	44.93	45.03	45.11	45.02	22.02	22.03	21.98	22.01	A1, A5, B3, C1, D1, E1	Unaltered (Sat)	2.0
4H	45.09	45.12	44.93	45.05	21.88	21.97	22.11	21.99	A1, A5, B3, C1, D1, E1, E3, F4	Unaltered	2.0
4K	45.17	45.13	45.08	45.13	24.37	24.71	24.35	24.48	A1, A5, B3, C1, D1, E1	Unaltered	1.8
6B	44.64	44.94	44.83	44.80	20.84	20.35	20.34	20.51	A1, A5, B3, C1, D1, E1, E3	Unaltered	2.2
6F	44.99	45.14	44.8	44.98	22.7	22.87	22.87	22.81	A1, A5, B3, C1, D1, E1	Unaltered	2.0
8B	45.1	44.91	44.89	44.97	25.48	25.3	25.4	25.39	A1, A5, B3, C1, D1, E1	Unaltered	1.8
8C	44.99	45.03	45.06	45.03	21.84	21.87	21.92	21.88	A1, A5, B3, C1, D1, E1	Unaltered (Sat)	2.1
8D	44.97	45.03	45.15	45.05	23.78	23.65	23.62	23.68	A1, A5, B3, C1, D3, E1	Unaltered (Sat)	1.9
8E	45.07	45.14	45.04	45.08	23.5	23.65	23.85	23.67	A1, A5, B3, C1, D3, E1	Unaltered	1.9
9A	45.18	45.13	45.08	45.13	22.67	22.62	22.35	22.55	A1, A5, B3, C1, D1, E1	Unaltered	2.0
9D	45.18	45.17	45.07	45.14	27.24	26.94	27.22	27.13	A1, A5, B3, C1, D1, E1, D8	Unaltered	1.7
9E	45.14	45.19	45.13	45.15	21.94	21.69	21.8	21.81	A1, A5, B3, C1, D1, E1, E3	Unaltered (Sat)	2.1
10B	45.16	45.27	45.3	45.24	24.5	24.5	24.67	24.56	A1, A5, B3, C1, D1, E3	Unaltered	1.8
10F	45.15	45.08	45.06	45.10	21.18	21.2	21.11	21.16	A1, A5, B3, C1, D1, E1	Unaltered (Sat)	2.1
10G	45.06	45.15	45.11	45.11	25.75	26.18	25.43	25.79	A1, A5, B3, C1, D1, E1	Unaltered	1.7
11A	44.83	44.9	45.11	44.95	22.55	22.7	22.53	22.59	A1, A5, B3, C1, D1, E1	Unaltered	2.0
11C	45.17	45.16	45.29	45.21	21.98	22.07	22.02	22.02	A1, A5, B3, C1, D1, E1	Unaltered	2.1
12A	45.08	45.09	45.08	45.08	20.31	20.32	20.38	20.34	A1, A5, B3, C1, D1, E1, E12	Unaltered	2.2
12B	45.01	45.13	45.19	45.11	23.48	23.55	23.75	23.59	A1, A5, B3, C1, D1, E1	Unaltered	1.9

13C	45.04	45.1	45.18	45.11	23.82	23.8	23.85	23.82	A1, A5, B3, C1, D1, E1	Unaltered	1.9
13D	45.06	44.95	45.04	45.02	24.87	25.04	24.85	24.92	A1, A5, B3, C1, D1, E1	Unaltered	1.8
14A	45.11	45.18	45.2	45.16	23.05	22.96	23.18	23.06	A1, A5, B3, C1, D1, E1	Unaltered	2.0
14D	45.11	45.24	45.15	45.17	21.42	21.36	21.32	21.37	A1, A5, B3, C1, D1, E1	Unaltered (Sat)	2.1
14G	44.88	44.98	45.13	45.00	24.2	24.3	24.2	24.23	A1, A5, B3, C1, D1, E1	Unaltered	1.9
14J	45.12	45.11	45.14	45.12	21.93	21.95	21.94	21.94	A1, A5, B3, C1, D1, E1	Unaltered	2.1
14M	45.17	45.22	45.10	45.16	22.62	22.4	22.39	22.47	A1, A5, B3, C1, D1, E1, F4	Unaltered (Sat)	2.0
15A	45.00	45.05	44.97	45.01	21.08	20.96	20.9	20.98	A1, A5, B3, C1, D1, E1	Unaltered	2.1
15D	44.98	45.03	45.11	45.04	21.8	21.58	21.74	21.71	A1, A5, B3, C1, D1, E1	Unaltered	2.1
15G	45.02	45.05	45.01	45.03	23.78	23.59	23.43	23.60	A1, A5, B3, C1, D1, E1	Unaltered (Sat)	1.9
16A	44.92	44.97	44.99	44.96	24.54	24.59	24.76	24.63	A1, A5, B3, C1, D1, E1	Unaltered	1.8
16E	44.99	44.93	44.92	44.95	22.95	23.05	22.99	23.00	A1, A5, B3, C1, D1, E1	Unaltered	2.0
16I	44.95	44.97	44.95	44.96	23.41	23.32	23.35	23.36	A1, A5, B3, C1, D3, E1, E10, E12	Unaltered	1.9
17A	45.04	45.14	45.11	45.10	23.33	23.32	23.42	23.36	A1, A5, B3, C1, D1, E1	Unaltered	1.9
17B	45.09	45.14	45.15	45.13	22.42	22.03	22.2	22.22	A1, A5, B3, C1, D1, E1	Unaltered (Sat)	2.0
17D	45.01	45.1	45.08	45.06	24.63	24.62	24.51	24.59	A1, A5, B3, C1, D3, E1, E12	Unaltered	1.8
20A	44.84	44.92	44.91	44.89	20.44	20.43	20.3	20.39	A1, A5, B3, C1, D1, E1	Unaltered	2.2
20C	45.02	45.02	45.04	45.03	24.32	24.33	24.36	24.34	A1, A5, B3, C1, D1, E1	Unaltered	1.9
21A	45.09	45.14	45.06	45.10	22.37	22.36	22.26	22.33	A1, A5, B3, C1, D3, E1	Unaltered	2.0
21E	45.15	45.09	45.12	45.12	23.26	23.42	23.37	23.35	A1, A5, B3, C1, D1, E1	Unaltered	1.9
21H	44.91	44.86	44.95	44.91	22.94	22.85	23	22.93	A1, A5, B3, C1, D4, E1	Unaltered	2.0
22B	45.14	45.12	45.09	45.12	21.51	21.58	22.02	21.70	A1, A5, B3, C1, D1, E1	Unaltered	2.1
22E	45.1	45.12	45.13	45.12	22.89	22.88	22.83	22.87	A1, A5, B3, C1, D8, E1	Unaltered	2.0
24A	45.15	45.21	45.2	45.19	23.79	23.59	23.57	23.65	A1, A5, B3, C1, D2, E1	Unaltered	1.9
24D	45.18	45.12	45.17	45.16	23.5	23.54	23.5	23.51	A1, A5, B3, C1, D1, E1	Unaltered (Sat)	1.9
24E	45.21	45.18	45.23	45.21	24.12	24.07	24.1	24.10	A1, A5, B3, C1, D1, E1	Unaltered	1.9
25A	45.11	45.13	45.08	45.11	22.77	22.91	22.78	22.82	A1, A5, B3, C1, D8, E1, localised porous bands	Unaltered	2.0
25D	45.08	45.24	45.15	45.16	21.79	21.86	21.89	21.85	A1, A5, B3, C1, D1, E1, localised porous bands	Unaltered	2.1
25E	44.95	44.97	45.03	44.98	24.71	24.7	24.73	24.71	A1, A5, B3, C1, D1, E1, localised porous bands	Unaltered	1.8
37A	45.14	45.08	45.1	45.11	23.49	23.51	23.44	23.48	A1, A5, B3, C1, D1, E1, localised porous bands	Unaltered	1.9

3A	50.53	50.45	50.46	50.48	24.95	25.04	25.4	25.13	A1, A5, B3, C1, D1, E1	Unaltered	2.0
3D	50.48	50.5	50.57	50.52	25.05	25.8	25.28	25.38	A1, A5, B3, C1, D1, E1, E3, F1	Unaltered	2.0
18B	44.98	44.93	44.89	44.93	21.49	21.5	21.48	21.49	A1, A5, B3, C1, D1, E3, F2	Unaltered	2.1
18F	44.9	44.84	44.85	44.86	22.07	22.22	22.07	22.12	A1, A5, B3, C1, D1, E1, F2	Unaltered	2.0
18G	44.96	44.84	44.92	44.91	26.17	26.36	26.28	26.27	A1, A5, B3, C1, D1, E3, F4	Unaltered	1.7
23B	45.24	45.17	45.22	45.21	23.45	23.65	23.53	23.54	A1, A5, B3, C1, D1, E1, E3, F2	Unaltered	1.9
23F	45.21	45.1	45.11	45.14	21.22	21.02	21.13	21.12	A1, A5, B3, C1, D1, E1, F2	Unaltered	2.1
23A	45.14	45.09	45.13	45.12	23.7	23.66	23.79	23.72	A1, A5, B3, C1, D1, E1, F2	Unaltered	1.9
23C	45.05	45.11	45.15	45.10	22.37	22.72	22.24	22.44	A1, A5, B3, C1, D1, E1, F2	Unaltered	2.0
19A	44.91	44.93	44.89	44.91	24.33	24.03	23.79	24.05	A1, A5, B3, C1, D2, E1, F2	Unaltered	1.9
19C	44.62	44.87	45	44.83	19.68	20.17	20.43	20.09	A1, A5, B3, C1, D2, E1, F2	Unaltered	2.2
26A	45.14	45.16	45.11	45.14	19.8	19.78	19.86	19.81	A1, A5, B3, C1, D1, D8, E1	Unaltered	2.3
26D	44.97	44.99	45.01	44.99	24.15	23.83	23.97	23.98	A1, A5, B3, C1, D1, E3	Unaltered	1.9
26G	45.15	45.13	45.15	45.14	22.2	22.33	22.24	22.26	A1, A5, B3, C1, D1, E1, E3	Unaltered (Sat)	2.0
27A	44.91	44.98	44.98	44.96	22.85	22.83	22.81	22.83	A1, A5, B3, C1, D1, E1, F2	Unaltered	2.0
27C	45.2	45.19	45.19	45.19	25.31	25.35	25.37	25.34	A1, A5, B3, C1, D3, E1, F2	Unaltered	1.8
27F	45.05	45.21	45.01	45.09	20.18	20.04	20.17	20.13	A1, A5, B3, C1, D1, E1, F2, E10	Unaltered (Sat)	2.2
28C	45.17	45.08	45.28	45.18	23.37	22.78	23.12	23.09	A1, A5, B3, C1, D3, E1	Unaltered	2.0
34A	45.41	45.37	45.4	45.39	23.22	22.84	23	23.02	A1, A5, B3, C1, D1, E1, E3	Unaltered	2.0
35B	45.39	45.36	45.37	45.37	23.42	23.49	23.61	23.51	A1, A5, B3, C1, D4, E1, E3	Unaltered	1.9
35F	45.35	45.3	45.38	45.34	23.45	23.72	23.21	23.46	A1, A5, B3, C1, D8, E3	Unaltered	1.9
36C	45.35	45.39	45.28	45.34	24	23.78	23.67	23.82	A1, A5, B3, C1, D8, E3	Unaltered	1.9
36E	45.32	45.3	45.33	45.32	21.31	21.3	21.32	21.31	A1, A5, B3, C1, D1, E1	Unaltered (Sat)	2.1
36I	45.3	45.31	45.3	45.30	24.8	24.98	24.87	24.88	A1, A5, B3, C1, D1, E3	Unaltered	1.8
30A	44.91	45.05	44.8	44.92	24.33	24.37	24.39	24.36	A1, A7, B3, C1, D1, E1, D8	Unaltered	1.8
30D	44.95	45.07	44.94	44.99	21.54	21.6	21.63	21.59	A1, A7, B3, C1, D1, E1, D8	Unaltered	2.1
31A	44.78	44.86	44.71	44.78	22.71	22.68	22.69	22.69	A1, A7, B3, C1, D1, E1, D8	Unaltered	2.0
32A	45.3	45.33	45.29	45.31	25.23	25.07	25.09	25.13	A1, A7, B3, C1, D2, E1, F2	Unaltered	1.8
33A	45.44	45.4	45.53	45.46	23.7	23.63	23.74	23.69	A1, A7, B3, C1, D2, E1, E3, F2	Unaltered	1.9
33D	45.41	45.32	45.42	45.38	25.25	25.06	25.29	25.20	A1, A7, B3, C1, D3, E1, E3	Unaltered	1.8

BAf	D1	D2	D3	D avg (mm)	L1	L2	L3	L avg (mm)	Specimen description	Test	Ratio D/L
1A	44.8	44.81	44.78	44.80	24.10	24.11	24.07	24.09	A2, A3, A5, B1, C1, D1, E1, E4, E6, E7, F1, F2	Unaltered	1.9
1D	44.66	44.63	44.85	44.71	22.50	22.42	22.58	22.50	A2, A3, A5, B1, C1, D1, E1, E4, E6, E7, F1, F2	Unaltered (Sat)	2.0
3A	44.76	44.77	44.71	44.75	21.51	21.36	21.63	21.50	A2, A3, A5, B1, C1, D1, E1, E5, E7, F1, F2, F3	Unaltered	2.1
3D	45.02	44.9	44.82	44.91	21.08	21.45	21.13	21.22	A2, A3, A5, B1, C1, D1, E1, E5, E7, F1, F2, F3	Unaltered (Sat)	2.1
3E	44.87	44.86	44.56	44.76	23.61	23.57	23.67	23.62	A2, A3, A5, B1, C1, D1, E1, E7, F1, F2	Unaltered	1.9
3H	44.88	44.95	44.74	44.86	24.47	24.36	24.64	24.49	A2, A3, A5, B1, C1, D1, E1, E7, F1, F2, F3	Unaltered	1.8
4A	45.02	45.05	45.12	45.06	24.78	24.80	24.93	24.84	A1, A3, A5, B1, C1, D1, E5, E7, F1, F2	Unaltered	1.8
4E	44.91	44.94	44.9	44.92	21.93	21.72	21.67	21.77	A1, A3, A5, B1, C1, D1, E1, E3, E7, F1, F2	Unaltered (Sat)	2.1
4F	45.19	45.14	44.89	45.07	23.32	23.51	23.34	23.39	A1, A3, A5, B1, C1, D1, E1, E3, E7, F1, F2	Unaltered (Sat)	1.9
4G	45.12	45.03	45.2	45.12	22.49	22.38	22.54	22.47	A1, A3, A5, B1, C1, D1, E1, E7, F1, F2	Unaltered (Sat)	2.0
4H	44.94	45.02	45.08	45.01	25.62	25.69	25.47	25.59	A1, A3, A5, B1, C1, D1, E1, E7, F1, F2	Unaltered (Sat)	1.8
5A	45.25	45.29	45.21	45.25	21.06	21.09	21.18	21.11	A1, A3, A5, B1, C1, D1, D8, E8, E7, F1, F2	Unaltered	2.1
5B	45.28	45.34	45.27	45.30	23.19	23.02	23.25	23.15	A1, A3, A5, B1, C1, D1, E8, F1, F2, F3	Unaltered	2.0
5D	45.39	45.25	45.28	45.31	26.81	26.89	26.83	26.84	A1, A3, A5, B1, C1, D1, E8, F1, F2	Unaltered	1.7
5G	45.42	45.29	45.31	45.34	19.45	19.66	19.48	19.53	A1, A3, A5, B1, C1, D1, E1, E8, F1, F2	Unaltered (Sat)	2.3
5I	45.26	45.39	45.23	45.29	21.10	21.24	21.14	21.16	A1, A3, A5, B1, C1, D1, E1, E8, F1, F2	Unaltered (Sat)	2.1
6B	45.34	45.32	45.27	45.31	24.27	24.23	24.20	24.23	A1, A3, A5, B1, C1, D1, E1, E4, E8, F1, F2	Unaltered	1.9
6F	45.3	45.27	45.31	45.29	19.44	19.49	19.50	19.48	A1, A3, A5, B1, C1, D1, E1, E3, E8, F1, F2	Unaltered (Sat)	2.3
10A	45.26	45.36	45.28	45.30	21.92	21.94	21.95	21.94	A1, A3, A5, B1, C1, D2, D8, E1, E8, F1, F2	Unaltered	2.1
10D	45.3	45.25	45.33	45.29	23.57	23.64	23.67	23.63	A1, A3, A5, B1, C1, D2, D8, E1, E8, F1, F2	Unaltered	1.9
13A	45.23	45.33	45.24	45.27	20.38	20.29	20.32	20.33	A2, A3, A5, B1, C1, D1, E1, E8, E7, F2	Unaltered	2.2
13D	45.24	45.29	45.13	45.22	19.37	19.04	19.19	19.20	A3, A5, B1, C1, D1, E1, E8, F2, F3	Unaltered (Sat)	2.4
2A	44.87	45.17	44.91	44.98	21.81	21.86	21.97	21.88	A2, A3, A5 to A7, B1, C1, D1, E1, E3, E9, E8, F1, F2	Unaltered	2.1
2B	44.8	44.93	44.79	44.84	22.56	22.44	22.43	22.48	A2, A3, A5 to A7, B1, C1, D9, E1, E3, E9, E8, F1, F2	Unaltered	2.0
2D	45.04	44.85	44.71	44.87	22.35	22.27	22.40	22.34	A2, A3, A5 to A7, B1, C1, D1, E1, E3, E9, E8, F1, F2	Unaltered	2.0

7A	45.26	45.31	45.3	45.29	24.46	24.42	24.44	24.44	A2, A3, A5 to A7, B1, C1, D1, E1, E3, E9, E8, F2	Unaltered	1.9
7B	45.33	45.31	45.29	45.31	20.58	20.71	21.00	20.76	A2, A3, A5 to A7, B1, C1, D1, E1, E3, E9, E8, F2	Unaltered	2.2
7C	45.3	45.32	45.33	45.32	23.69	23.75	23.65	23.70	A2, A3, A5 to A7, B1, C1, D1, E1, E3, E9, E8, F1, F2	Unaltered	1.9
7K	45.29	45.34	45.39	45.34	23.50	23.73	23.64	23.62	A2, A3, A5 to A7, B1, C1, D3, D4, E1, E3, E9, E8, F2, F3	Unaltered	1.9
7N	45.31	45.26	45.33	45.30	22.55	22.89	22.69	22.71	A2, A3, A5 to A7, B1, C1, D1, E1, E3, E8, E9, E10, F2	Unaltered (Sat)	2.0
7Q	45.28	45.32	45.3	45.30	20.68	20.56	20.70	20.65	A2, A3, A5 to A7, B1, C1, D1, E1, E3, E8, E9, E10, F2	Unaltered	2.2
7R	45.3	45.31	45.33	45.31	21.91	21.98	21.73	21.87	A2, A3, A5 to A7, B1, C1, D1, E1, E3, E8, E9, F2	Unaltered (Sat)	2.1
7S	45.28	45.34	45.3	45.31	21.03	21.06	20.99	21.03	A2, A3, A5 to A7, B1, C1, D8, E1, E3, E8, F2	Unaltered (Sat)	2.2
7T	45.3	45.32	45.28	45.30	23.17	22.86	22.73	22.92	A2, A3, A5 to A7, B1, C1, D1, E1, E3, E8, F2	Unaltered	2.0
7U	45.28	45.27	45.29	45.28	23.04	23.15	23.09	23.09	A2, A3, A5 to A7, B1, C1, D2, E1, E3, E8, F2	Unaltered (Sat)	2.0
8A	45.25	45.26	45.24	45.25	22.30	22.16	22.23	22.23	A2, A3, A5 to A7, B1, C1, D1, E1, E8, F2	Unaltered	2.0
8B	45.27	45.25	45.29	45.27	22.05	21.96	22.03	22.01	A2, A3, A5 to A7, B1, C1, D1, E1, E8, F2	Unaltered	2.1
8C	45.25	45.22	45.23	45.23	20.05	20.03	20.06	20.05	A2, A3, A5 to A7, B1, C1, D1, E1, E8, F2	Unaltered	2.3
8I	45.25	45.32	45.3	45.29	19.63	19.67	19.68	19.66	A2, A3, A5 to A7, B1, C1, D1, E1, E8, F2	Unaltered (Sat)	2.3
11A	45.27	45.29	45.24	45.27	21.25	21.16	21.21	21.21	A2, A3, A5 to A7, B1, C1, D1, E1, E3, E8, E9, F2	Unaltered	2.1
11B	45.26	45.3	45.29	45.28	21.33	21.28	21.32	21.31	A2, A3, A5 to A7, B1, C1, D1, E1, E3, E8, E9, F2	Unaltered	2.1
11C	45.24	45.35	45.28	45.29	21.25	21.43	21.55	21.41	A2, A3, A5 to A7, B1, C1, D1, E1, E3, E8, F2	Unaltered	2.1
11J	45.23	45.2	45.25	45.23	22.74	22.93	22.80	22.82	A2, A3, A5 to A7, B1, C1, D1, E1, E4, E8, F2	Unaltered (Sat)	2.0
11K	45.24	45.31	45.27	45.27	24.16	24.21	24.22	24.20	A2, A3, A5 to A7, B1, C1, D1, E1, E3, E8, F2	Unaltered (Sat)	1.9
11L	45.24	45.27	45.28	45.26	20.58	20.65	20.67	20.63	A2, A3, A5 to A7, B1, C1, D1, E1, E4, E8, F2	Unaltered (Sat)	2.2
12D	45.2	45.23	45.2	45.21	19.76	19.60	19.66	19.67	A2, A3, A5 to A7, B1, C1 to C2, D4, E1, E3, E8, F2	Unaltered (Sat)	2.3
12F	45.24	45.22	45.3	45.25	23.86	22.95	23.01	23.27	A2, A3, A5 to A7, B1, C1, D4, E1, E3, E9, E8, F2	Unaltered	1.9
9A	45.25	45.21	45.24	45.23	21.35	21.34	21.37	21.35	A1, A3, A6, B1, C1 to C2, D8, E1, E3, E4, E8, F2	Unaltered	2.1
9B	45.24	45.25	45.18	45.22	22.75	22.69	22.73	22.72	A1, A3, A6, B1, C1 to C2, D8, D9, E1, E3, E4, E8, F2	Unaltered	2.0

9C	45.25	45.28	45.31	45.28	20.13	20.21	20.15	20.16	A1, A3, A7, B1, C1 to C2, D8, E1, E3, E4, E8, F2	Unaltered	2.2
9D	45.28	45.29	45.29	45.29	21.57	21.55	21.52	21.55	A1, A3, A7, B1, C1 to C2, D1, E1, E3, E4, E8, F2	Unaltered	2.1
9E	45.28	45.26	45.28	45.27	20.70	20.73	20.68	20.70	A1, A3, A7, B1, C1 to C2, D2, E1, E3, E4, E8, F2	Unaltered	2.2
9F	45.32	45.3	45.28	45.30	22.01	22.03	22.04	22.03	A1, A3, A7, B1, C1 to C2, D8, E1, E3, E4, E8, F2	Unaltered	2.1
9H	45.35	45.26	45.3	45.30	22.44	22.42	22.40	22.42	A1, A3, A7, B1, C1 to C2, D1, E1, E3, E4, E8, F2	Unaltered	2.0
9I	45.18	45.27	45.22	45.22	21.70	21.72	21.83	21.75	A1, A3, A7, B1, C1 to C2, D1, E1, E3, E4, E8, F2	Unaltered (Sat)	2.1
9J	42.23	45.3	45.2	44.24	20.22	20.16	20.09	20.16	A1, A3, A7, B1, C1 to C2, D1, E1, E3, E4, E8, F2	Unaltered (Sat)	2.2
9L	45.25	45.3	45.33	45.29	22.90	23.16	23.05	23.04	A1, A3, A7, B1, C1 to C2, D1, E1, E3, E4, E8, E9, F2	Unaltered (Sat)	2.0
BF	D1	D2	D3	D avg (mm)	L1	L2	L3	L avg (mm)	Specimen description	Test	Ratio D/L
1A	50.78	50.73	50.83	50.78	26.08	26.18	26.12	26.13	A3, A6, B1, C1, D1, E2, E3, E5 to E7, E9	Unaltered	1.9
1D	50.84	50.75	50.83	50.81	26.48	26.53	26.4	26.47	A3, A6, B1, C1, D1, E2, E3, E5 to E7, E9	Unaltered	1.9
8A	50.92	50.88	50.87	50.89	24.82	24.6	34.37	27.93	A3, A6, B1, C1, D1, E2, E3, E8, E9	Unaltered	1.8
8D	50.87	50.9	50.9	50.89	23.1	22.79	22.82	22.90	A3, A6, B1, C1, D1, E2, E3, E8, E9	Unaltered	2.2
9A	50.88	50.85	50.86	50.86	24.41	24.59	24.66	24.55	A3, A6, B1, C1, D1, E2, E3, E8	Unaltered	2.1
9D	50.87	50.91	50.9	50.89	24.68	24.7	24.73	24.70	A3, A6, B1, C1, D1, E2, E3, E8	Unaltered	2.1
9G	50.92	50.94	50.89	50.92	26.21	26.06	26.33	26.20	A3, A6, B1, C1, D1, E2, E3, E8, F2	Unaltered	1.9
9J	50.9	50.88	50.89	50.89	25.34	25.05	25.41	25.27	A3, A6, B1, C1, D1, E2, E3, E5 to E8	Unaltered	2.0
9M	50.92	50.89	50.85	50.89	27.03	27.25	26.81	27.03	A3, A6, B1, C1, D1, E2, E3, E8	Unaltered (Sat)	1.9
25B	50.79	50.72	50.8	50.77	24.44	24.46	24.09	24.33	A3, A6, B1, C1, D1, E2, E3, E5 to E7	Unaltered	2.1
25H	50.72	50.73	50.76	50.74	24.01	24.05	23.96	24.01	A3, A6, B1, C1, D1, E2, E3, E7	Unaltered	2.1
25K	50.74	50.75	50.88	50.79	23.72	23.1	23.49	23.44	A3, A6, B1, C1, D1, E2, E3, E7	Unaltered	2.2
26A	50.63	50.71	50.71	50.68	25.82	25.63	25.5	25.65	A3, A6, B1, C1, D1, E2, E3, E5 to E7, E9	Unaltered	2.0
26D	50.71	50.69	50.66	50.69	26.05	25.69	25.72	25.82	A3, A6, B1, C1, D1, E2, E3, E5 to E7, E9	Unaltered	2.0
26G	50.64	50.74	50.67	50.68	23.32	23.25	23.76	23.44	A3, A6, B1, C1, D1, E2, E3, E5 to E7, E9, E10	Unaltered (Sat)	2.2
27A	50.68	50.71	50.7	50.70	24.97	24.96	25.02	24.98	A3, A6, B1, C1, D1, E2, E3, E8, E10	Unaltered	2.0
27E	50.73	50.76	50.73	50.74	25.58	25.54	25.74	25.62	A3, A6, B1, C1, D1, E2, E3, E8	Unaltered	2.0
31A	49.27	49.55	49.37	49.40	30.02	29.74	29.7	29.82	A3, A6, B1, C1, D1, E2, E3, E8	Unaltered	1.7
31E	49.37	49.35	49.39	49.37	26.21	26.5	26.23	26.31	A3, A6, B1, C1, D1, E2, E3, E8	Unaltered	1.9

34A	50.06	49.93	49.84	49.94	25.69	25.28	25.37	25.45	A3, A6, B1, C1, D1, E2, E3, E8, E9	Unaltered	2.0
34D	49.8	49.92	49.89	49.87	25.38	25.88	25.43	25.56	A3, A6, B1, C1, D1, E2, E3, E8, E9	Unaltered	2.0
34J	49.94	50	50.06	50.00	24.49	25.08	24.63	24.73	A3, A6, B1, C1, D1, E2, E3, E8, E9	Unaltered (Sat)	2.0
35A	50.25	50.15	50.22	50.21	27.23	27.08	27.29	27.20	A3, A6, B1, C1, D1, E2, E3, E8, E9	Unaltered	1.8
35B	49.85	50.22	50.46	50.18	24.03	23.86	23.87	23.92	A3, A6, B1, C1, D1, E2, E3, E8, E9	Unaltered	2.1
15A	50.6	50.59	50.57	50.59	25.17	25.33	25.29	25.26	A3, A6, B1, C1, D1, E2 (round), E3, E8, E9	Unaltered	2.0
12C	50.49	50.61	50.55	50.55	27.16	27.26	26.76	27.06	A3 (more plagioclase), A6, B1, C1, D1, E2, E3, E5/E6/E7, E9	Unaltered	1.9
12G	50.85	50.84	50.92	50.87	26.1	26.33	26.25	26.23	A3 (more plagioclase), A6, B1, C1, D1, E2, E3, E5/E6/E7	Unaltered	1.9
14A	50.81	50.8	50.78	50.80	24.32	24.54	24.24	24.37	A3 (more plagioclase), A6, B1, C1, D1, E2, E3, E5/E6/E7	Unaltered	2.1
13A	50.39	50.58	50.56	50.51	24.82	25.24	24.77	24.94	A3 (more plagioclase), A6, B1, C1, D1, E2, E3, E8	Unaltered	2.0
28A	50.7	50.77	50.66	50.71	23.34	23.45	23.34	23.38	A3 (more plagioclase), A6, B1, C1, D1, E2, E3, E5 a E7	Unaltered	2.2
28D	50.7	50.71	50.7	50.70	26.33	26.25	26.4	26.33	A3 (more plagioclase), A6, B1, C1, D1, E2, E3, E8, E9	Unaltered	1.9
29A	50.56	50.53	50.64	50.58	23.43	23.42	23.37	23.41	A3 (more plagioclase), A6, B1, C1, D1, E2, E3, E5 a E7, F2	Unaltered	2.2
36A	50.75	50.83	50.72	50.77	27.39	27.51	27.33	27.41	A3 (more plagioclase), A6, B1, C1, D1, E2, E3, E8	Unaltered	1.9
36D	50.7	50.74	50.66	50.70	28.56	28.6	28.61	28.59	A3 (more plagioclase), A6, B1, C1, D1, E2, E3, E8	Unaltered	1.8
36G	50.78	50.8	50.73	50.77	26.31	26.28	26.05	26.21	A3 (more plagioclase), A6, B1, C1, D1, E2, E3, E5 a E7, E9	Unaltered	1.9
36L	50.85	50.79	50.84	50.83	27.69	27.67	27.84	27.73	A3 (more plagioclase), A6, B1, C1, D1, E2, E5 a E7	Unaltered (Sat)	1.8
36P	50.69	50.64	50.79	50.71	26.03	26.28	26.02	26.11	A3 (more plagioclase), A6, B1, C1, D1, E2, E8, E9	Unaltered (Sat)	1.9

2G	50.87	50.86	50.9	50.88	24.01	24.22	24.08	24.10	A3, A6, B1, C2, D1, E2, E3, E5 a E7, E10, F2	Unaltered	2.1
4A	50.8	50.85	50.83	50.83	26	25.97	26.11	26.03	A3, A6, B1, C2, D1, E2, E3, E5 a E7, E9	Unaltered	2.0
11A	50.93	50.96	50.95	50.95	25.44	25.23	25.21	25.29	A3, A6, B1, C2, D1, E2, E5 a E7, E9	Unaltered	2.0
11D	50.67	50.82	50.8	50.76	24.76	24.73	25.02	24.84	A3, A6, B1, C2, D1, E2, E8, E9	Unaltered	2.0
11G	50.68	50.84	50.73	50.75	25.26	25.15	25.08	25.16	A3, A6, B1, C2, D1, E2, E8, E9	Unaltered	2.0
11J	50.91	50.96	50.93	50.93	23.96	23.92	24.05	23.98	A3, A6, B1, C2, D1, E2, E8, E9	Unaltered	2.1
11M	50.43	50.39	50.54	50.45	24.62	24.25	24.42	24.43	A3, A6, B1, C2, D1, E2, E8, E9, E10, F4	Unaltered (Sat)	2.1
16A	50.61	50.48	50.56	50.55	26.06	26.5	26.31	26.29	A3, A6, B1, C2, D1, E2, E8, F4	Unaltered	1.9
16D	50.55	50.62	50.66	50.61	24.83	24.74	24.78	24.78	A3, A6, B1, C2, D1, E2, E5 a E7	Unaltered	2.0
17A	50.75	50.6	50.57	50.64	25.66	25.64	25.68	25.66	A3, A6, B1, C2, D1, E2, E8, E10, W1-2	Unaltered	2.0
17E	50.72	50.77	50.8	50.76	26.02	26.36	26.07	26.15	A3, A6, B1, C2, D1, E2, E5 a E7, E3	Unaltered	1.9
17G	50.77	50.54	50.58	50.63	26.12	26.82	26.18	26.37	A3, A6, B1, C2, D1, E2, E8, E9	Unaltered (Sat)	1.9
18A	50.77	50.79	50.65	50.74	27.52	27.53	27.94	27.66	A3, A6, B1, C2, D1, E2, E8, E9	Unaltered	1.8
18D	50.99	50.76	50.68	50.81	26.17	27.18	26.73	26.69	A3, A6, B1, C2, D1, E2, E8, E9, F2, F4	Unaltered	1.9
18G	50.79	50.75	50.83	50.79	27.71	27.88	28.1	27.90	A3, A6, B1, C2, D1, E2, E8, E9	Unaltered	1.8
18I	50.67	50.69	50.79	50.72	25.92	25.98	25.88	25.93	A3, A6, B1, C2, D1, E2, E3, E5 a E7, E9	Unaltered	2.0
20A	50.81	50.78	50.75	50.78	26.13	26.16	26.1	26.13	A3, A6, B1, C2, D1, E2, E8, F2	Unaltered	1.9
20D	50.79	50.71	50.26	50.59	25.26	25.7	25.54	25.50	A3, A6, B1, C2, D1, E2, E8, E9	Unaltered	2.0
21A	50.76	50.88	50.76	50.80	26.76	26.7	26.76	26.74	A3, A6, B1, C2, D1, E2, E3, E5 a E7, E9	Unaltered	1.9
21D	50.73	50.79	50.67	50.73	24.15	24.17	24.13	24.15	A3, A6, B1, C2, D1, E2, E3, E5 a E7, E10	Unaltered	2.1
33B	50.03	50.11	50.08	50.07	23.03	23.04	22.98	23.02	A3, A6, B1, C3, D1, E2, E8, E9	Unaltered	2.2
33E	49.7	49.93	49.92	49.85	23.63	23.42	23.53	23.53	A3, A6, B1, C3, D1, E2, E3, E7 a E5	Unaltered	2.1
33H	49.97	49.91	49.85	49.91	26.04	26.23	26.04	26.10	A3, A6, B1, C3, D1, E2, E8, E9	Unaltered (Sat)	1.9
7A	50.78	50.83	50.72	50.78	24.09	24.17	24.14	24.13	A3, A6, B3, C3, D1, E1, E3, E8	Unaltered	2.1
7C	50.87	50.89	50.88	50.88	25.25	25.39	25.09	25.24	A3, A6, B3, C3, D1, E1, E3, E8	Unaltered	2.0
7E	50.86	50.89	50.92	50.89	25.01	24.97	25.08	25.02	A3, A6, B3, C3, D1, E1, E3, E8	Unaltered	2.0
35A	50.73	50.57	50.3	50.53	26.19	26.1	26.09	26.13	A3, A6, B1, C3, D1, E2, E3, E7 a E5, E9, E10	Unaltered	1.9
37B	50.57	50.68	50.7	50.65	28.37	28.33	28.32	28.34	A3, A6, B1, C3, D1, E2, E8, E9	Unaltered	1.8
37E	50.68	50.72	50.65	50.68	25.5	25.57	25.41	25.49	A3, A6, B1, C3, D1, E2, E8, E9	Unaltered	2.0
5A	50.85	50.89	50.9	50.9	22.36	22.4	22.43	22.40	A1 and A3, A6, B1, C1, D1, E1, E3, E8	Unaltered	2.3

22A	50.79	50.74	50.73	50.8	25.73	25.63	25.92	25.76	A1 and A3, A6, B1, C1, D1, E1, E3, E8	Unaltered	2.0
22B	50.77	50.73	50.76	50.8	26.59	26.61	27.02	26.74	A1 and A3, A6, B1, C1, D1, E1, E3, E8	Unaltered	1.9
22C	50.8	50.76	50.78	50.8	29.44	29.37	29.33	29.38	A1 and A3, A6, B1, C2, D1, E1, E3, E8	Unaltered	1.7
22D	50.7	50.82	50.82	50.8	28.37	27.96	28.13	28.15	A1 and A3, A6, B1, C2, D1, E1, E3, E8	Unaltered	1.8
22E	50.74	50.8	50.79	50.8	26.32	25.88	26.14	26.11	A1 and A3, A6, B1, C2, D1, E1, E3, E8	Unaltered (Sat)	1.9
23A	50.81	50.69	50.76	50.8	27.22	27.04	27.04	27.10	A1 and A3, A6, B1, C2, D1, E1, E3, E5 a E7	Unaltered	1.9
23B	50.76	50.71	50.8	50.8	25.16	25.09	25.32	25.19	A1 and A3, A6, B1, C2, D1, E1, E3, E5 a E7	Unaltered	2.0
23C	50.74	50.77	50.72	50.7	30	30.26	30.17	30.14	A1 and A3, A6, B1, C2, D1, E1, E3, E5 a E7	Unaltered	1.7
23D	50.75	50.76	50.74	50.8	23.69	23.91	23.81	23.80	A1 and A3, A6, B1, C2, D1, E1, E3, E5 a E7	Unaltered	2.1
23E	50.81	50.85	50.78	50.8	24.99	24.93	25.11	25.01	A3, A6, B1, C2, D1, E1, E3, E5 a E7	Unaltered (Sat)	2.0
3A	50.85	50.86	50.82	50.84	25.88	25.82	25.94	25.88	A3, B1, C1 a C2, E1, E3, D2	Unaltered	2.0
3D	50.84	50.86	50.9	50.87	25.43	25.5	25.44	25.46	A3, B1, C1 a C2, D1, E1, E3	Unaltered	2.0
10B	50.9	50.96	50.91	50.92	23.24	23.51	23.77	23.51	A3, B1, C1 a C2, E1, E3, D2	Unaltered	2.2
10E	50.87	50.89	50.91	50.89	24	23.95	24.32	24.09	A3, B1, C1, E1, E3, D1	Unaltered	2.1
10K	50.8	50.84	50.88	50.84	24.26	24.13	24.32	24.24	A3, B1, C1, E1, E3, D1	Unaltered	2.1
10L	50.84	50.84	50.8	50.83	22.92	22.7	22.69	22.77	A3, B1, C1, E1, E3, D1	Unaltered (Sat)	2.2
32A	49.88	49.99	50	49.96	25.2	25.22	25.19	25.20	A3, B1, C1, E1, E3, D1	Unaltered	2.0
32D	50	50.03	50.05	50.03	25.7	25.59	25.62	25.64	A3, B1, C1, E1, E3, D8	Unaltered	2.0
32G	49.24	49.42	49.4	49.35	26.16	26.18	26.29	26.21	A3, B1, C1, E1, E3, D9	Unaltered	1.9
32K	49.33	49.4	49.3	49.34	24.54	24.42	24.52	24.49	A3, B1, C1, E1, E3, D8	Unaltered	2.0
32N	49.84	49.89	49.85	49.86	24.51	24.41	24.57	24.50	A3, B1, C1 to C2, E1, E3, D2	Unaltered (Sat)	2.0
30B	50.7	50.76	50.76	50.74	26.26	26.47	26.38	26.37	A3, B1, C1 to C2, E1, E3, E8, D1, F2	Unaltered	1.9
30E	50.66	50.76	50.6	50.67	23.46	23.55	23.55	23.52	A3, B1, C1 to C2, E1, E3, E8, D	Unaltered	2.2
30H	50.73	50.76	50.77	50.75	24.83	24.78	24.79	24.80	A3, B1, C1 to C2, E1 to E2, E3, E8, D8	Unaltered	2.0
30M	50.6	50.72	50.75	50.69	25.7	25.62	25.48	25.60	A3, B1, C1 to C2, D1, E1 to E2, E3, E8	Unaltered (Sat)	2.0
T	D1	D2	D3	D avg (mm)	L1	L2	L3	L avg (mm)	Specimen description	Test	Ratio D/L
1A	45.03	44.86	45.07	44.99	18.95	19.12	18.99	19.02	A4, A5, B4, C1, D1, E11, F1, F3, F4	Unaltered	2.4
1B	45.03	45.20	45.28	45.17	19.29	19.32	19.26	19.29	A4, A5, B4, C1, D1, E11, F1, F3, F4	Unaltered	2.3
1C	45.22	45.33	45.30	45.28	21.25	21.46	21.35	21.35	A4, A5, B4, C1, D1, E11, F1, F3, F4	Unaltered	2.1

1D	45.25	45.16	45.29	45.23	20.94	21.00	20.91	20.95	A4, A5, B4, C1, D2, E11, F1, F3, F4	Unaltered (Sat)	2.2
2A	45.23	45.22	45.23	45.23	19.95	20.55	20.76	20.42	A4, A5, B4, C1, D1, E11, F1, F3, F4	Unaltered	2.2
2B	45.29	45.17	45.15	45.20	22.17	21.94	21.50	21.87	A4, A5, B4, C1, D1, E11, F1, F3, F4	Unaltered	2.1
4B	44.56	44.46	44.59	44.54	22.16	21.78	21.81	21.92	A4, A5, B4, C1, D1, E11, F1, F3, F4	Unaltered (Sat)	2.0
4C	44.58	44.48	44.41	44.49	22.49	22.51	22.53	22.51	A4, A5, B4, C1, D1, E11, F1, F3, F4	Unaltered	2.0
7A	45.01	44.94	44.88	44.94	22.25	22.45	22.34	22.35	A4, A5, B4, C1, D1, E11, F1	Unaltered	2.0
7B	45.03	45.16	45.02	45.07	22.89	23.01	22.99	22.96	A4, A5, B4, C1, D1, E11, F1	Unaltered	2.0
8A	45.07	44.98	44.95	45.00	23.33	22.71	23.25	23.10	A4, A5, B5, C1, D1, E11, F1, F3	Unaltered	1.9
5A	44.99	45.04	44.93	44.99	20.55	20.67	20.31	20.51	A4, A5, B4, C1, D1, E11, F1	Unaltered	2.2
6A	45.08	45.06	45.09	45.08	22.16	22.05	22.04	22.08	A4, A5, B4, C1, D1, E11, E13	Unaltered	2.0
6B	45.07	45.01	45.04	45.04	21.91	21.92	21.93	21.92	A4, A5, B4, C1, D1, D6, E11	Unaltered	2.1
9A	44.93	45.07	45.10	45.03	22.46	22.49	22.58	22.51	A4, A5, B4, C1, D1, E11	Unaltered	2.0
9B	44.94	44.98	45.05	44.99	21.31	21.35	21.30	21.32	A4, A5, B4, C1, D1, E11	Unaltered	2.1
9C	45.13	45.01	44.99	45.04	21.36	21.57	21.35	21.43	A4, A5, B4, C1, D1, E11	Unaltered (Sat)	2.1
10A	44.96	45.01	45.18	45.05	22.21	21.88	22.31	22.13	A4, A5, B4, C1 (metasomatic), E11, E13, F2	Unaltered	2.0
10B	45.15	45.06	45.00	45.07	22.25	22.57	22.90	22.57	A4, A5, B4, C1 (metasomatic), E11, E13, F2	Unaltered	2.0
12A	45.24	45.26	45.29	45.26	21.18	21.11	21.19	21.16	A4, A5, B4, C1 to C2 (metasomatic), E11, E13	Unaltered	2.1
13A	45.30	45.25	45.29	45.28	22.19	22.00	22.31	22.17	A4, A5, B4, C1, D1, E11	Unaltered	2.0
13B	45.24	45.24	45.24	45.24	22.32	22.38	22.30	22.33	A4, A5, B4, C1, D1, E11	Unaltered	2.0
13C	45.27	45.24	45.23	45.25	21.64	21.48	21.75	21.62	A4, A5, B4, C1, D1, E11	Unaltered (Sat)	2.1
15C	45.22	44.95	44.99	45.05	19.03	19.04	19.02	19.03	A4, A5, B4 to B5, C1, D1, E11	Unaltered	2.4
21A	45.30	45.35	45.34	45.33	22.58	22.50	22.67	22.58	A4, A5, B4, C1, D5, D8, E11, E13	Unaltered	2.0
21B	45.33	45.34	45.34	45.34	22.52	22.56	22.61	22.56	A4, A5, B4, C1, D8, E11, E13	Unaltered	2.0
21C	45.33	45.34	45.38	45.35	21.14	21.38	21.46	21.33	A4, A5, B4, C1, D5, D8, E11, E13	Unaltered	2.1
24A	45.19	44.93	45.06	45.06	22.37	22.35	22.18	22.30	A4, A5, B4, C1, D5, E11, E13	Unaltered	2.0
24B	45.15	45.24	45.17	45.19	23.92	24.14	24.05	24.04	A4, A5, B4, C1, D5, E11, E14	Unaltered	1.9
25A	45.30	45.26	45.14	45.23	22.10	22.31	22.05	22.15	A4, A5, B4, C1, D1, E11, E13	Unaltered	2.0
25B	45.23	45.28	45.35	45.29	25.66	25.75	25.43	25.61	A4, A5, B4, C1, D1, E11, E13	Unaltered	1.8
25C	45.16	45.28	45.26	45.23	19.28	19.24	19.22	19.25	A4, A5, B4, C1, D1, E11, E13, F4	Unaltered	2.4
11A	45.04	45.06	45.01	45.04	22.76	22.67	22.71	22.71	A4, A5, B4, C1, D1, E11	Unaltered	2.0

11B	45.06	45.19	45.09	45.11	21.81	21.71	21.82	21.78	A4, A5, B4, C1, D1, E11	Unaltered	2.1
19A	45.32	45.31	45.32	45.32	21.04	20.97	21.01	21.01	A4, A5, B4, C1, D1, E11	Unaltered	2.2
19D	45.31	45.34	45.36	45.34	20.70	20.69	20.58	20.66	A4, A5, B4, C1, D1, E11	Unaltered	2.2
20A	45.40	45.31	45.38	45.36	19.57	20.12	20.49	20.06	A4, A5, B4, C1, D1, D8, E11	Unaltered	2.3
20B	45.33	45.37	45.37	45.36	18.74	18.83	18.79	18.79	A4, A5, B4, C1, D1, E11, F2	Unaltered	2.4
20C	45.33	45.35	45.31	45.33	18.63	18.70	18.76	18.70	A4, A5, B4, C1, D1, E11, F2	Unaltered (Sat)	2.4
22A	45.18	45.08	45.11	45.12	21.59	21.72	21.68	21.66	A4, A5, B4, C1, D1, E11, F2	Unaltered	2.1
22D	45.21	45.10	45.12	45.14	22.66	22.67	22.69	22.67	A4, A5, B4, C1, D1, E11, F2	Unaltered	2.0
23A	45.10	44.93	45.02	45.02	21.18	21.06	21.22	21.15	A4, A5, B4, C2, D1, E11, E13	Unaltered (Sat)	2.1
23B	44.91	44.90	45.32	45.04	21.08	20.88	21.01	20.99	A4, A5, B4, C2, D1, E11, E13	Unaltered	2.1
23C	45.12	45.03	45.13	45.09	22.76	22.95	22.97	22.89	A4, A5, B4, C2, D2, E11, E13	Unaltered (Sat)	2.0
23E	45.23	45.01	45.17	45.14	21.39	21.17	21.35	21.30	A4, A5, B4, C2, D2, E11, E13	Unaltered	2.1
18B	45.31	45.33	45.33	45.32	23.04	23.16	23.05	23.08	A4, A5, B4, C2, D1, D8, E11	Unaltered	2.0
14A	45.15	45.23	45.17	45.18	21.20	21.05	21.06	21.10	A4, A5, B4, C1 to C2, D3, D8, E11, E13	Unaltered	2.1
14B	45.17	45.13	45.17	45.16	18.73	18.97	18.75	18.82	A4, A5, B4, C1 to C2, D1, E11, E13	Unaltered	2.4
14G	44.97	45.05	45.06	45.03	20.13	20.19	20.17	20.16	A4, A5, B4, C1 to C2, D1, E11, E13	Unaltered (sat)	2.2
17B	45.27	45.30	45.33	45.30	23.95	24.30	24.33	24.19	A4, A5, B4, C1 to C2, D1, E11, E13, F2	Unaltered	1.9
17C	45.25	45.29	45.25	45.26	23.67	23.70	23.53	23.63	A4, A5, B4, C2, D1, E11, E13, F2	Unaltered	1.9
26A	45.34	45.29	45.32	45.32	18.42	18.45	18.63	18.50	A4, A5, B4, C2, D2, E11, E13	Unaltered	2.4
26B	45.29	45.31	45.36	45.32	21.30	21.43	21.33	21.35	A4, A5, B4, C2, D1, E11, E13, F1	Unaltered	2.1
27A	44.93	45.11	44.97	45.00	16.77	16.73	16.66	16.72	A4, A5, B4, C2, D1, E11, E13	Unaltered	2.7
27B	45.29	45.07	44.81	45.06	19.41	19.55	19.64	19.53	A4, A5, B4, C2, D1, E11, E13, F2 (metasomatic)	Unaltered	2.3
27C	45.14	44.92	45.12	45.06	19.95	19.69	20.13	19.92	A4, A5, B4, C2, D1, E11, E13, F3 (metasomatic)	Unaltered	2.3
16B	45.28	45.27	45.32	45.29	21.08	21.25	21.30	21.21	A4, A7, B5, C3, D5, E4, E8, E13	Unaltered	2.1
16D	45.27	45.34	45.29	45.30	19.17	19.54	19.37	19.36	A4, A7, B5, C3, D5, D8, E4, E8, E13	Unaltered	2.3
16F	45.29	45.28	45.27	45.28	22.85	22.91	22.67	22.81	A4, A7, B5, C3, D5, E4, E8, E13	Unaltered	2.0
16G	45.28	45.30	45.29	45.29	19.28	19.43	19.50	19.40	A4, A7, B5, C3, D5, E4, E8, E13, F3	Unaltered (Sat)	2.3
16H	45.27	45.25	45.28	45.27	22.35	22.65	22.57	22.52	A4, A7, B5, C3, D5, E4, E8, E13	Unaltered	2.0

Compression Test

Table 3.2. (Appendix). Size and specimen description for the Compression tests. D – diameter; L – length (or height); UCS – uniaxial test; Tri – triaxial test. Calliper uncertainty: $\pm 0,01$ mm. All specimens were tested for the P-wave velocity.

BP	D1	D2	D3	D avg (mm)	L1	L2	L3	L avg (mm)	Specimen description	Test	Ratio D/L
1A	42.04	41.84	42.1	41.99	90.2	90.05	90.03	90.09	A1, A5, B3, C1, D1, D8, E1, E4 to E11, E8, (olivine megacrysts, diagonal)	Tri Unaltered	2.1
5A	41.96	41.94	41.86	41.92	91.4	91.11	91.13	91.21	A1, A5, B3, C1, D1, D8, E1, E4, E8, and E10, F4	Tri Unaltered	2.2
6A	45.00	45.10	45.12	45.07	91.24	91.63	91.50	91.46	A1, A5, B3, C1, D1, D8, E1, E4 to E11, E7	UCS Unaltered	2.0
6B	44.92	44.98	44.98	44.96	91.51	91.68	91.58	91.59	A1, A3, A5, B1, C1, D3, E9, E1, E4, E7, E5, F3	UCS Unaltered	2.0
8A	44.78	44.68	44.98	44.81	92.61	92.60	92.64	92.62	A1, A5, B3, C1, D1, E1, E4 to E11, E8	UCS Unaltered	2.1
13A	41.63	41.73	41.87	41.74	90.22	90.2	90.21	90.21	A1, A5, B3, C1, D1, E1 and E4, E8	Tri Unaltered	2.2
13B	45.13	45.24	45.20	45.19	93.07	93.02	93.36	93.15	A1, A5, B3, C1, D8, E1, E13, E7 (localised porous bands)	UCS Unaltered	2.1
15A	41.78	41.45	41.72	41.65	90.8	90.43	90.33	90.52	A1, A5, B3, C1, D1, E1, E4, E8	Tri Unaltered	2.2
15G	45.03	45.02	45.04	45.03	90.78	91.09	90.80	90.89	A1, A5, B3, C1, D1, E1, E4, E8	UCS unaltered	2.0
15I	41.69	41.78	41.85	41.77	90.25	90.22	90.26	90.24	A1, A5, B3, C1, D1, E1, E4, E8	Tri Unaltered	2.2
16A	44.88	44.89	44.84	44.87	92.89	93.28	93.18	93.12	A1, A5, B3, C1, D2 (horizontal, middle), E1, E4	UCS Unaltered	2.1
20A	41.97	41.74	41.85	41.85	90.42	90.42	90.38	90.41	A1, A5, B3, C1, D1, E1, E4, E8, F4	Tri Unaltered	2.2
21A	45.08	45.08	45.09	45.08	92.90	92.90	92.94	92.91	A1, A5, B3, C1, D3, E1, E4, E8	UCS Unaltered	2.1
22C	41.86	41.89	41.92	41.89	90.24	90.34	90.26	90.28	A1, A5, B3, C1, D1, E1, E4, E8	Tri unaltered	2.2
25A	45.03	45.13	45.12	45.09	92.85	92.81	92.89	92.85	A1, A5, B3, C1, D1, E1, E4, E8	UCS Unaltered	2.1
25C	42.17	41.86	41.87	41.97	90.37	90.78	90.49	90.55	A1, A5, B3, C1, D1, E1, E4, E8, E10 w/ olivine	Tri Unaltered	2.2
25G	41.81	41.45	41.59	41.62	90.55	90.52	90.56	90.54	A1, A5, B3, C1, D1, E1, E4, E8	Tri Unaltered	2.2
3A	50.52	50.66	50.66	50.61	103.39	103.45	103.62	103.49	A1, A5, B1, C1, D1, E4, E7, F1	UCS Unaltered	2.0
18A	42.07	41.79	41.95	41.94	90.55	90.61	90.5	90.55	A1, A5, B1, C1, D1, E4, E8	Tri Unaltered	2.2

18B	45.03	44.92	44.99	44.98	93.48	93.53	93.52	93.51	A1, A5, B1, C1, D1, D3, E4, E8, F1	UCS Unaltered	2.1
19A	41.78	41.79	41.99	41.85	91.06	90.42	90.32	90.60	A1, A5, B1, C1, D1, E1, E4, E8	Tri Unaltered	2.2
19C	44.94	45.01	44.93	44.96	93.15	93.16	93.43	93.25	A1, A5, B1, C1, D1, E1 to E11, E7, E10	UCS Unaltered	2.1
23A	45.15	45.22	45.17	45.18	92.90	93.05	93.03	92.99	A1, A3, A5, B1, C1, D1, E4 to E9, E8, F4	UCS Unaltered	2.1
23F	41.98	41.77	41.76	41.84	90.62	90.61	90.63	90.62	A1, A5, B1, C1, D1, E4, E8	Tri Unaltered	2.2
26A	45.18	45.27	45.18	45.21	92.64	92.43	92.35	92.47	A1, A5, B2, C1, D2 (diagonal and middle), E4 to E11	UCS Unaltered	2.0
27A	45.12	45.04	45.01	45.06	93.13	93.70	93.30	93.38	A1, A5, B2, C1, D2 (small), D8 (diagonal and middle), E4 to E11	UCS Unaltered	2.1
29A	45.21	45.03	45.07	45.10	92.80	92.78	92.87	92.87	A1, A5, B2, C1, D2 (diagonal to vertical), E4 to E11	UCS Unaltered	2.1
30A	45.04	44.83	45.08	44.98	93.03	92.97	93.14	93.05	A1, A7, B3, C1, D3, E1 (small), E8	UCS Unaltered	2.1
33A	45.36	45.38	45.39	45.38	93.00	92.85	92.98	92.94	A1, A5, B2, C1, D1 (diagonal and middle), E3 (almost fissure). E7	UCS Unaltered	2.0
33B	45.32	45.35	45.36	45.343333	93.07	93.29	93.03	93.13	A1, A5, B2, C1, D1 (diagonal and middle), E3 (almost fissure), E7, megacryst Olivine	Tri Unaltered	2.1
35A	42.09	41.87	41.77	41.91	90.55	90.58	90.39	90.51	A1, A5, B3, C1, D3, E3, almost forming fractures, E7, mainly	Tri Unaltered	2.2
36A	41.8	41.89	41.94	41.88	90.64	90.49	90.47	90.53	A1, A5, B3, C1, D1, E1 (small), E8	Tri Unaltered	2.2
BAf	D1	D2	D3	D avg (mm)	L1	L2	L3	L avg (mm)	Specimen description	Test	Ratio D/L
6A	45.28	45.22	45.28	45.26	92.90	92.88	92.92	92.90	A1, A3, A5, B1, C1, D1, E9, E1, E4, E7, E5, F1, F2	UCS Unaltered	2.1
10A	45.26	45.24	45.25	45.25	92.78	92.96	92.97	92.90	A1, A3, A5, B1, C1, D2, D8, E1, E3, E5, E8, F1	UCS Unaltered	2.1
7A	41.69	41.8	41.66	41.72	90.42	90.78	90.41	90.54	A2, A3, A5 to A7, B1, C1, D3, E1, E4, E10, E7, F1	Tri Unaltered	2.2
7E	45.27	45.28	45.19	45.25	93.10	93.04	92.92	93.02	A2, A3, A5 to A7, B1, C1, D1 E1, E3, E7, E9, E10, F2	UCS Unaltered	2.1
8A	41.72	41.57	41.51	41.60	90.7	90.48	90.51	90.56	A1 and A3, A5, B1, C1, D1, E1 and E4, E8, F1	Tri Unaltered	2.2

8D	45.29	45.28	45.28	45.28	90.10	90.19	90.02	90.10	A2, A3, A5 to A7, B1, C1, D3, E1, E8, F1	UCS Unaltered	2.0
11A	41.9	42.01	41.82	41.91	90.47	90.49	90.52	90.49	A2, A3, A5 to A7, B1, C1, D1, E1 and E3, E10, E7 to E6, F1	Tri Unaltered	2.2
12A	41.34	41.65	41.58	41.52	90.16	90.1	90.15	90.14	A2, A3, A5 to A7, B1, C1, D1, E1, E3, E5, F1	Tri Unaltered	2.2
12C	45.17	45.12	45.17	45.15	93.03	93.10	93.01	93.05	A2, A3, A5 to A7, B1, C1, D1, E1, E3, E8	UCS Unaltered	2.1
12E	45.28	45.29	45.32	45.30	92.74	92.69	92.69	92.71	A2, A3, A5 to A7, B1, C1, D1, E1, E3, E7, E8	UCS Unaltered	2.0
9A	45.25	45.26	45.28	45.26	93.00	93.14	93.08	93.07	A1, A3, A7, B1, C1 to C2, D2, E1, E3, E4, E8, E9	UCS Unaltered	2.1
9B	45.25	45.35	45.28	45.29	92.01	91.71	91.67	91.80	A1, A3, A7, B1, C1 to C2, D1, E1, E3, E4, E8, F1	UCS Unaltered	2.0
9D	41.93	41.73	41.78	41.81	90.36	90.32	90.33	90.34	A1, A3, A7, B1, C1 to C2, D1, E1, E4 to E3, E8, F1	Tri Unaltered	2.2
BF	D1	D2	D3	D avg (mm)	L1	L2	L3	L avg (mm)	Specimen description	Test	Ratio D/L
8A	42.14	41.81	42.13	42.03	90.56	90.61	90.6	90.59	A3, A6, B1, C1, D1, E1, E3, E5, E7, E9,	Tri Unaltered	2.2
8C	50.90	50.94	50.96	50.93	102.01	102.06	101.91	101.99	A3, A6, B1, C1, D1, E1, E3, E5, E7, E9,	UCS Unaltered	2.0
8D	50.83	50.8	50.76	50.80	94.67	94.64	94.62	94.64	A3, A6, B1, C1, D1, E1, E3, E5, E7, E9,	UCS Unaltered	1.9
9A	50.86	50.84	50.99	50.90	101.66	101.60	101.68	101.65	A3, A6, B1, C1, D1, E1, E3, E5, E7, E9,	UCS Unaltered	2.0
9C	42	41.38	41.53	41.64	90.35	90.52	90.76	90.54	A3, A6, B1, C1, D1, E1, E3, E5 to E7, E9, F1	Tri Unaltered	2.2
25A	41.75	41.73	41.81	41.76	90.43	90.48	90.33	90.41	A3, A6, B1, C1, D1, E1, E3, E5, E7, E9,	Tri Unaltered	2.2
25C	50.76	50.70	50.74	50.73	106.60	106.92	106.55	106.69	A3, A6, B1, C1, D1, E1, E3, E5, E7, E9,	UCS Unaltered	2.1
25G	42.23	42.19	42.55	42.32	90.56	90.5	90.49	90.52	A3, A6, B1, C1, D1, E1, E3, E5, E7, E8, E9,	Tri Unaltered	2.1
31A	41.96	42.38	42.79	42.38	90.38	90.51	90.44	90.44	A3, A6, B1, C1, D1, E1, E3, E5, E7, E8, E9,	Tri Unaltered	2.1
34A	49.85	49.78	49.71	49.78	106.46	106.64	106.47	106.52	A3, A6, B1, C1, D1, E1, E3, E6, E7, E9,	UCS Unaltered	2.1
34B	42.69	42.5	42.12	42.44	90.54	90.4	90.49	90.48	A3, A6, B1, C1, D1, E1, E3, E5, E7, E8, E9, E10	Tri Unaltered	2.1
35A	50.45	50.20	50.15	50.27	103.78	103.89	103.82	103.83	A3, A6, B1, C1, D1, E1, E3, E5, E7, E9, E10	UCS Unaltered	2.1
35B	42.07	41.75	41.22	41.68	90.62	90.53	90.54	90.56	A3, A6, B1, C1, D1, E1, E3, E5, E7, E8, E9, E10	Tri Unaltered	2.2
35D	50.66	50.73	50.64	50.68	106.48	106.70	106.51	106.56	A3, A6, B1, C1, D1, E1, E3, E5, E7, E9,	UCS Unaltered	2.1
35J	42.06	42.13	42.05	42.08	90.34	90.53	90.32	90.40	A3, A6, B1, C1, D1, E1, E3, E5-E7, E9	Tri Unaltered	2.1

350	42.02	41.99	42.08	42.03	90.51	90.56	90.46	90.51	A3, A6, B1, C1, D1, E1, E3, E5 - E7, E9, F1	Tri Unaltered	2.2
12A	42.06	41.99	41.67	41.91	90.49	90.43	90.72	90.55	A3 (more porphyritic), A6, B1, C1 to C2 (pontual), D1, E1, E3, E8, E9	Tri Unaltered	2.2
12B	50.75	50.76	50.65	50.72	106.08	106.17	106.02	106.09	A3(more porphyritic), A6, B1, C1 to C2 (pontual), D1, E1, E3, E5-E87, E9, F1	UCS unaltered	2.1
12E	41.91	41.74	41.73	41.79	90.06	90.08	90.02	90.05	A3(more porphyritic), A6, B1, C1 to C2 (pontual), D1, E1, E3, E8, E9, F1	Tri Unaltered	2.2
14A	50.58	50.62	50.52	50.57	106.54	106.41	106.38	106.44	A3(more porphyritic), A6, B1, C1 to C2 (pontual), D1, E1, E3, E5-E8, E9, F1	UCS Unaltered	2.1
36A	41.55	41.79	42.03	41.79	90.99	90.46	90.62	90.69	A3(more porphyritic), A6, B1, C1 to C2 (pontual), D1, E1, E3, E5-E8, E9	Tri Unaltered	2.2
36B	50.71	50.73	50.71	50.72	106.52	106.51	106.67	106.57	A3(more porphyritic), A6, B1, C1 to C2 (pontual), D1, E1, E3, E8, E9	UCS Unaltered	2.1
36G	41.78	41.89	42.02	41.90	90.52	90.545	90.51	90.53	A3(more porphyritic), A6, B1, C1 to C2 (pontual), D1, E1, E3, E7, E9, E10	Tri Unaltered	2.2
2A	41.78	41.69	42.04	41.84	90.28	90.22	90.8	90.43	A3, A6, B2, C2, D1, E2, E3, E7, E10	Tri Unaltered	2.2
2B	50.80	50.85	50.80	50.82	99.73	99.72	99.51	99.65	A3, A6, B2, C2, D1, E2, E3, E7, E9, E10	UCS unaltered	2.0
17A	42.09	41.53	42.08	41.90	90.49	90.28	90.44	90.47	A3, A6, B2, C2 to C3, D1, E2, E3, E5 to E7, E9, E10	Tri Unaltered	2.2
20A	41.64	41.87	41.93	41.81	90.53	90.45	90.59	90.52	A3, A6, B2, C2, D1, E2, E3, mainly E7, E9, E10	Tri Unaltered	2.2
20B	50.55	50.60	50.80	50.65	106.82	106.89	106.67	106.79	A3, A6, B2, C2, D1, E2, E3, E6, E7, E9, E10	UCS Unaltered	2.1
33B	41.38	41.66	41.97	41.67	90.37	90.2	90.27	90.28	A3, A6, B2, C3, D1, E2, E3, E6 to E7, E9, E10	Tri Unaltered	2.2
37A	50.63	50.61	50.58	50.61	106.68	106.63	106.74	106.68	A3, A6, B2, C3, D1, E2, E3, E6, E7, E9, E10	UCS unaltered	2.1
7A	50.77	50.80	50.75	50.77	101.27	101.35	101.32	101.31	A3, A6, B3, C2, D1, E2, E3, E8 (all directions), E9	UCS Unaltered	2.0
5A	51.05	50.82	50.86	50.91	101.15	101.26	101.34	101.25	A1 and A3, B1, C1, D1, E1 to E3, E5-E7, F1, F4	UCS Unaltered	2.0
5B	50.88	50.84	50.74	50.82	101.01	101.51	101.18	101.23	A1 and A3, B1, C1, D1, E1 to E3, E5-E7, F1	UCS Unaltered	2.0

23A	50.75	50.67	50.76	50.73	106.48	106.36	106.86	106.57	A1 and A3, A7, B1, C1 to C2, D4 (diagonal), D3, E1, E4, F1	UCS Unaltered	2.1
23B	50.67	50.59	50.67	50.64	106.82	106.74	106.53	106.70	A1 and A3, A7, B1, C1 to C2, D4 (diagonal to horizontal), D3, E1, E4, F1	UCS Unaltered	2.1
10A	50.81	50.79	50.81	50.80	106.54	106.43	106.57	106.51	A3, A5 to A7, B1, C1 to C2, D1, E1 and E3, F1	UCS Unaltered	2.1
10B	41.75	41.9	42.03	41.89	90.63	90.61	90.57	90.60	A3, A5 to A7, B1, C1 to C2, D1, E1 and E3	Tri Unaltered	2.2
30A	41.88	41.90	41.82	41.87	90.61	90.59	90.52	90.57	A3, A5 to A7, B1, C1 to C2, D1, E1 and E3, oxidation spot	Tri Unaltered	2.2
T	D1	D2	D3	D avg (mm)	L1	L2	L3	L avg (mm)	Specimen description	Test	Ratio D/L
3A	41.88	41.96	42.09	41.98	90.44	90.45	90.44	90.44	A4, A5, B4, C1, D5, E11, F1	Tri Unaltered	
7A	44.92	45.07	45.02	45.00	92.73	92.63	93.06	92.81	A4, A5, B4, C1, D3, E11, F1, F4	UCS Unaltered	2.1
8A	41.97	41.84	41.98	41.93	90.54	90.45	90.41	90.47	A4, A5, B4, C1, D1, E11, F1	Tri Unaltered	2.2
11A	45.24	45.09	45.15	45.16	93.04	93.16	93.17	93.12	A4, A5, B4, C1, D3, E11, F1, F2	UCS Unaltered	2.1
11B	42.03	41.83	41.88	41.91	90.14	90.36	90.18	90.23	A4, A5, B4, C1, D3, E11, F1	Tri Unaltered	2.2
9B	45.07	44.94	45.06	45.02	92.89	93.14	92.98	93.00	A4, A5, B4, C1, D1, E11, F2, E13 (soft)	UCS Unaltered	2.1
13C	45.14	45.18	45.13	45.15	93.04	93.09	92.9	93.01	A4, A5, B4, C1, D2 (short), E11, F2, E13 (soft)	UCS Unaltered	2.1
12A	45.06	45.08	45.19	45.11	93.03	93.37	93.58	93.33	A4, A5, B4, C1 (metasomatic), D3, E11, E13	UCS Unaltered	2.1
15A	42.25	41.99	41.97	42.07	90.09	90.58	90.18	90.28	A4, A5, B4 to B5, C1, D1, E11	Tri Unaltered	2.1
19A	41.9	41.98	42.03	41.97	90.39	90.38	90.46	90.41	A4, A5, B4 to B5, C1, D1, E11	Tri Unaltered	2.2
19B	41.63	41.94	42.02	41.86	90.31	90.28	90.35	90.31	A4, A5, B4 to B5, C1, D1, E1 and E11	Tri Unaltered	2.2
22	45.01	45.09	45.15	45.08	92.95	93.32	93.01	93.09	A4, A5, B4, C1, D1, E11	UCS Unaltered	2.1
17A	42.08	41.82	41.91	41.94	90.43	90.41	90.42	90.42	A4, B4to B5, C1, D1 E11, E13	Tri Unaltered	2.2
26B	41.75	41.62	41.79	41.72	90.56	90.53	90.88	90.66	A4, B4 to B5, C1, D1 E11, E13 (flow structure in the vertical)	Tri Unaltered	2.2
26C	45.18	45.16	45.12	45.15	93.21	93.33	93.38	93.306667	A4, B4, C1 to C2, D8, E11, E13, F2	UCS Unaltered	2.1
23A	41.78	41.73	41.95	41.82	90.31	90.43	90.38	90.37	A4, A5, B4, C2, D2, E11, E13 (muito soft)	Tri Unaltered	2.2
18A	45.32	45.32	45.31	45.32	93.91	93.36	93.79	93.69	A4, A5, B4, C2, D1, E11	UCS Unaltered	2.1
18B	41.95	42	42.2	42.05	90.33	90.5	90.38	90.40	A4, A5, B4 to B5, C2, D1, E11 and E1	Tri Unaltered	2.1

18D	45.32	45.32	45.34	45.33	92.86	92.87	93.08	92.94	A4, A5, B4, C2, D1, E11, E12?	UCS Unaltered	2.1
14A	45.10	45.14	45.21	45.15	93.33	93.38	93.30	93.34	A4, A5, B4, C1 to C2, D1 E11, E13 (less proeminent, horizontal to diagonal)	UCS Unaltered	2.1
14B	45.03	45.10	44.97	45.03	93.42	93.03	92.96	93.14	A4, A5, B4, C1 to C2, D2 (diagonal), E11, E13	UCS Unaltered	2.1
14C	41.6	41.52	41.87	41.66	90.4	90.39	90.48	90.42	A4, A5, B4, C1 to C2, D2 (diagonal), E11, E13	Tri Unaltered	2.2
16A	45.27	45.25	45.30	45.27	92.95	92.95	93.02	92.97	A7, B5, C3, D5, E11, E8, E13 - vertical	UCS Unaltered	2.1
16B	45.25	45.27	45.23	45.25	93.07	92.84	92.97	92.96	A7, B5, C3, E3, E8, E13 - vertical	UCS Unaltered	2.1
16C	45.27	45.32	45.28	45.29	92.94	93.68	93.08	93.23	A7, B5, C3, D3, E1, E4, E8, E13	UCS Unaltered	2.1

Fresh preliminary samples – BP37, BP38, Baf14, Baf16, Baf18, BP3, BP13, BP15, T29, T31

Report Number: A23-08690										
Report Date: 11/7/2023										
Analyte Symbol	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃ (T)	MnO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅
Unit Symbol	%	%	%	%	%	%	%	%	%	%
Detection Limit	0.01	0.01	0.01	0.005	0.01	0.01	0.01	0.01	0.001	0.01
Analysis Method	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP
NIST 694 Meas	10.47	1.82	0.78	0.012	0.34	42.93	0.86	0.53	0.111	30.4
NIST 694 Cert	11.2	1.8	0.79	0.0116	0.33	43.6	0.86	0.51	0.11	30.2
GBW 07113 Meas	69.25	12.73	3.22	0.137	0.15	0.59	2.46	5.34	0.287	0.05
GBW 07113 Cert	72.8	13	3.21	0.14	0.16	0.59	2.57	5.43	0.3	0.05
SY-4 Meas	50	20.11	6.05	0.103	0.52	7.89	6.95	1.66	0.291	0.13
SY-4 Cert	49.9	20.69	6.21	0.108	0.54	8.05	7.1	1.66	0.287	0.131
BIR-1a Meas	48.26	15.51	11.05	0.166	9.68	13.39	1.83	0.03	0.983	0.02
BIR-1a Cert	47.96	15.5	11.3	0.175	9.7	13.3	1.82	0.03	0.96	0.021
DNC-1a Meas	46.93	18.24	9.61	0.143	10.05	11.25	1.91	0.22	0.474	0.07
DNC-1a Cert	47.15	18.34	9.97	0.15	10.13	11.49	1.89	0.234	0.48	0.07
BCR-2 Meas	54.7	13.59	13.67	0.19	3.57	7.26	3.06	1.79	2.272	0.37
BCR-2 Cert	54.1	13.5	13.8	0.196	3.59	7.12	3.16	1.79	2.26	0.35
W-2b Meas	53.12	15.65	10.79	0.16	6.33	10.9	2.21	0.62	1.089	0.15
W-2b Cert	52.4	15.4	10.7	0.163	6.37	10.9	2.14	0.626	1.06	0.14
Method Blank	0.02	< 0.01	0.01	< 0.005	< 0.01	0.01	< 0.01	< 0.01	< 0.001	< 0.01

“_alt” samples – BP37, BP38, BAF18, BF3, BF13, BF15, T29, T31

Report Number: A25-02509											
Report Date: 21/4/2025											
Analyte Symbol	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃ (T)	MnO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	S
Unit Symbol	%	%	%	%	%	%	%	%	%	%	%
Detection Limit	0.01	0.01	0.01	0.005	0.01	0.01	0.01	0.01	0.001	0.01	0.001
Analysis Method	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	TD-ICP
NIST 694 Meas	11.44	1.89	0.77	0.012	0.33	42.97	0.85	0.54	0.12	30.62	
NIST 694 Cert	11.2	1.8	0.79	0.0116	0.33	43.6	0.86	0.51	0.11	30.2	
NCS DC71305 (GBW 07113) Meas	71.2	12.64	3.35	0.143	0.14	0.59	2.42	5.33	0.287	0.03	
NCS DC71305 (GBW 07113) Cert	72.8	13	3.21	0.14	0.16	0.59	2.57	5.43	0.3	0.05	
NIST 696 Meas	3.79	53.28	8.36	< 0.005	0.02	0.03		< 0.01	2.609	0.04	
NIST 696 Cert	3.79	54.5	8.7	0.004	0.01	0.02		0.009	2.64	0.05	
OREAS 101b (4 Acid) Meas											
OREAS 101b (4 Acid) Cert											
DNC-1a Meas	46.58	18.17	9.72	0.147	9.87	11.61	1.88	0.22	0.489	0.07	
DNC-1a Cert	47.15	18.34	9.97	0.15	10.13	11.49	1.89	0.234	0.48	0.07	
BHVO-2 Meas	50.27	13.98	12.26		7.14	11.77	2.26	0.52	2.835	0.27	
BHVO-2 Cert	49.9	13.5	12.3		7.23	11.4	2.22	0.52	2.73	0.27	
OREAS 903 (4 Acid) Meas											0.49
OREAS 903 (4 Acid) Cert											0.5
OREAS 520 (4 Acid) Meas											1.08
OREAS 520 (4 Acid) Cert											1.01
W-2b Meas	53.24	15.56	10.83	0.17	6.28	11.34	2.24	0.62	1.129	0.13	
W-2b Cert	52.68	15.45	10.83	0.167	6.37	10.86	2.2	0.626	1.06	0.14	
OREAS 683 (4 Acid) Meas											0.222
OREAS 683 (4 Acid) Cert											0.205
OREAS 247 (4 Acid) Meas											0.746

OREAS 247 (4 Acid) Cert										0.714
OREAS 603c (4 Acid) Meas										3.9
OREAS 603c (4 Acid) Cert										4
OREAS 601c (4 acid) Meas										1.68
OREAS 601c (4 acid) Cert										1.58
OREAS 931 (4 Acid) Meas										5.33
OREAS 931 (4 Acid) Cert										4.12
OREAS 750 (4 Acid) Meas										0.078
OREAS 750 (4 Acid) Cert										0.073
OREAS 45h (4-Acid) Meas										0.037
OREAS 45h (4-Acid) Cert										0.035
SY-5 (Fusion ICP) Meas	50.28	14.11	0.131	3.2	7.35	4.04	4.21	1.87	2.02	
SY-5 (Fusion ICP) Cert	50.1	14.35	0.1283	3.235	7.12	4.15	4.17	1.777	2.04	
BF15 Orig										0.02
BF15 Dup										0.014
Method Blank										0.002
Method Blank										0.001
Method Blank										0.001
Method Blank										0.003

Descriptive statistics (stats) for the different subgroups of samples. avg – average; std.dv – standard deviation; med – median; max – maximum; min – minimum; N – number of specimens; Text – texture.

	Stats	n _{eff} %	ρ _{dry} g/cm ³	ρ _{sat} g/cm ³	V _p m/s	σ _{c,UCS} MPa	σ _t MPa	n _{eff} %	ρ _{dry} g/cm ³	ρ _{sat} g/cm ³	V _p m/s	σ _{c,UCS} MPa	σ _t MPa	n _{eff} %	ρ _{dry} g/cm ³	ρ _{sat} g/cm ³	V _p m/s	σ _{c,UCS} MPa	σ _t MPa
BP Low to medium porosity	BP.A							BP.B											
	Avg	5.15	2.763	2.814	4806	93.19	10.62	18.55	2.151	2.336	3796	46.67	8.71						
	Med	3.94	2.822	2.868	4755	91.25	10.08	20.46	2.054	2.260	3796	46.67	8.79						
	std.dv	4.09	0.206	0.183	365	26.12	2.83	6.90	0.261	0.196	-	-	3.57						
	Min	1.58	2.042	2.112	4026	56.91	3.97	5.33	1.973	2.226	3796	46.67	4.96						
	Max	20.12	3.070	3.108	5549	155.67	17.51	25.31	2.678	2.731	3796	46.67	12.30						
	N	82	82	82	34	20	64	6	6	6	1	1	4						
BAf Low to medium porosity	BAf.A							BAf.B											
	Avg	6.13	2.585	2.646	4615	94.77	11.21	13.79	2.483	2.621	3593	46.30	6.81						
	Med	4.80	2.634	2.685	4572	84.12	11.77	13.69	2.477	2.616	3563	46.30	7.27						
	std.dv	3.31	0.161	0.158	371	31.61	4.12	0.92	0.041	0.037	100	3.77	0.98						
	Min	2.10	2.235	2.264	4142	61.50	0.65	12.38	2.419	2.563	3511	43.63	5.20						
	Max	15.37	2.796	2.824	5196	147.49	18.91	15.37	2.552	2.684	3704	48.96	7.97						
	N	40	40	40	12	8	28	13	13	13	3	2	7						
BF Vesicular/ high porosity	BF.AI							BF.AII						BF.AIII					
	Avg	18.65	2.173	2.359	3334	28.21	5.33	17.75	2.205	2.383	4024	47.98	5.26	21.58	2.100	2.316	3991	20.56	5.55
	Med	19.15	2.178	2.337	3215	26.98	4.84	16.63	2.223	2.376	4309	52.74	5.30	21.12	2.138	2.346	4115	19.75	5.77
	std.dv	3.87	0.128	0.105	510	4.57	1.25	4.62	0.118	0.084	497	13.29	1.38	4.96	0.150	0.122	491	3.94	1.55
	Min	7.03	1.742	1.995	2708	22.65	3.41	11.66	1.931	2.252	3400	29.05	2.55	10.49	1.738	1.936	3120	16.83	2.18
	Max	25.27	2.390	2.510	4444	36.15	8.09	33.50	2.498	2.614	4636	57.40	7.75	36.05	2.294	2.504	4464	25.93	7.68
	N	32	32	32	16	7	20	21	21	21	9	4	16	26	26	26	7	4	19

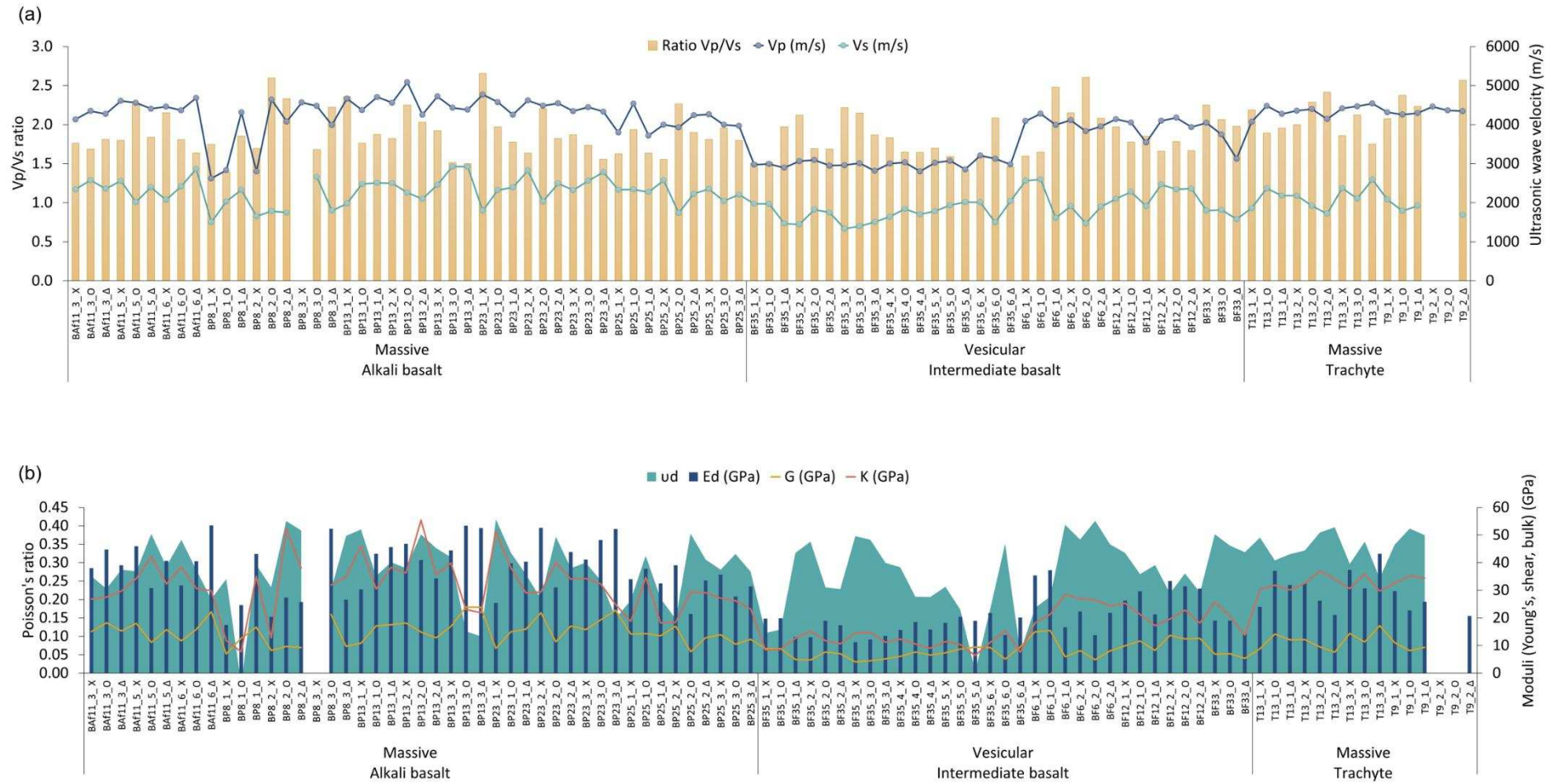
	Stats	n _{eff} %	ρ _{dry} g/cm ³	ρ _{sat} g/cm ³	V _p m/s	σ _{c,UCS} MPa	σ _t MPa	n _{eff} %	ρ _{dry} g/cm ³	ρ _{sat} g/cm ³	V _p m/s	σ _{c,UCS} MPa	σ _t MPa	n _{eff} %	ρ _{dry} g/cm ³	ρ _{sat} g/cm ³	V _p m/s	σ _{c,UCS} MPa	σ _t MPa
BF Medium porosity	BF.B							BF.C											
	Avg	13.75	2.515	2.653	3834	44.31	8.17	13.11	2.303	2.435	4437	77.81	9.66						
	Med	13.72	2.497	2.636	3707	36.00	8.20	11.00	2.322	2.419	4592	77.81	10.14						
	std.dv	2.28	0.090	0.072	276	19.57	2.43	5.11	0.209	0.165	293	-	2.62						
	Min	9.64	2.346	2.510	3677	30.14	3.87	7.72	1.948	2.168	4099	77.81	4.98						
	Max	17.52	2.694	2.790	4246	78.60	11.19	21.93	2.551	2.630	4619	77.81	14.66						
	N	11	11	11	4	5	9	12	12	12	3	1	12						
T Low porosity	TA.I							TA.II						TA.III					
	Avg	2.47	2.507	2.532	4620	111.16	10.84	7.30	2.361	2.434	3309	51.07	7.17	12.87	1.973	2.102	3477	50.61	3.88
	Med	2.58	2.505	2.537	4663	121.33	11.17	7.34	2.347	2.433	3419	51.81	6.83	11.99	1.986	2.104	3444	48.16	4.08
	std.dv	0.96	0.066	0.064	272	28.47	1.93	1.50	0.077	0.067	442	16.84	1.40	4.59	0.092	0.049	185	10.02	1.49
	Min	1.03	2.250	2.264	4097	77.40	5.95	5.03	2.158	2.260	2711	29.81	5.17	7.31	1.813	2.016	3310	42.05	1.95
	Max	5.11	2.690	2.707	5027	153.43	16.04	10.23	2.436	2.513	3863	70.84	9.45	20.37	2.086	2.167	3676	61.63	5.97
	N	60	60	60	17	7	39	14	14	14	7	4	8	10	10	10	3	3	5

Data for the lava rocks assessed for the crack stress initiation (22 lavas; σ_{ci}) and damage (24 lavas; σ_{cd}) thresholds. V_p – P-wave velocity. n_{eff} – open porosity; σ_{c_UCS} – unconfined compressive strength; % peak σ – percentage of the peak stress.

Texture	Specimen	V_p (m/s)	n_{eff} (%)	σ_{c_UCS} (MPa)	σ_{ci} (MPa)	% peak σ	σ_{cd} (MPa)	% peak σ
Massive	BP6B	4740	3.66	67.15	23.46	35	39.81	59
Massive	BP14A	4892	5.96	112.08	42.98	38	63.54	57
Massive	BP15B	4920	3.14	71.75	39.78	55	49.58	69
Massive	BP21A	4489	2.20	124.76	59.60	48	105.00	84
Massive	BP18C	4973	4.24	104.04	47.54	46	82.42	79
Massive	BP19A	4769	10.33	61.26	-	-	51.17	84
Massive	BP23C	4559	4.13	92.54	56.70	61	86.32	93
Massive	BP29A	5345	5.78	98.28	53.23	54	82.34	84
Massive	BP33A	5027	4.33	102.29	44.82	44	81.21	79
Massive	BAf6A	4429	4.94	140.79	-	-	120.10	85
Massive	BAf7E	4745	4.17	86.27	39.71	46	60.49	70
Massive	BAf8B	4973	11.56	86.58	44.80	52	67.35	78
Massive	BAf12E	4326	13.65	81.97	20.21	25	44.20	54
Massive	BAf9A	3563	13.83	48.96	24.02	49	29.00	59
Massive	T12A	4097	2.94	84.09	23.93	28	44.00	52
Massive	T13C	4721	3.69	129.09	43.34	34	59.04	46
Massive	T26C	4429	1.92	77.40	16.59	21	42.43	55
Massive	T16C	3444	12.87	48.16	23.64	49	38.67	80
Massive	BF10A	4592	11.09	77.81	37.50	48	72.77	94
Vesicular	BF8D	3626	21.72	26.45	16.59	63	23.95	91
Vesicular	BF35D	3333	19.42	36.15	16.78	46	31.70	88
Vesicular	BF14A	4309	14.37	57.40	17.40	30	42.39	74
Vesicular	BF36C	3400	18.20	29.05	14.06	48	24.96	86
Vesicular	BF20B	4115	18.79	18.63	9.39	50	14.84	80
Vesicular	BF37A	3120	24.33	20.86	10.19	49	16.38	79
Vesicular	BF23B	3677	11.95	41.26	21.44	52	31.36	76

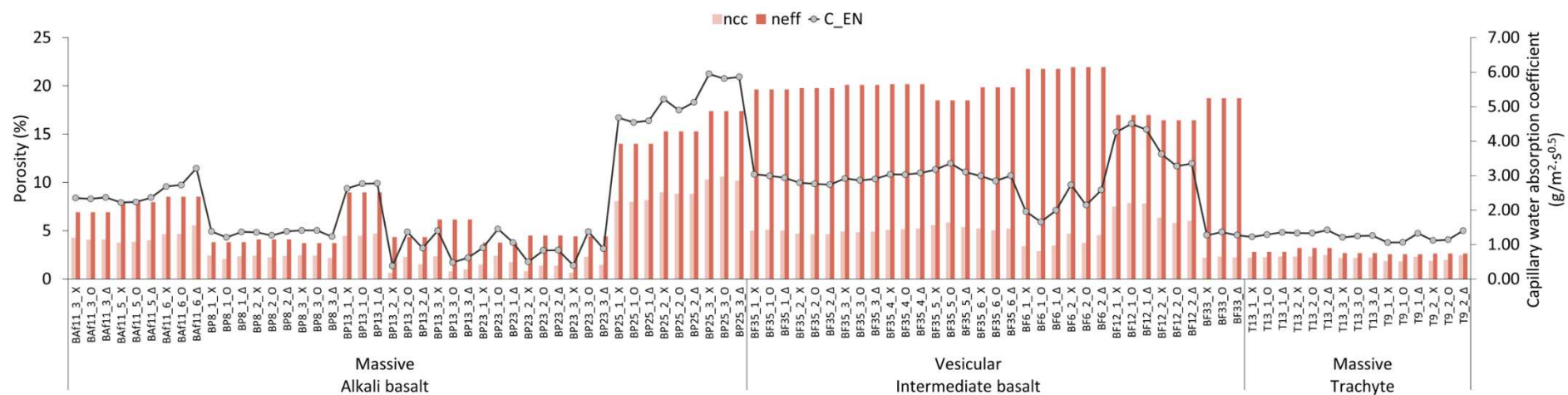
Extended version of Table 5.4, comprising the single blocks BP15, BP25, BF, 35, BF12, and BF36. c , σ_{c_UCS} , σ_{3max} , σ_t , σ_m , and σ_c in MPa, ϕ in °, and E_i and E_{rm} in GPa.

	BP	BP.A	BP15	BP25	BAf	BAf.A	BAf.B	BF. Ves	BF.A	BF35	BF.B	BF36	BF12	BFAB.II	BF.D	T	T.AI	TA.II
Mohr-Coulomb criterion																		
RSS	68884	63217	2907	2907	62014	22505	12737	10709	2705	586	4549	325	1083	461	2459	73582	34463	1337
c	15.83	16.17	17.10	15.75	13.96	16.63	9.05	6.02	5.82	6.79	7.49	7.22	9.10	4.86	12.00	14.75	16.69	8.63
ϕ	49.01	48.99	50.47	50.28	45.28	49.42	39.45	36.87	36.28	41.05	38.72	35.65	41.93	27.79	40.39	52.78	54.30	55.24
σ_{c_UCS}	84.70	86.48	95.15	87.21	67.86	89.97	38.32	24.06	23.00	29.83	31.21	28.15	40.80	16.12	51.95	87.59	103.63	55.14
Hoek-Brown Classification (D = 0; GSI = 55)																		
σ_{ci}	94.61	96.90	89.91	89.97	86.06	101.43	57.37	31.85	29.62	38.83	48.45	34.77	56.53	20.21	77.09	83.45	118.92	50.13
m_i	19.92	19.21	28.92	23.90	13.12	21.03	7.08	7.94	7.85	10.63	7.15	7.17	8.04	3.49	7.50	34.26	22.22	38.48
E_i	44.64	44.03	38.10	37.14	35.92	38.43	30.89	19.42	19.22	19.22	27.74	27.74	27.74	15.35	45.25	23.64	29.37	16.32
Hoek-Brown criterion																		
RSS	36828	34324	1094	1168	47647	10756	11882	8287	1652	190	874	46	7	286	52	36735	12839	1347
m_b	3.99	3.85	5.80	4.79	2.63	4.22	1.42	1.59	1.57	2.13	1.43	1.44	1.61	0.70	1.50	6.87	4.45	7.71
s	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
a	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
σ_{3max}	9.25	10.01	12.35	9.63	10.65	10.85	10.25	7.14	7.09	7.41	8.99	8.53	7.66	7.98	9.76	9.57	11.02	9.55
Mohr-Coulomb fit																		
c	3.34	3.51	4.37	3.52	3.20	3.85	2.30	1.51	1.46	1.80	1.99	1.69	1.99	1.06	2.57	3.75	4.16	3.30
ϕ	45.82	45.06	46.21	46.63	40.23	45.54	31.76	30.90	30.27	34.76	31.54	29.30	35.12	20.15	35.08	49.07	47.18	45.94
Rock Mass Parameters																		
σ_t	-0.16	-0.17	-0.10	-0.13	-0.22	-0.16	-0.27	-0.13	-0.13	-0.12	-0.23	-0.16	-0.24	-0.19	-0.35	-0.08	-0.18	-0.04
σ_c	7.61	7.79	7.23	7.24	6.92	8.16	4.61	2.56	2.38	3.12	3.90	2.80	4.55	1.63	6.20	6.71	9.57	4.03
σ_m	25.49	25.66	29.02	26.47	19.01	28.05	9.56	5.59	5.17	7.78	8.11	5.83	9.97	2.51	13.18	29.26	33.78	18.61
E_{rm}	18.22	17.97	15.85	15.16	14.66	15.69	12.61	7.93	7.85	7.85	11.33	11.33	11.33	6.27	18.47	9.65	11.99	6.66
ν_{rm}	0.33	0.33	0.32	0.32	0.31	0.29	0.35	0.34	0.31	0.31	0.31	0.31	0.31	0.36	0.31	0.4	0.42	0.35



(a) P-wave velocity (V_p), S-wave velocity (V_s), and V_p/V_s ratio per direction (X, O, Δ) and specimen.

(b) Derived dynamic moduli (Young's modulus, E_d ; shear modulus, G ; bulk modulus, K) and Poisson's ratio (u_d) per direction and specimen.



European Standard water absorption coefficient (C_{EN}), capillary connected porosity (n_{cc}) and effective porosity (n_{eff}), per direction (X, O, Δ) and specimen. n_{eff} has the same value per specimen, as the measure did not account for different directions.

Table S1. Data compilation of the physical and mechanical properties of rocks from different volcanoes and geothermal fields. ρ – bulk density (g/cm3); n – porosity (%); k – permeability (m2); Vp – P-wave velocity (km/s); Vs – S-wave velocity (km/s); UCS – unconfined/ uniaxial compressive strength (MPa); ITS – indirect tensile strength (MPa); Ed – dynamic Young's modulus (GPa); νd – dynamic Poisson's coefficient; Es – static Young's modulus (GPa); νs – static Poisson's coefficient; c – cohesion (MPa); φ – angle of internal friction (°); ** saturated bulk density, Vp and Vs. Pyroclastics – pyroclastic rocks.																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																	
Location	Reference	Host Rocks	Host rocks simplified	Secondary Minerals	Hydrothermal alteration facies	Fluid pH	Degree of hydrothermal alteration	ρ (g/cm³)			n (%)			k(m²)			Vp (km/s)			Vs (km/s)			UCS (MPa)			ITS (MPa)			Ed (GPa)			νd			Es (GPa)			νs			c (MPa)			φ (°)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
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Kuril-Kamchatka (Russia)	Frolova et al. (2014)	Tuffs and Tuffites	Tuffs and Tuffites				Unaltered/ Fresh	0.86	2.13	1.47	25 (10.5)	63.8 (54.9)	44.3 (35.0)				0.70	3.10	1.83				1.00	42.00	15.00	0.18	7.56	2.70																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					

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TD

Characterisation of the properties of rocks composing Azores volcanoes

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