NORDIC VOLCANOLOGIAL INSTITUTE 9401

University of Iceland

FURNAS VOLCANO

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1991-1993

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ABSTRACT

Monitoring of crustal deformation on Furnas volcano, Sao Miguel, Azores, began in early 1991 by construction of optical levelling tilt stations and stations for observing Lagoa Furnas lake level. Frequent measurements over a period of two and a half years suggest some tilting of the ground at two stations, amounting to 3-5 μ-rad per year, but the observations do not agree with a simple deformation model.

INTRODUCTION

A cooperation between the Nordic Volcanological Institute, Reykjavik, Iceland and the Department of Geosciences of the Azores University, Ponta Delgada, Portugal has been established to study certain aspects of volcanic activity of Furnas volcano, Sao Miguel, The Azores. Other volcanoes of the Azores archipelago are also included in this cooperative study, but to a lesser degree. One aspect of this study was investigation of the present rate of deformation of the volcano. It is known that Furnas volcano has been intermittently active during many millennia (Booth et al 1978, Moore 1990) and that the present repose period which has lasted since 1630 can come to an end at any time. Many of the Furnas eruptions of the past have been violent explosive eruptions which have produced thick layers of tephra as can be seen in numerous road cuts and other exposures. Similar eruptions can cause great disasters if they occur in the near or distant future. Therefore we consider it of importance to gather information which can shed a light on the possible future activity of the volcano. The rate and character of the ground deformation will improve our knowledge of the present activity of the volcano, and aid in interpreting possible future activity.

Measurements to detect and observe ground deformation at Furnas were initiated in early 1991 by establishing three optical levelling (dry tilt) tilt stations, installing three recording tiltmeters, constructing markers for lake level observations at Lagoa das Furnas, and planning and partially constructing a network for repeated distance measurements. The dry tilt stations were all located inside the Furnas caldera, but two of the recording tilt stations were constructed outside but near the caldera rim, while one is located near the center of the caldera (Fig. 1). Initial measurements at the dry tilt stations and the lake level markers were made in May 1991 and the recording tiltmeters started recording at the same time.

One of the dry tilt stations consisted of 5 permanent markers placed in a circular array of 20.0 m radius. The precision of tilt observations at this type of stations is low; standard error of computed tilt is generally greater than 2 μ-rad, frequently 3-5 μ-rad according to experience in Iceland (Tryggvason 1983). Still larger errors are experienced if the markers are not securely attached to the bedrock or if great ground deformation occurs.

The other two optical levelling tilt stations consist of lines of bench marks, usually at less than 50 m intervals. The precision of observed tilt in a specified azimuth depends

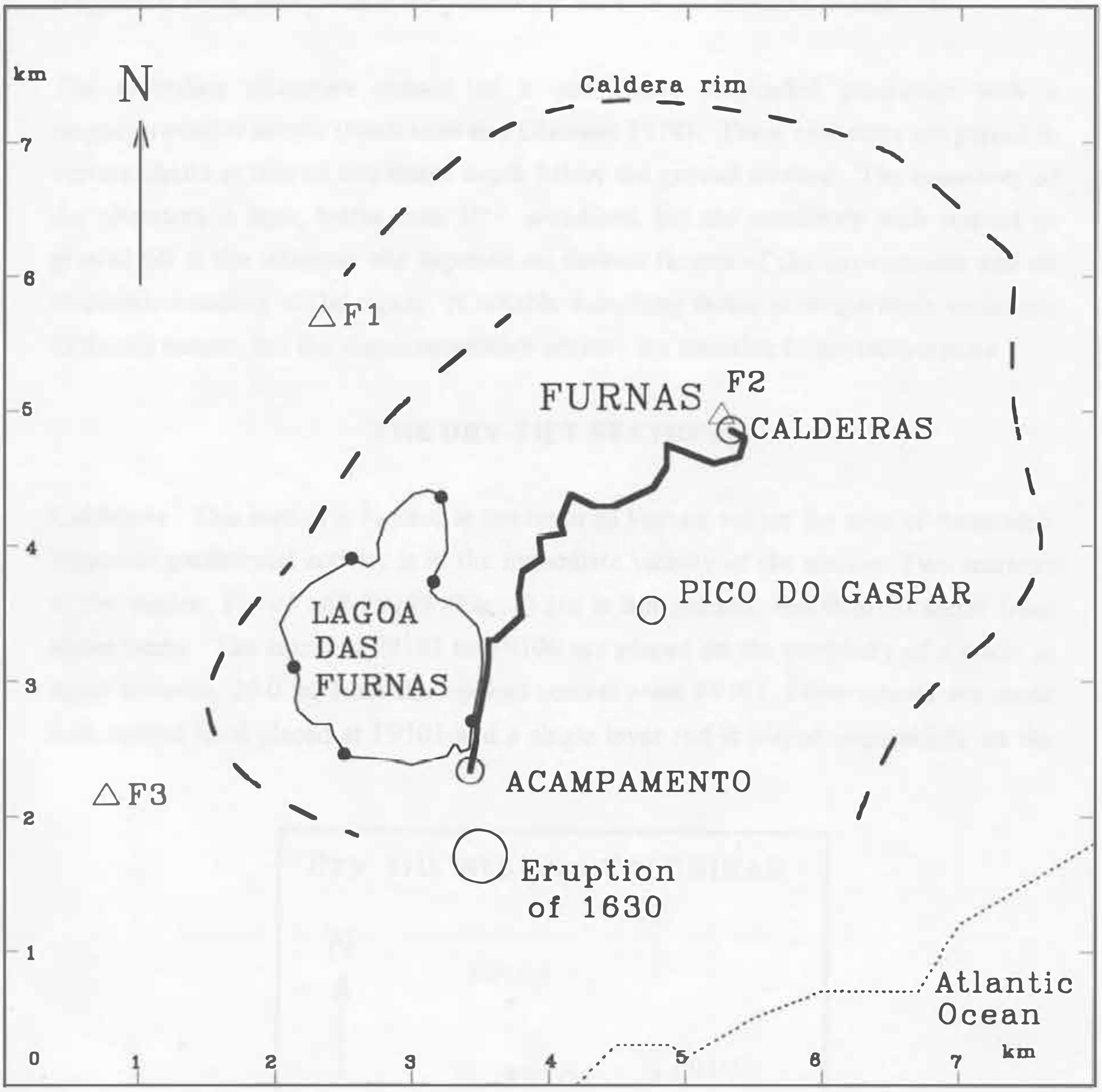

Fig. 1. Simplified map of the Furnas area showing dry tilt stations (small open circles), long levelling line (thick line), recording tiltmeters (open triangles), lake level stations (solid dots), the caldera rim (dashed line) and the site of the last eruption in the area (large open circle).

on the horizontal dimension of the bench mark array in that azimuth. The horizontal dimensions of these stations are usually more than 100 m, and the standard error of tilt is typically about one μ-rad if the permanent markers are attached to bedrock.

The recording tiltmeters consist of a one meter suspended pendulum with a magnetoresistive sensor (Sindrason and Olafsson 1978). These tiltmeters are placed in vertical shafts at two to five meter depth below the ground surface. The sensitivity of the tiltmeters is high, better than 10^{-2} μ-radians, but the sensitivity with respect to ground tilt at the tiltmeter site depends on various factors of the environment and on electronic handling of the signal. A notable disturbing factor is temperature variations of the tilt sensor, but the magnetoresistive sensors are sensitive to the temperature.

THE DRY-TILT STATIONS

Caldeiras: This station is located in the town of Furnas, within the area of fumaroles. Vigorous geothermal activity is in the immediate vicinity of the station. Two markers of the station, F9104 and F9105 (Fig. 2) are in hot ground, less than 10 meter from steam vents. The markers F9102 to F9106 are placed on the periphery of a circle at equal distance, 20.0 m, from the marked central point F9101. Observations are made with optical level placed at F9101 and a single invar rod is placed sequentially on the

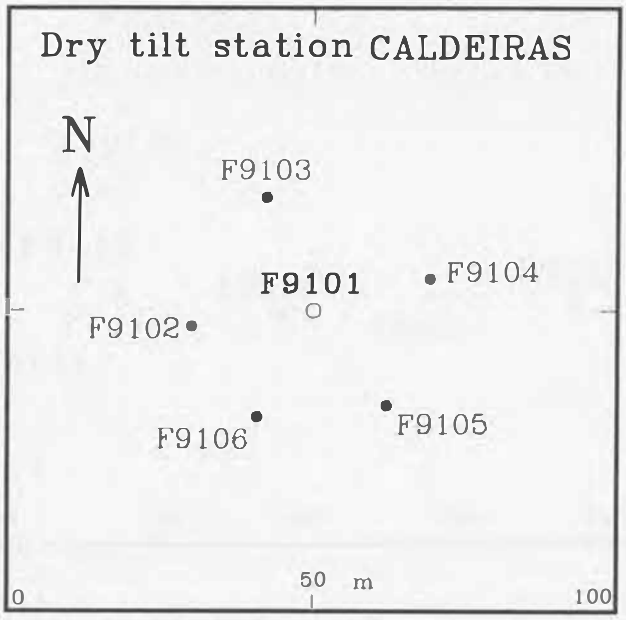

Fig. 2. Relative marker location of the dry tilt station Caldeiras (solid dots). Open circle marks the center of the circular station.

markers of the circle, thus obtaining the relative elevation of each of the markers of the circle. Repeated observations give the relative elevation at another time and the relative vertical displacement of the markers is converted into ground tilt. This station was first observed on 14 May 1991 and frequent observations in 1991 and 1992 detected anomalous vertical displacements of the two markers F9104 and F9105, making determination of ground tilt dubious.

Acampamento. This station consists of two lines , each consisting of 5 markers placed at approximately 50 m intervals on flat ground near the south end of Lagoa das Furnas (Fig. 3). Markers F9113 to F9118 follow the main road to Furnas while F9119 to F9123 follow a dirt road used by farmers and for lumber transport. Marker F9115 is common for both lines. Observations of this station consist of conventional precision

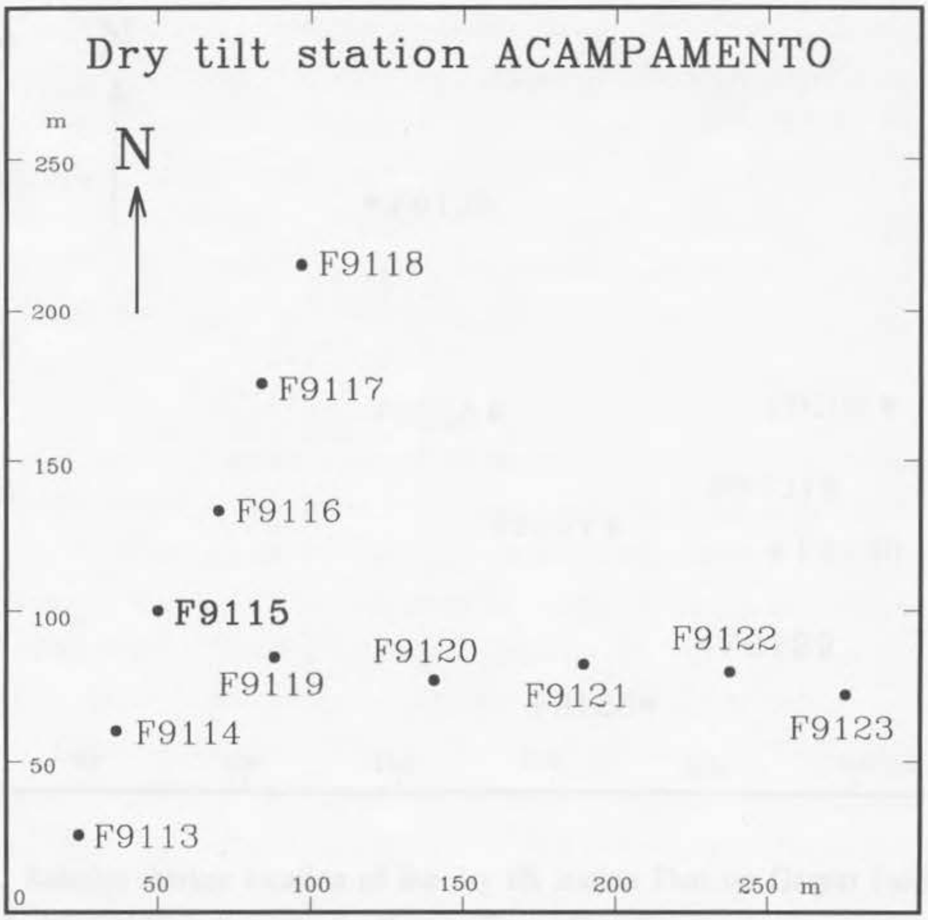

Fig. 3. Relative marker location of the dry tilt station Acampamento (solid dots). Marker F9115 is common for the two lines of levelling.

levelling. It was first observed 15 May 1991, and observations repeated at 6 to 12 months intervals. Heavy traffic or road grading on the dirt road have caused some downwards displacements of two of the markers, and the marker F9123 was destroyed before observation of September 1993. The accidental marker displacements can be estimated and corrected for and marker F9123 will be replaced by two new markers.

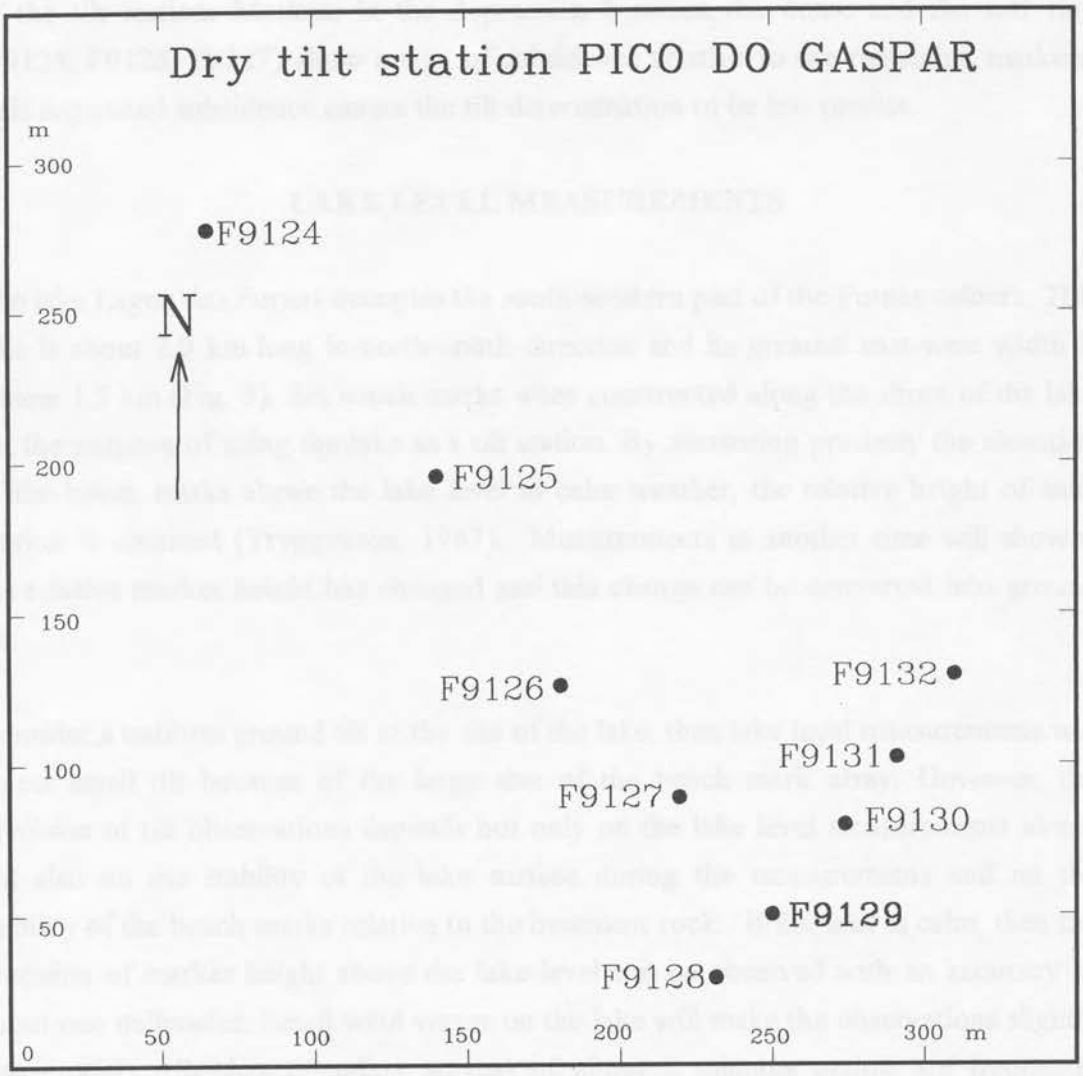

Fig. 4. Relative marker location of the dry tilt station Pico do Gaspar (solid dots). Marker F9129 is common for the two lines of levelling.

Pico do Gaspar. The small volcanic dome Pico do Gaspar is located near the center of the Furnas caldera, 1-2 km south-west of the town of Furnas. The dome is surrounded by a tuff ring. The dry tilt station Pico do Gaspar consists of two lines of markers (Fig. 4). Marker F9124 is located at the base of the dome and markers F9125 to F9127 follow a road across the depression between the dome and the tuff ring. These markers together with F9129 make up one line of the tilt station. Markers F9128 to F9132 follow a road on the inner flank of the tuff ring and form the other line of the tilt station. Markers in the depression between the dome and the tuff ring (F9125, F9126, F9127) show a sign of subsidence relative to the remaining markers. This suggested subsidence causes the tilt determination to be less precise.

LAKE LEVEL MEASUREMENTS

The lake Lagoa das Furnas occupies the south-western part of the Furnas caldera. This lake is about 2.0 km long in north-south direction and its greatest east-west width is almost 1.5 km (Fig. 5). Six bench marks were constructed along the shore of the lake for the purpose of using the lake as a tilt station. By measuring precisely the elevation of the bench marks above the lake level in calm weather, the relative height of each marker is obtained (Tryggvason, 1987). Measurements at another time will show if the relative marker height has changed and this change can be converted into ground tilt.

Consider a uniform ground tilt at the site of the lake, then lake level measurements will detect small tilt because of the large size of the bench mark array. However, the precision of tilt observations depends not only on the lake level measurements alone, but also on the stability of the lake surface during the measurements and on the stability of the bench marks relative to the basement rock. If the lake is calm, then the precision of marker height above the lake level can be observed with an accuracy of about one millimeter. Small wind waves on the lake will make the observations slightly less precise. Seiches (standing waves) of about 2 minutes period are frequently observed. They lower the measurement precision. Gradual change in lake level during the 2 to 3 hours it takes to measure all six stations may disturb the measurements. This change is corrected for by assuming uniform change in the lake level during each observational period.

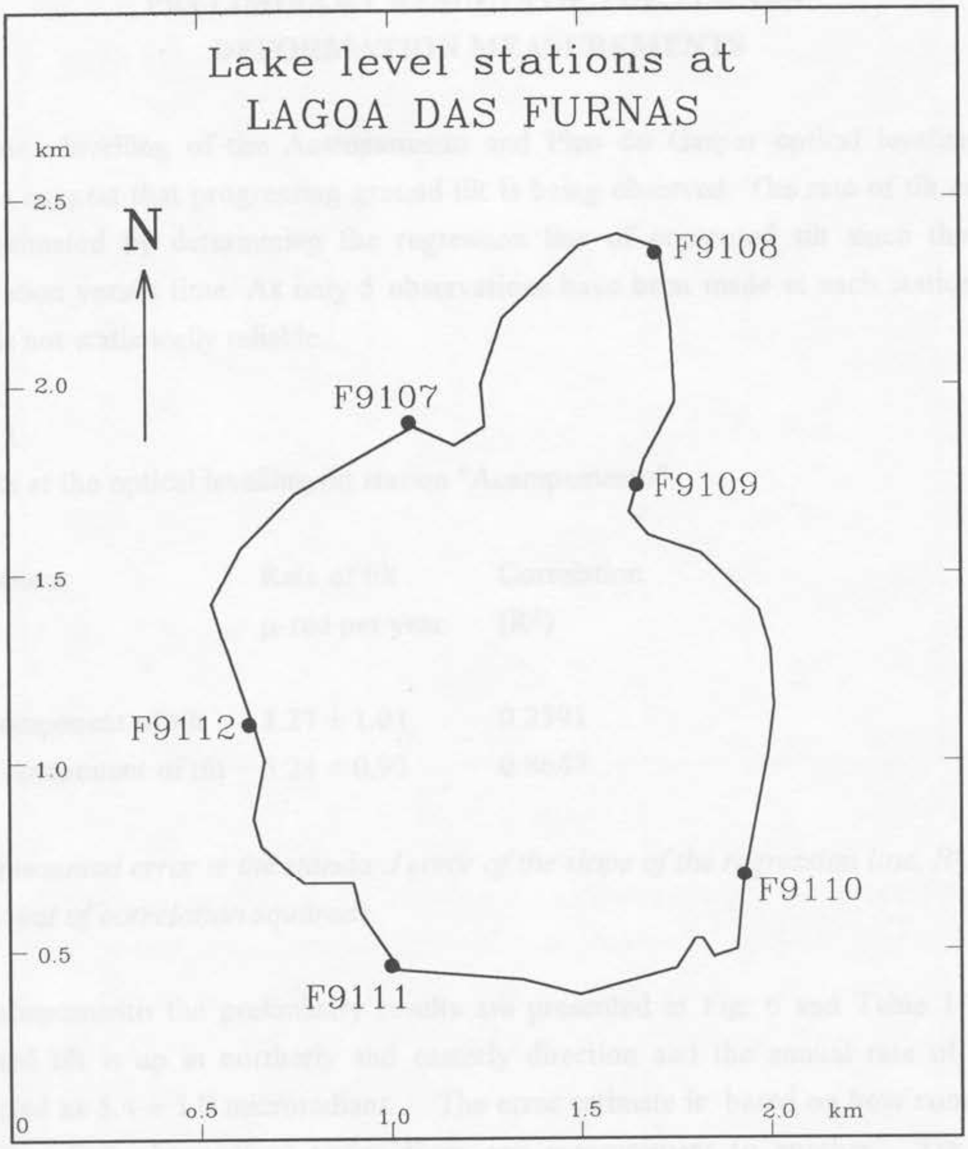

Fig. 5. Relative location of stations for lake level measurements at Lagoa das Furnas.

PRELIMINARY RESULTS OF THE FURNAS DEFORMATION MEASUREMENTS

Precision levelling of the Acampamento and Pico do Gaspar optical levelling tilt stations suggest that progressing ground tilt is being observed. The rate of tilt can be best estimated by determining the regression line of computed tilt since the first observation versus time. As only 5 observations have been made at each station, the rcsult is not statistically reliable.

Table 1
Tilt rate at the optical levelling tilt station "Acampamento"

Component of tilt	Rate of tilt μ-rad per year	Correlation (R^2)
East component of tilt	1.27 ± 1.01	0.2391
North component of tilt	5.24 ± 0.93	0.8647

(*The presented error is the standard error of the slope of the regression line, R^2 is the coefficient of correlation squared*)

At Acampamento the preliminary results are presented in Fig. 6 and Table 1. The indicated tilt is up in northerly and easterly direction and the annual rate of tilt is computed as 5.4 ± 1.0 microradians. The error estimate is based on how computed tilt (since first observation) varies from one measurement to another. Tilt error computed from the observed vertical displacements of individual bench marks is significantly smaller, with standard error consistently less than one microradian. This suggests vaguely that the tilt rate is variable.

The optical levelling tilt station Pico do Gaspar was levelled 5 times from May 1991 to May 1993. Three of the nine permanent markers of the tilt station showed sign of slight subsidence, relative to the remaining six markers. Although this suggested relative subsidence is only about 0.2 mm in two years at two of the markers, and almost one mm at one station, this makes the observational result in term of ground tilt, somewhat questionable.

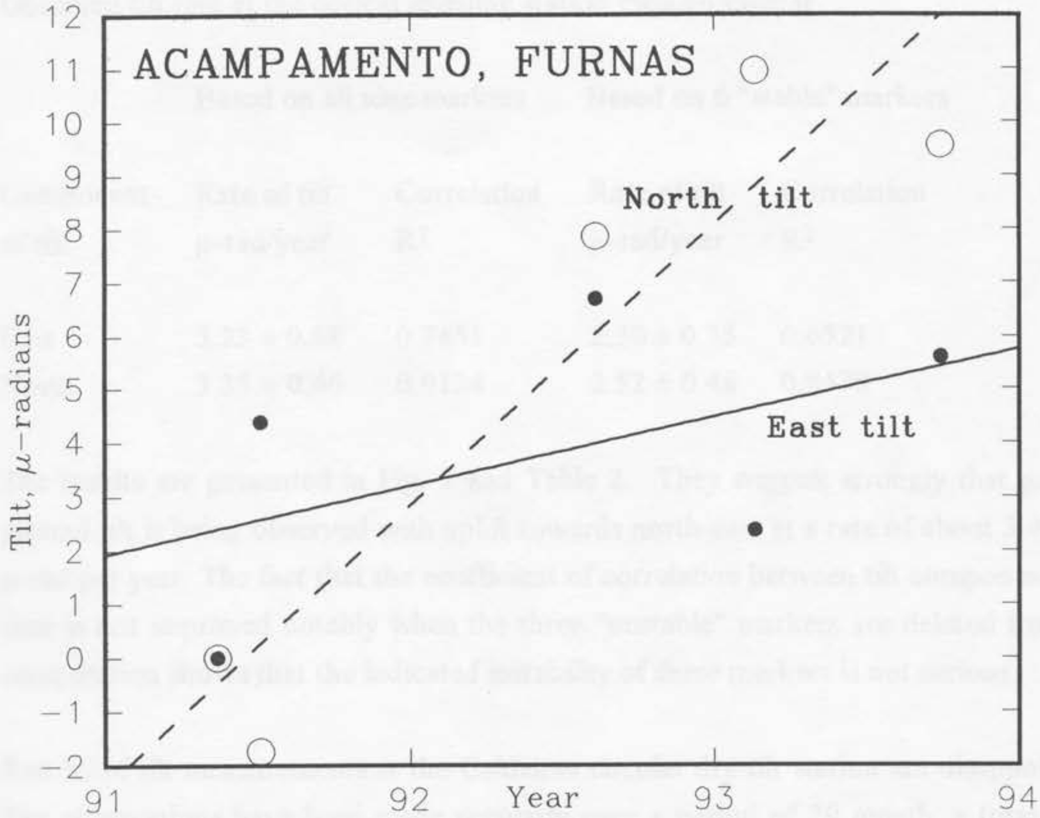

Fig. 6. Observed ground tilt at the dry tilt station Acampamento. Solid dots represent computed east component of tilt since first observation of May 1991 and solid line is the corresponding regression line. Open circles represent the north component of tilt and dashed line is the corresponding regression line. Positive tilt is uplift towards east and north.

Table 2
Observed tilt rate at the optical levelling station Pico do Gaspar

	Based on all nine markers		Based on 6 "stable" markers	
Component of tilt	Rate of tilt μ-rad/year	Correlation R^2	Rate of tilt μ-rad/year	Correlation R^2
East	3.33 ± 0.88	0.7451	2.30 ± 0.75	0.6521
North	3.35 ± 0.46	0.9134	2.52 ± 0.48	0.8478

The results are presented in Fig. 7 and Table 2. They suggest strongly that genuine ground tilt is being observed with uplift towards north-east at a rate of about 3.4 ± 0.7 μ-rad per year. The fact that the coefficient of correlation between tilt components and time is not improved notably when the three "unstable" markers are deleted from the computation shows that the indicated instability of these markers is not serious.

Results of tilt measurements at the Caldeiras circular dry tilt station are disappointing. The observations have been made regularly over a period of 29 month, a total of 20 measurements. One marker of the Caldeiras tilt station has been uplifted relative to the other markers at a rate of nearly one millimeter per year while another marker has subsided. These two moving markers are side by side in the circular array, and the observed vertical displacements are not the result of general tilting of the ground surface. Table 3 shows how relative elevation of each marker has changed with time, assuming linear relation between time and elevation. The elevation is related to the average elevation of all five markers and the presented error is the standard error of the slope of the regression line of relative elevation versus time

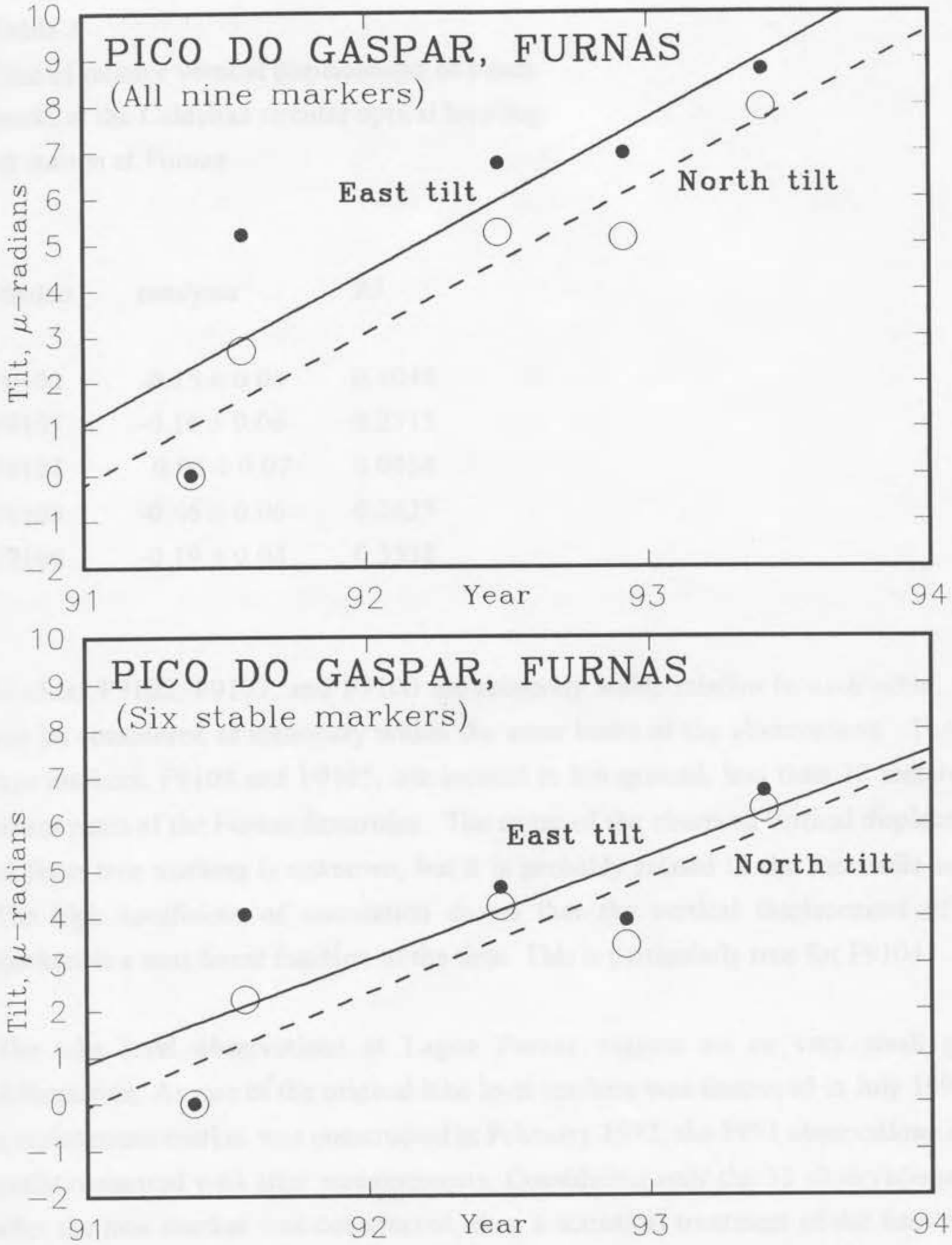

Fig. 7. Observed ground tilt at the dry tilt station Pico do Gaspar based on all nine permanent bench marks of the station (top), and on the six permanent bench marks which appear stable relative to each other (bottom). Solid dots represent east component of tilt since first observation of May 1991 and solid lines are the corresponding regression lines. Open circles represent the north component of tilt since the first observation of May 1991, and dashed lines are the corresponding regression lines. Positive tilt is up towards east and north.

Table 3
Rate of relative vertical displacement of bench marks at the Caldeiras circular optical levelling tilt station at Furnas

Marker	mm/year	R^2
F9102	-0.15 ± 0.04	0.4048
F9103	-0.16 ± 0.06	0.2713
F9104	0.95 ± 0.07	0.9054
F9105	-0.46 ± 0.06	0.7625
F9106	-0.19 ± 0.04	0.5538

Markers F9102, F9103, and F9106 are relatively stable relative to each other. They can be considered as stationary within the error limits of the observations. The other two markers, F9104 and F9105, are located in hot ground, less than 10 meters from steam vents of the Furnas fumaroles. The cause of the observed vertical displacements of these two markers is unknown, but it is probably related to the fumarolic activity. The high coefficient of correlation shows that the vertical displacement of these markers is a near linear function of the time. This is particularly true for F9104.

The lake level observations at Lagoa Furnas suggest no or very small ground deformation. As one of the original lake level markers was destroyed in July 1991, and a replacement marker was constructed in February 1992, the 1991 observations are not easily compared with later measurements. Considering only the 13 observations made after the new marker was constructed, then a statistical treatment of the data can tell how precise and reliable the observations are, and how large ground deformation can have occurred without being observed by the lake level observations.

Vertical component of ground deformation at Lagoa Furnas will cause individual bench marks to be displaced vertically, relative to the average elevation of all markers. It is assumed that any ground deformation is a linear function of the time. The slope of the regression line of relative marker elevation versus time, and the standard error of the slope using all lake level measurements since February 1992, is shown in Table 4.

Table 4
Rate of relative vertical displacement of lake level bench marks at Lagoa das Furnas

Marker	Vertical displ. mm/year	R^2	Standard deviation
F9107	-0.77 ± 0.59	0.1165	1.14 mm
F9108	-1.03 ± 1.24	0.0503	2.30 mm
F9109	0.06 ± 0.55	0.0008	1.00 mm
F9110	0.19 ± 0.90	0.0035	1.65 mm
F9111	1.07 ± 0.88	0.1033	1.68 mm
F9112	0.67 ± 0.70	0.0644	1.32 mm

(*The standard deviation is computed from the deviation of height of each marker from its average height*).

If there is no correlation between marker elevation and time, then about 67% of the computed slopes should be smaller than the computed standard error of the slope. In our case, two of the computed slopes (F9107 and F9111) exceed the computed standard errors by a small amount. This suggests that no correlation exists between relative marker elevation and time, and thus no progressing vertical component of ground deformation at Lagoa Furnas.

Similar treatment of the ground tilt as computed from the observed relative marker elevation at Lagoa Furnas gives similar result. Again the deformation is assumed to be a linear function of the time. The computed rate of tilt based on 13 lake level measurements from February 1992 to October 1993 is presented in Table 5.

Table 5
Rate of tilt at Lagoa das Furnas, as obtained from the lake level observations from February 1992 to May 1993

Tilt component	Rate of tilt μ - rad/year	Correlation R^2
East	-0.32 ± 0.63	0.0204
North	-0.98 ± 0.68	0.1393

This suggests very vaguely a tilt, down towards north. However, the tilt rate has to exceed the standard error by a factor of about 2 for the result to be significant at the 95% confidence level. This means that lake level observations at Lagoa Furnas over a period of about 20 months will not show with confidence any ground tilt at a rate below about 2 microradians per year. If the bench marks are stable and remain stable over several years, then similar measurements over an extended time span will detect smaller tilt. The standard error of the tilt decreases with increasing number of observations and also with increased time between first and last observation. Thus it can be assumed, that the limit of detectable ground tilt is inversely proportional to the time span of the observations. If actual ground tilt at Lagoa Furnas progresses at a rate of 1 microradian per year, lake level observations over a period of 2 or more years are required to detect this tilt with confidence.

RECORDING TILTMETERS

Three recording tiltmeters of the NVI type (Sindrason and Olafsson 1978) have been operated at Furnas since May 1991. There are a few short periods missing in the records of these stations, but the general picture of the tiltmeter records is available for investigation. The first hand impression of these records is that the recorded tilt variations are much greater than, and unrelated to, the ground tilt which is indicated by the optical levelling tilt measurements.

All the tiltmeters recorded settling drift for a period of less than one month after installation. Subsequently, irregular tilt variations are recorded, indicating tilt changes of 5 to 50 microradians per month. One component at one of the stations shows annual tilt cycle of about 50 μ-rad amplitude. A very preliminary comparison of weather records and the tilt records shows that heavy rain causes notable tilt

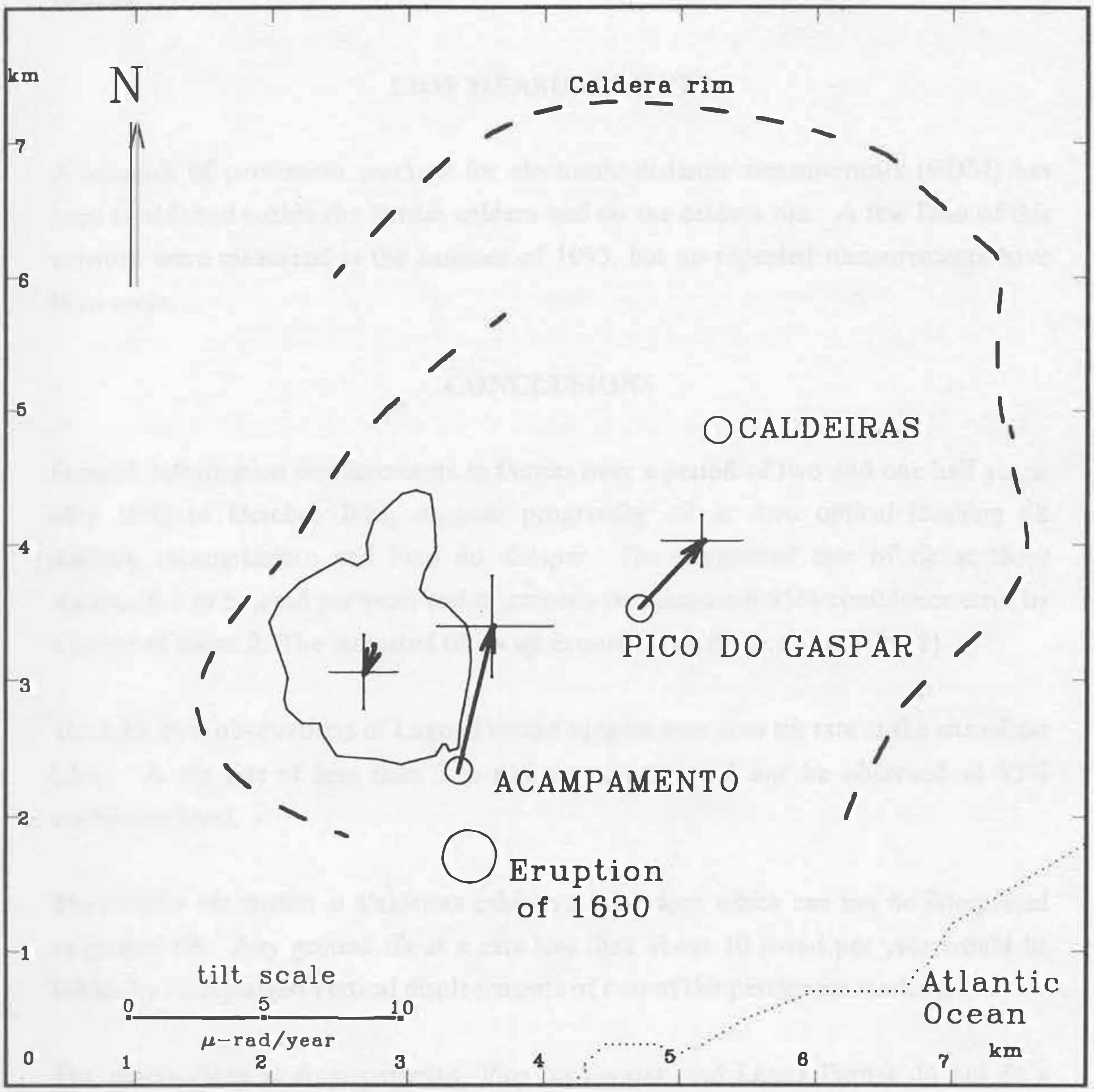

Fig. 8. Tilt rate at the dry tilt stations Acampamento and Pico do Gaspar, and at Lagoa das Furnas as derived from measurements of 1991 to 1993. Error bars show two times standard errors.

variations. A systematic study of the tilt records and their correlation with known external processes should be made in an effort to explain and understand the tiltmeter records.

EDM MEASUREMENTS

A network of permanent markers for electronic distance measurements (EDM) has been established within the Furnas caldera and on the caldera rim. A few lines of this network were measured in the summer of 1993, but no repeated measurements have been made.

CONCLUSIONS

Ground deformation measurements in Furnas over a period of two and one half years, May 1991 to October 1993, suggest progressing tilt at two optical levelling tilt stations, Acampamento and Pico do Gaspar. The suggested rate of tilt at these stations is 3 to 5 μ-rad per year, and it exceeds the computed 95% confidence error by a factor of about 2. The indicated tilt is up in north-easterly direction (Fig. 8).

The lake level observations of Lagoa Furnas suggest near zero tilt rate at the site of the lake. A tilt rate of less than 2 μ-rad per year would not be observed at 95% confidence level.

The circular tilt station at Caldeiras exhibits a behaviour which can not be interpreted as ground tilt. Any ground tilt at a rate less than about 10 μ-rad per year would be hidden by unexplained vertical displacements of two of the permanent markers.

The observations at Acampamento, Pico do Gaspar, and Lagoa Furnas do not fit a simple deformation model. The observations at Acampamento and Pico do Gaspar agree with either a single point source subsidence centred south-east of Lagoa Furnas or a single point source inflation centred near or east of the town of Furnas. However, lake level observations of Lagoa Furnas do not agree with either of these centers of deformation.

No simple deformation model can at the present time be constructed for the Furnas caldera based on the deformation measurements. However, some progressing deformation is strongly suggested.

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