INTERPRETATION OF GROUND DEFORMATION IN THE AZORES

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ABSTRACT

Geodetic measurements in Fayal, Pico and San Jorge showed some horizontal expansion of these islands. The total expansion during the interval 1936-1979 amounts to several metres, being considerably greater than the average sea floor spreading for that area of the Atlantic Ocean. This suggests that the spreading could be a discontinuous phenomenon, depending on short lived epochs of quick strain release. A vertical pulsation on the central part of Pico volcano was also detected; the pulsation has amplitude of about one metre and period close to one year. It seems due to periodic changes of pressure inside the magma chamber.

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INTRODUCTION

Plate displacements at the triple junction of the Azores are probably responsible for the tectonic activity of the islands, as well as for the associated seismic swarms.

A tectonic model of the Azores (Fig. 1a) has been proposed previously (*Machado* & al., 1972); this model was based primarily on the geological features of the islands. Another simpler model (Fig. 1b) had been proposed by *Krause* and *Watkins* (1970; see also *White* & al., 1976). In this latter model, based on oceanographic and geomagnetic data, it is assumed that the mid-Atlantic rift passes undisturbed between Fayal and Flores, whereas the model of *Machado* & al. assumes that the rift has been shifted to the east and crosses all the islands having present-day volcanic activity.

Both models can probably be reconciled if the rift is divided into two branches: one passing between Fayal and Flores and the other through the active volcanoes (Fig. 1c). The existence of parallel branches of the mid-Atlantic rift has been considered also in Iceland (see, for instance, *Walker*, 1965).

The main purpose of the present research was to monitor the behaviour of Pico volcano and find out if any actual displacements could be attributed to the transform faults of Fig. 1a (or 1c). The measurements revealed that the transcurrent movement is complicated by general horizontal expansion of the volcano and by a vertical pulsation.

These phenomena seem to represent a remarkable feature of some of the active volcanoes of the Azores.

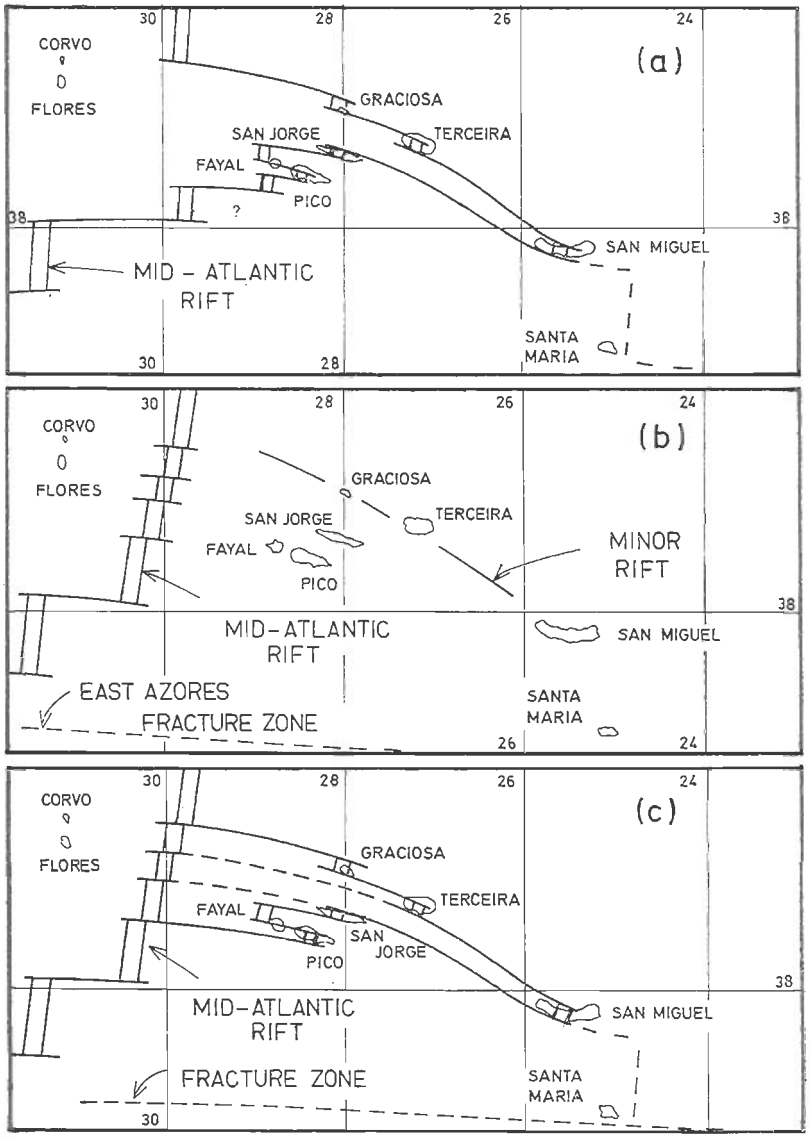


Fig. 1 — Tectonic models of the Azores : (a) after MACHADO & al., 1972 (with slight changes) ; (b) after WHITE & al., 1976 ; (c) superposition of models (a) and (b).

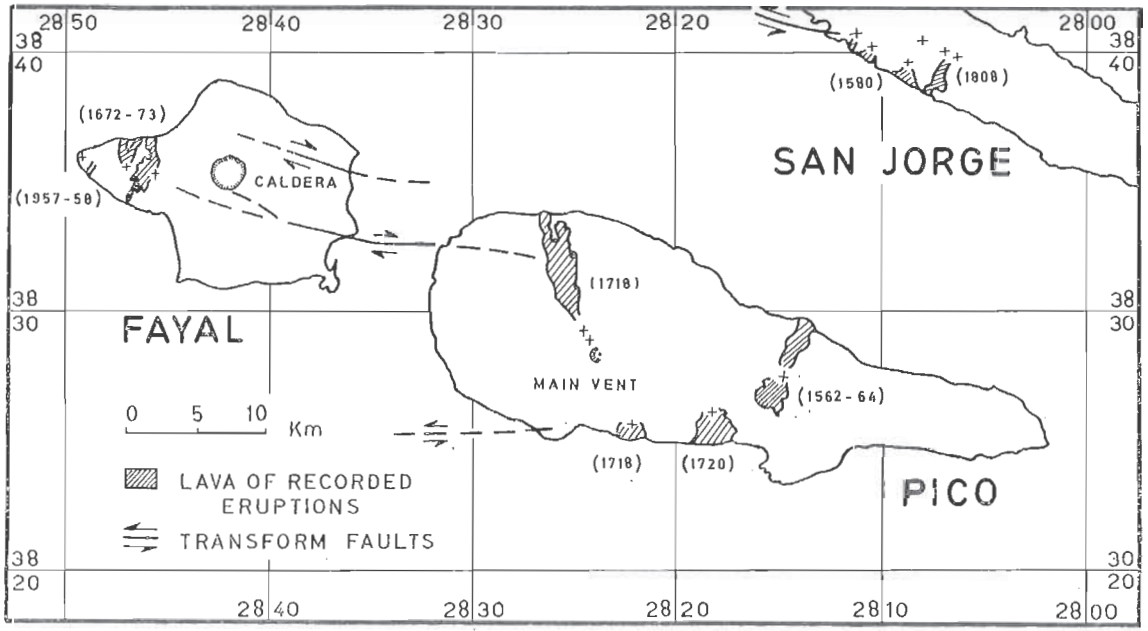


Fig. 2 — Islands of Fayal and Pico (with indication of the recorded eruptions and active transform faults).

LONG TERM HORIZONTAL DISPLACEMENTS

Measurements, using geodetic methods, were made in Fayal and Pico (Fig. 2), where a transform fault has considerable seismic activity. In fact, along this fault have been located the epicentre of the great earthquake of 1926 (*Agostinho,* 1927) and those of some strong shocks of the 1973 swarm (*Machado* & al., 1974). Pico is a very young volcano having a regular big central cone with steep slopes ; Fayal is older and exhibits at present a summit caldera.

The work of 1975 consisted of a simple triangulation (using a Wild T2 theodolite) with the likely assumption that the length of one of the lines (conveniently selected) had not changed. The results, when compared with the geodetic survey of 1935 (made by Instituto Geográfico e Cadastral from Lisbon), showed some transcurrent movement superposed on a general horizontal expansion (*Machado* and *Possolo,* 1976).

As there were some doubts about the general expansion, the field work was repeated in 1979, a small base being then measured with a Wild DI3S (which gives a precision of 1 part in 10^5). The results (Fig. 3) are not significantly different from the previous ones.

A radial expansion of Pico volcano is apparent, whereas Fayal seems to move practically as a rigid block. If we subtract the E-W expansion (and the small N-S expansion found for Fayal), the residuals (Fig. 4) show some movement along two transform faults. In addition there seems to exist a minor N-S fault which makes compatible the N-S components of Pico expansion with the simple translation of Fayal, where radial expansion is practically non-existent.

In any case, the E-W extension is much bigger than expected. The average floor spreading of the Atlantic at this latitude is only about 1.3 cm per year on either direction.

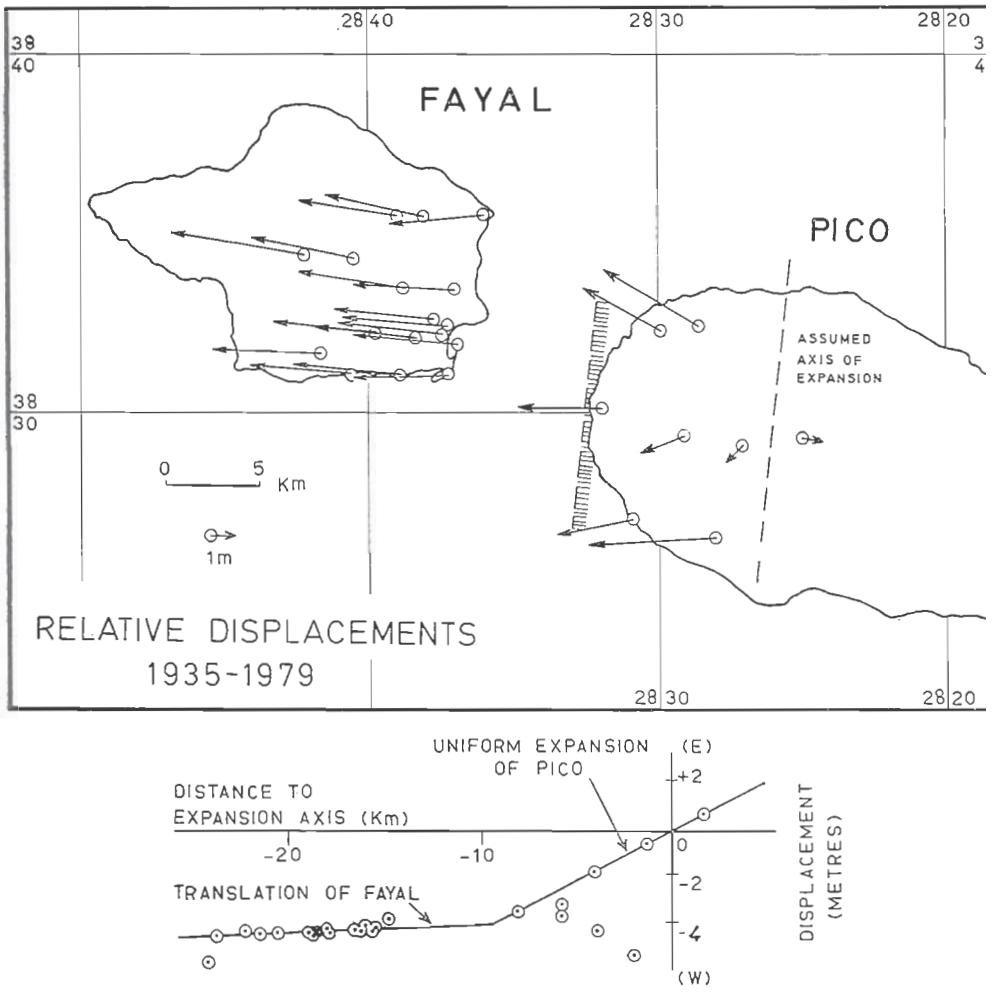


Fig. 3 — Horizontal displacements in Fayal and Pico, during the interval 1935-1979.

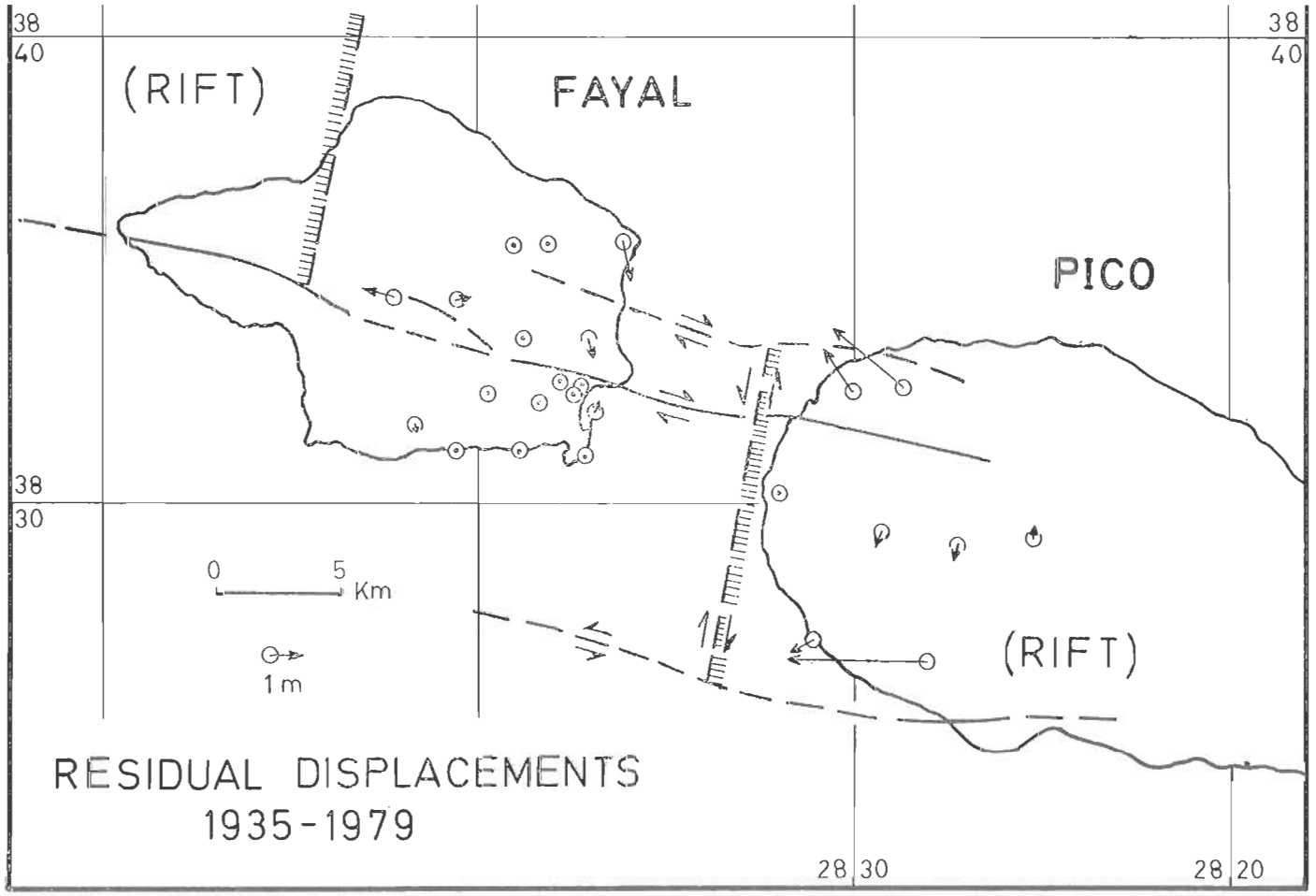


Fig. 4 — Residuals of horizontal displaceemnts after subtraction of E-W expansion (and small N-S expansion of Fayal).

Displacement in Fayal amounts to 4 or 5 meters in 44 years (relatively to a central line close to the main vent of Pico volcano), instead of the 50 or 60 cm which would correspond to the average spreading.

Also in a N-S direction the average movement assumed for the Azores-Gibraltar belt (*Machado* & al., 1972) is several times smaller than the N-S expansion of Pico.

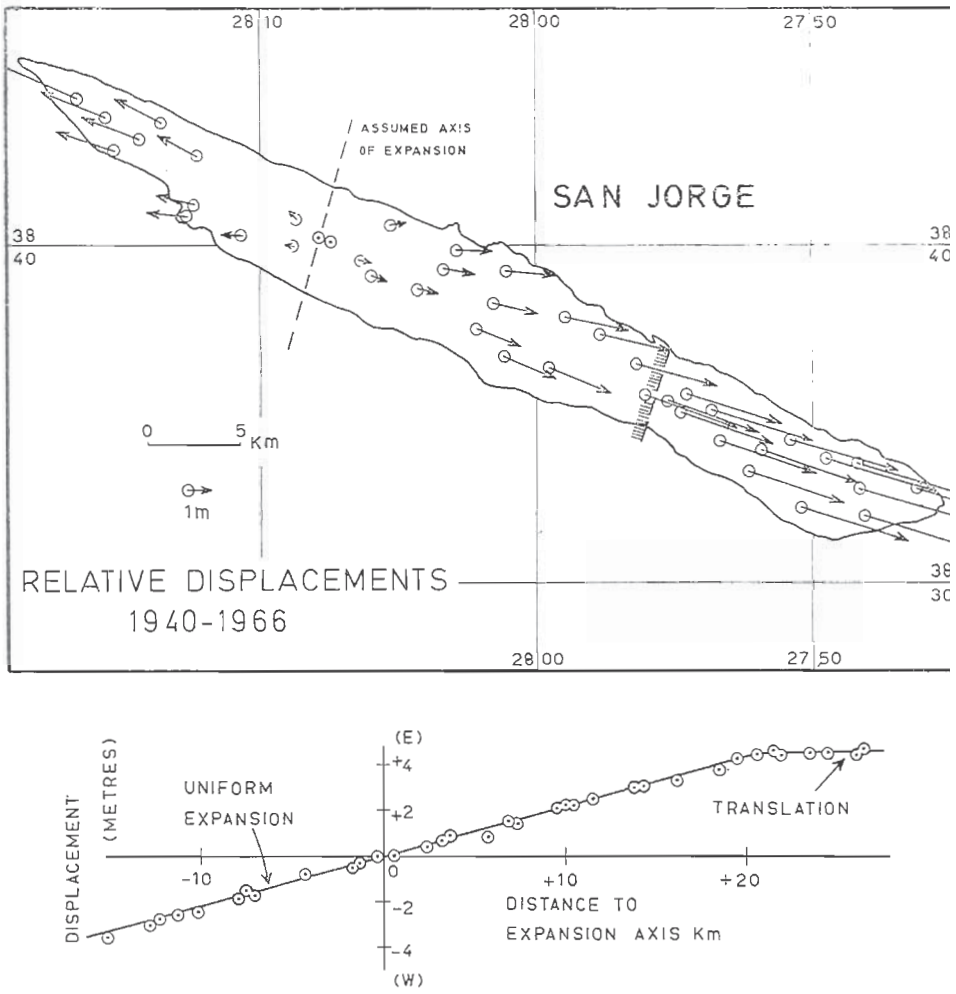


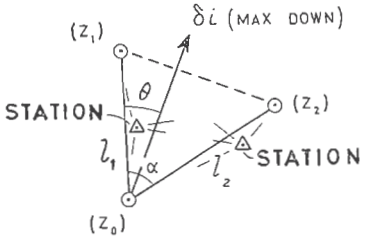
Fig. 5 — Horizontal displacements in San Jorge, during the interval 1940-1946.

Very similar results were found in San Jorge (Fig. 5), where Instituto Geográfico e Cadastral repeated in 1966 the geodetic survey of the island, the first survey having been made in 1940.

These results suggest that sea floor spreading is not a continuous phenomenon. Strain could, in fact, accumulate during several centuries, being released in a quick way probably in connection with earthquake swarms or volcanic eruptions.

After 1936, there occurred the eruption of Capelinhos, Fayal, in 1957-1958 with all its seismic activity (*Zbyszewski*, 1960) and also a severe earthquake swarm in 1973 which was felt mainly in Pico (*Machado* & al., 1974). In San Jorge there was a seismic swarm in 1964 (*Machado* and *Forjaz*, 1964).

On the other hand, the last eruptions in Pico occurred in 1718 and 1720, and in San Jorge in 1808. Fayal had another eruption in 1672.



SURFACE DILATATION:

$$\Delta = \frac{\delta l_1}{l_1} + \frac{\delta l_2}{l_2} + \frac{\tan \delta\alpha}{\tan\alpha}$$

TILT:

$$\delta i = \frac{\sqrt{(\delta\xi_1)^2 + (\delta\xi_2)^2 - 2\,\delta\xi_1\,\delta\xi_2 \cos\alpha}}{\sin\alpha}$$

$$\theta = \tan^{-1} \frac{\delta\xi_2 - \delta\xi_1 \cos\alpha}{\delta\xi_1 \sin\alpha}$$

Fig. 6 — Diagram of the triangles for measurement of surface dilation and tilt.

VERTICAL DISPLACEMENT OF PICO

In adition to the horizontal expansion, the volcano of Pico shows a vertical oscillation which is being measured since 1975.

Until October, 1977 the measurements were made on small triangles with sides about 10 m long (Fig. 6) materialized by three stainless steel marks cemented to selected rock exposures.

At intervals of about 3 months we measured the level difference and length between every two marks of the triangles. This was performed by triangulation (with the Wild T2 theodolite) from two adequate stations about 5 meters apart, whose exact distance was measured with an invar stadia. The changes found between sucessive measurements were adjusted to Mogi's model (*Mogi,* 1958 ; see also *Machado,* 1974). In this model, changes of pressure in a small spherical magma chamber (Fig. 7), at depth h, produce at the surface radial and vertical displacements, respectively u_r and u_z, given by the equations

$$u_r = C \frac{r}{R^3} \qquad (1)$$

$$u_z = C \frac{h}{R^3} \qquad (2)$$

where C is a factor proportional to the change of pressure, and R is given by the equation

$$R^2 = r^2 + h^2 \qquad (3)$$

r being the radial coordinate.

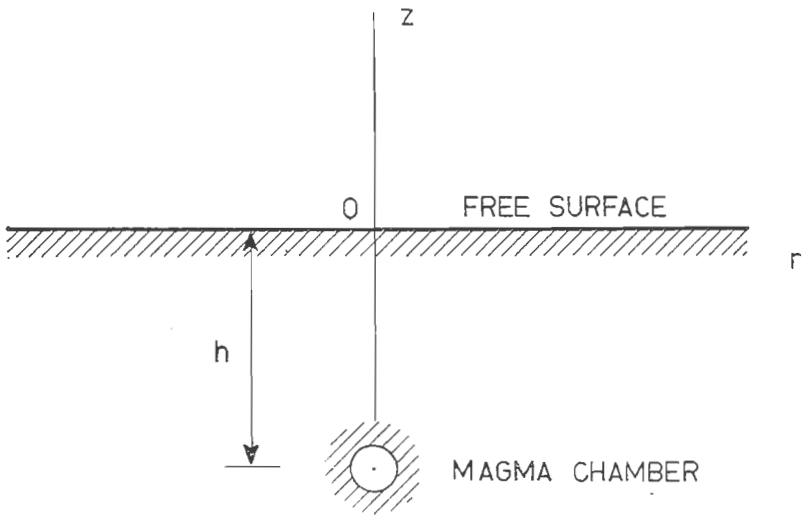


Fig. 7 — Diagram of Mogi's model (the size of the magma chamber is supposed to be small when compared to the depth).

The most convenient quantities to consider in each triangle are the surface dilatation Δ and the radial tilt δi, which are easily deduced from the field measurements. For Mogi's model these quantities are

$$\Delta = \frac{du_r}{dr} + \frac{u_r}{r} = C \frac{2h^2 - r^2}{R^5} \qquad (4)$$

$$\delta i = -\frac{du_z}{dr} = C \frac{3hr}{R^5} \qquad (5)$$

Comparison of the measured values to equations (4) and (5) allowed to estimate the depth h (which was always about 4.7 km) and the factor C, and therefore the maximum vertical displacement

$$u_{z\,(r=o)} = \frac{C}{h^2} \qquad (6)$$

The field work used to last for several days and the subsequent computation was slightly involved. As said before, this method was used only until Oct. 1977. Afterwards the heights of several existing geodetic monuments are being simply determined by triangulation (using the Wild T2 theodolite), but the atmospheric refraction has to be obtained for each set of observations (which lasts for only 3 or 4 hours).

The level changes are again adjusted to equation (2) and the maximum vertical displacement is then computed using equation (6).

Fig. 8 shows the small triangles and the geodetic monuments which have been used, and Fig. 9 and 10 are examples of the changes using either method.

The final results are fairly consistent. An area centred close to Pico's main vent seems to be pulsating with a period of about 1 year. Vertical displacements at the centre of the oscillating area are given in Fig. 11. Apparently the epochs of maximum height occurred at the beginning of summer until 1976, but are occurring at the beginning of winter since 1978. The amplitude is about 1 m.

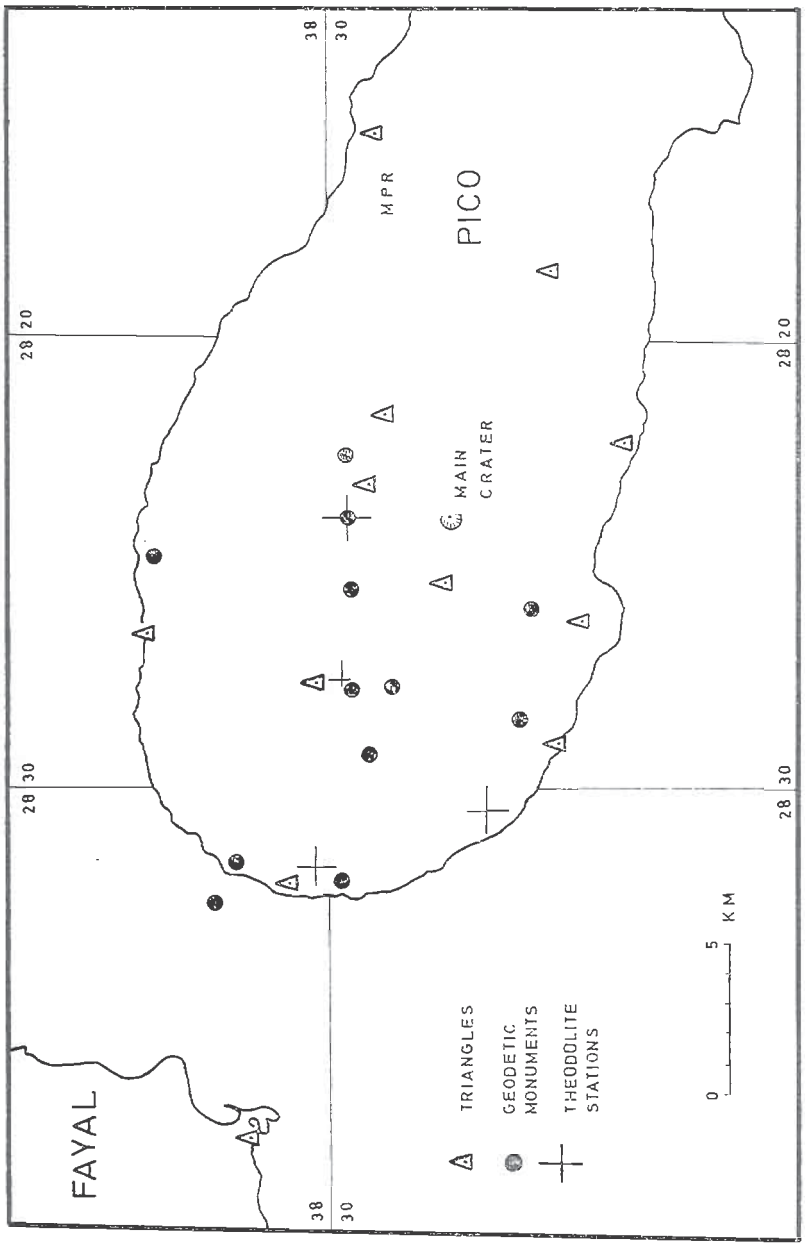


Fig. 8 — Location of the small triangles and of geodetic monuments in Pico Island.

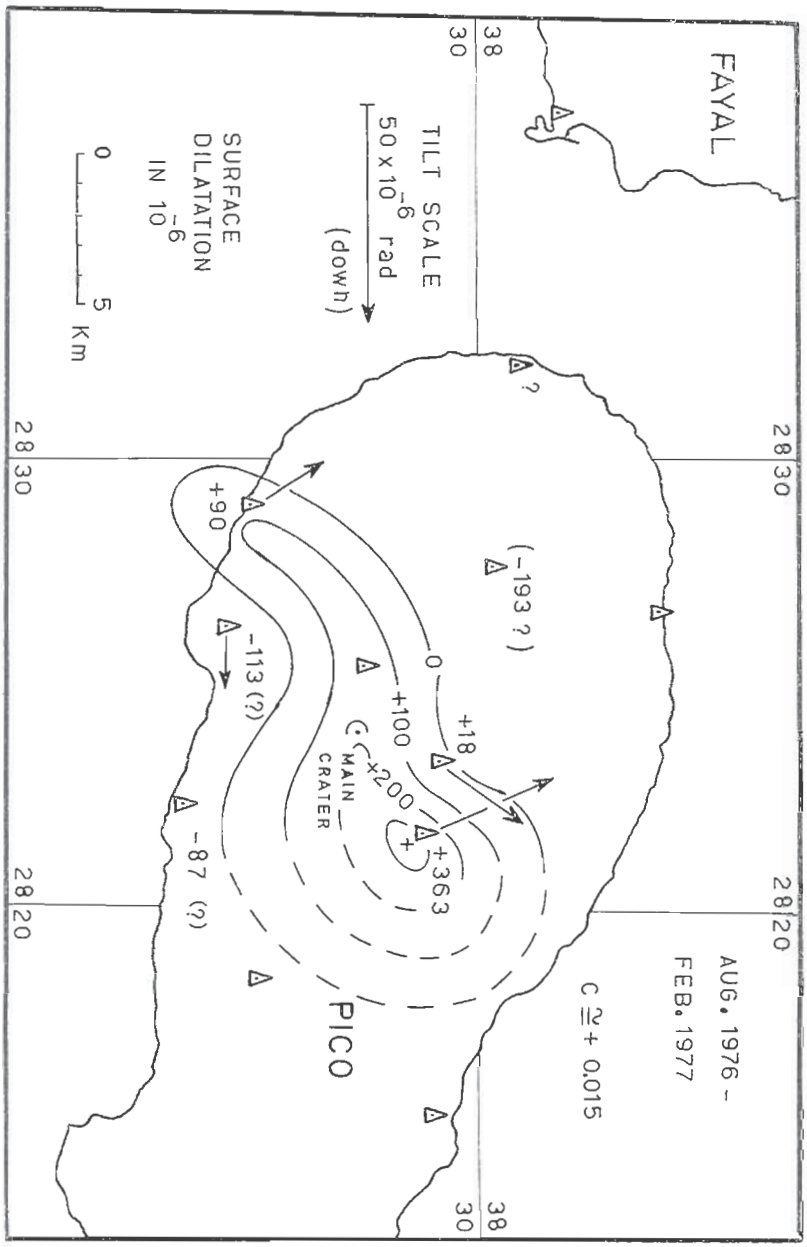


Fig. 9 — Surface dilatation and tilt in Pico for the interval Aug. 1976 — Feb. 1977.

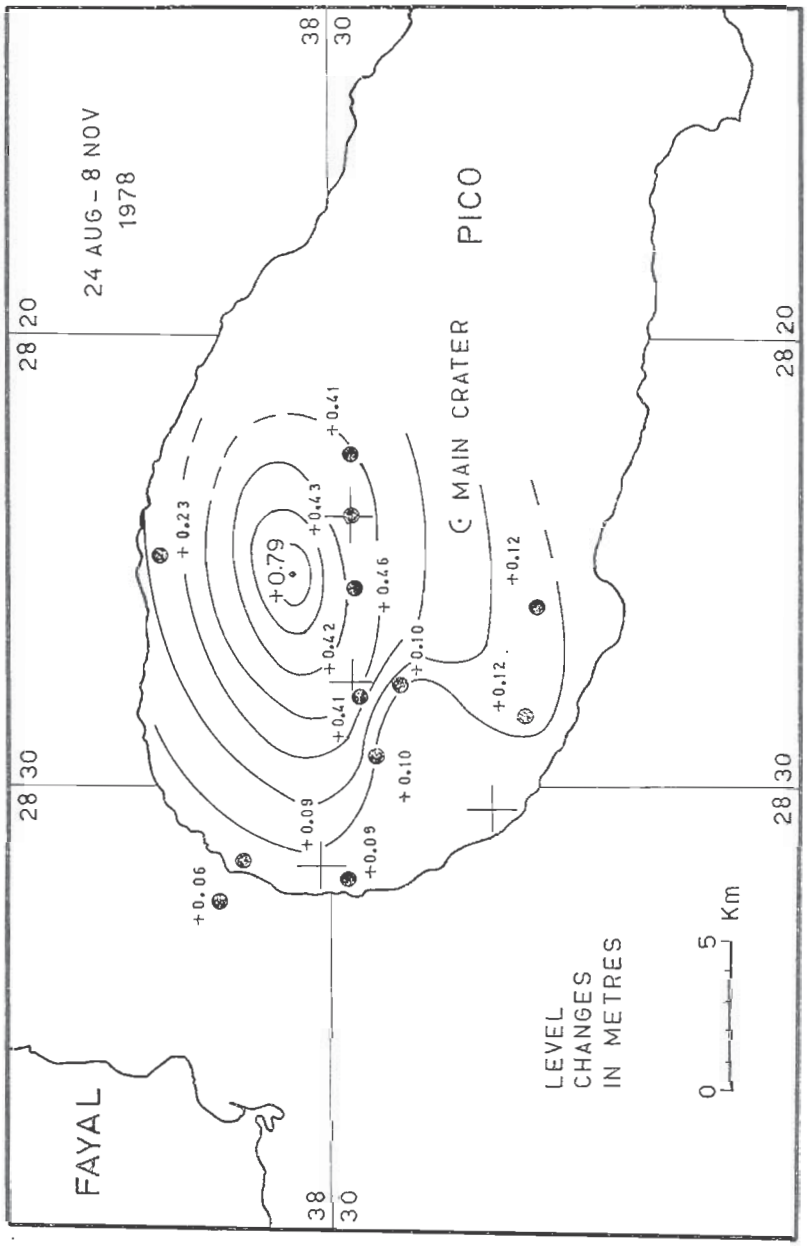


Fig. 10 — Level changes in Pico for the interval 24 Aug. — 8 Nov. 1978.

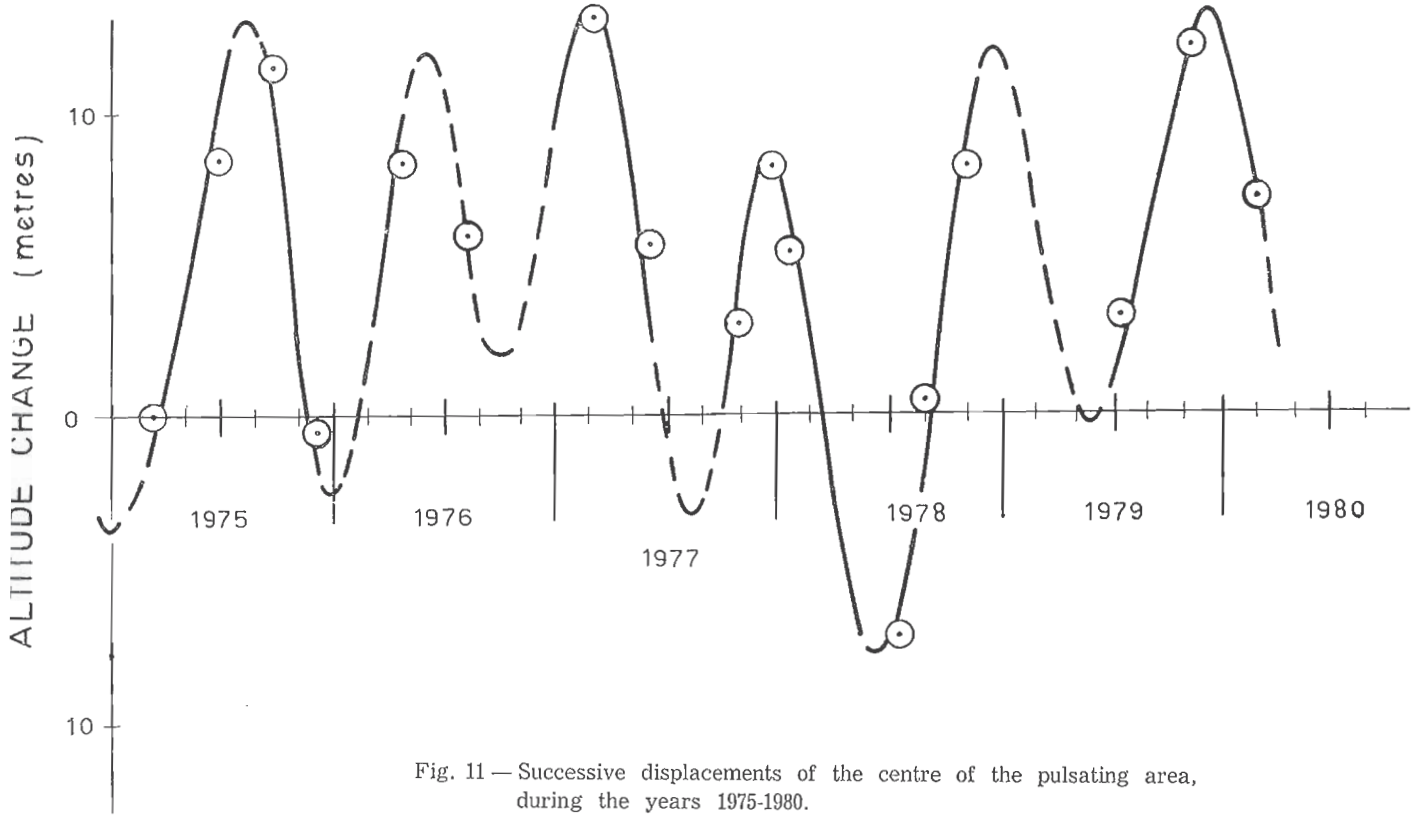


Fig. 11 — Successive displacements of the centre of the pulsating area, during the years 1975-1980.

CONCLUSIONS

In Pico Island the expected transcurrent movement along transform faults is superposed on a radial expansion (which is probably an irreversible displacement) and a vertical pulsation with period close to 1 year. The two latter phenomena seem to occur on the same area (centred near the main vent of the volcano).

A detailed interpretation is uncertain ; the expansion could well have increased the effect of some pulsation of pressure in the magma chamber of the volcano. This could be a usual feature of the active volcanoes of the Azores, but, except for the expansion of San Jorge, no similar measurements have been made on the other islands.

The phenomena could also be related to gravitational pulsations as proposed elsewhere (*Machado,* 1973 ; 1975) ; this is a speculative interpretation which has, however, to be worked out.

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