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TILTS ASSOCIATED WITH VOLCANIC ACTIVITY GUADELOUPE, FRENCH WEST INDIES FALL 1976

by

F. G. West, G. H. Heiken, E. F. Homuth, R. W. Peterson, B. M. Crowe, and K. H. Wohletz

ABSTRACT

Shortly after the August 30, 1976 ash eruption of La Soufrière, four borehole tiltmeters were emplaced on the southwest flank of the volcano at distances of 0.8 to 8 km from the vent area. Logistics did not allow immediate placement of the instruments in permanent holes, but meaningful data were obtained by timely emplacement in carefully selected temporary sites. Instrument drift related to aging or curing of the installations was of a different character and less dynamic than volcanic related tilt.

Tilts observed were complex both in their character and orientation. The character of the tilt ranged from gentle rates of tilt to rapid tilt events some of which approximated a straight line on a plot of tilt versus the logarithm of time. Substantial tilt events preceeded some of the ash eruptions, but other substantial tilt events were recorded which resulted in no ash eruptions. The tilt events recorded have a character one might expect during the rapid pressurization of a volcano by low viscosity phreatic fluids where mass transport is by hydraulic fracturing and flow through a porous media.

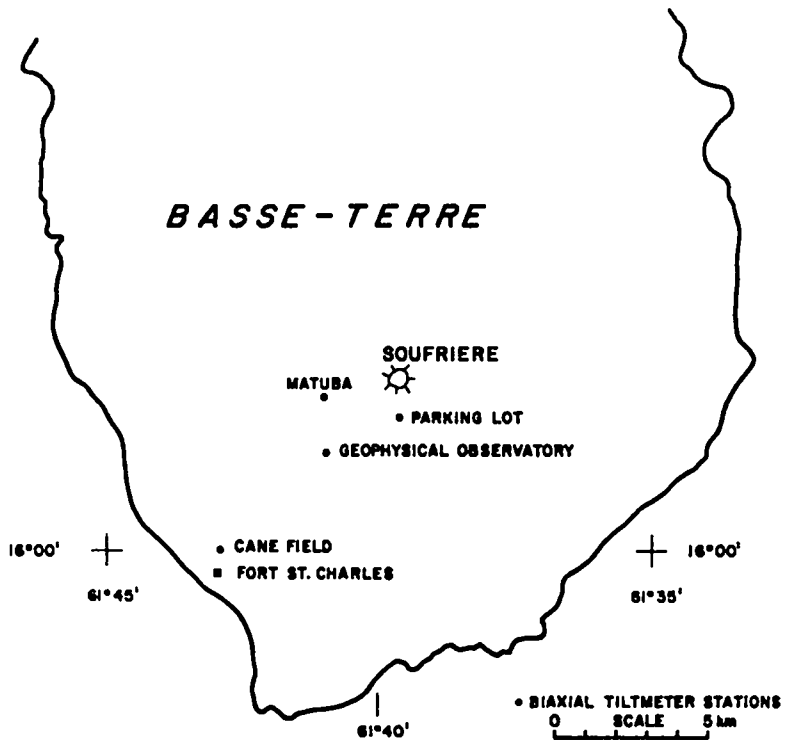
I. INTRODUCTION

Seismic activity increased from the fall of 1975 through early 1977 at La Soufrière, a silicic volcanic dome with an elevation of 1467m on the French West Indies island of Guadeloupe. During this period several phreatic eruptions took place, the first eruption occurring on July 8, 1976. This activity coupled with the memory of catastrophies elsewhere caused by similar volcanic conditions prompted the evacuation of most of the inhabitants of the southern part of the island. Instruments to monitor various geophysical parameters were installed in

an effort to predict volcanic activity. Staff from the Los Alamos Scientific Laboratory installed four tiltmeters.

II. TILT MEASUREMENTS

Shortly after the August 30, 1976 phreatic eruption of La Soufrière, four borehole tiltmeters were emplaced on the volcano's southwest flank at distances of about 0.8 to 8 km from the vent area (Fig. 1). Although logistics did not allow immediate placement of the instruments in permanent holes, it was decided upon consultation with M. Feuillard of the Geophysical Observatory in Basse Terre that until permanent holes were available meaningful data could be obtained by timely emplacement in carefully selected temporary sites. Any instrument drift related to aging, curing or type of installation would, it was assumed, be of a different character and less dynamic than volcanic related tilt. This proved to be the case.



GUADELOUPE ISLAND F.W.I.

Fig. 1.
Location Map

The tiltmeters used were the biaxial electrolytic bubble type, previously used by Endo et al[1] and Wadge[2]. The housing for the bubble transducer is a metal tube 5-cm in diameter and 1 m long. The tiltmeters were installed in 1 m deep holes. The attitude of the bubble is monitored electronically to produce an X and Y voltage proportional to the tilt. Outputs of two of the tiltmeters were continuously recorded on strip charts, while outputs of the other tiltmeters were telemetered to Ft. Saint Charles in Basse Terre where the data was recorded at 30 second intervals. Continuously recorded tiltmeters were also utilized as long period seismometers allowing the precise correlation of tilt and seismic events. The telemetering of data had the advantage of a low power drain at the tiltmeter site and the recording of data at a safe central location.

III. OBSERVATIONS

Tilts associated with the phreatic eruption of September 22, 1976 (0615 local) illustrate most of the characteristics of tilt observed at La Soufrière. The eruption was preceeded by nominal tilt changes. The eruption (recording shown in Fig. 2) began as a low amplitude-high frequency disturbance, which built in amplitude in an exponential manner, and lasted for 2 minutes. Tilting began at the Geophysical Observatory Station 13 minutes after the start of the eruption by tilting toward the southwest or radially away from the volcano in a linear fashion with time for 7 hours, 47 minutes. This tilt event was terminated by a sharp tilt event to the southeast which lasted 13 minutes. Major radial tilting began toward the northeast or toward the volcano, and lasted for 3 hours, 26 minutes. The change in tilt for this event when plotted against the logarithm of time approximates a straight line. This event was followed by a number of similar semilogarithmic events. The direction of tilt changed in each of the first four events. Some of the events exhibit partial recovery toward the state of tilt at the start of the event.

The eruption of October 2, 1976 (Fig. 3) was preceeded by some 8 hours of tilt activity. The summit station became very noisy about 3 hours before the eruption and began tilting substantially away from the volcano about an hour and a half before the eruption. After the eruption the summit tilted abruptly in toward the volcano, this was followed by a substantial linear type of event away from the volcano. The other stations showed relatively little tilt when compared with the summit.

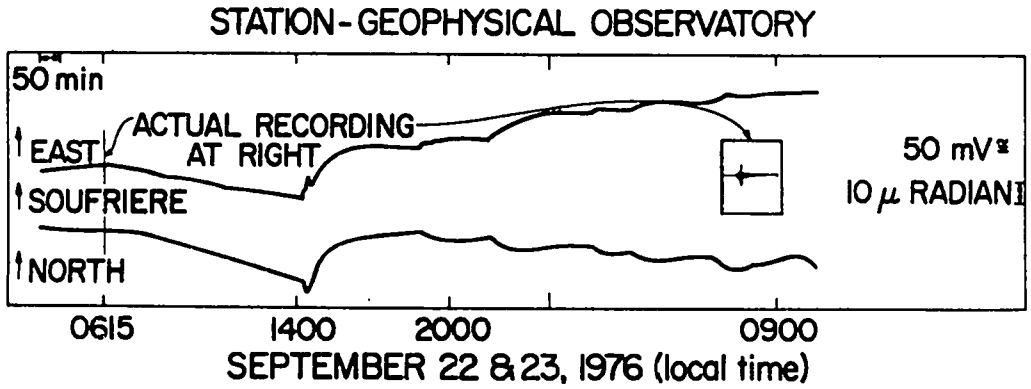


Fig. 2.
Tilt events of September 22 and 23, 1976.

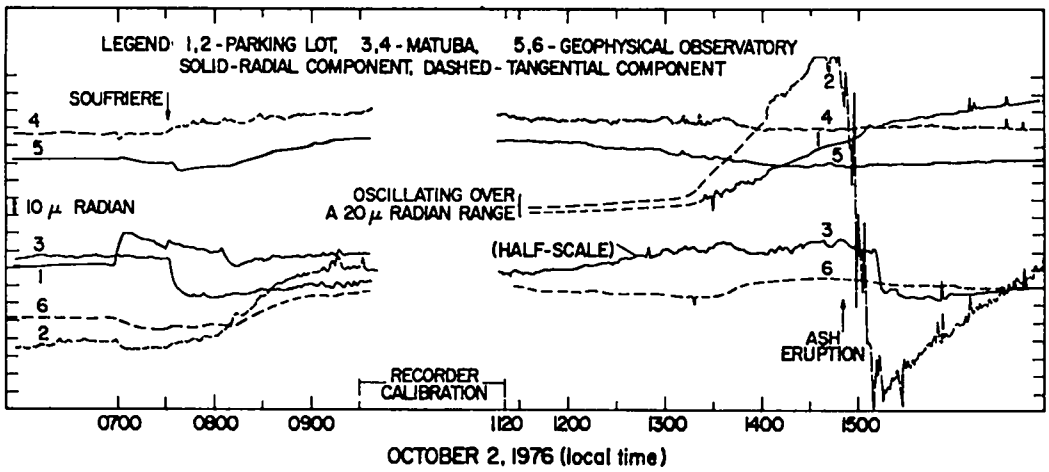


Fig. 3.
Tilt events of October 2, 1976.

September 27, 1976 (Fig. 4) was marked by considerable tilt activity, but no eruptions occurred. This event illustrates the time differentials that occasionally existed between the onset of tilt at two stations. For instance, a major tilt event began at the summit station at about 2005 hours, at 2030 hours at the Geophysical Observatory Station and at 2110 hours at the Matuba Station.

In view of the temporary nature of the tiltmeter installations, it is only prudent to look at other possible agents of tilt to explain the rapid tilt events, especially the semilogarithmic character. Rainfall appeared to have little or no effect on the tilt. In fact a particularly hard rain caused the Chutes Du Carbet (waterfalls) to be visible for a distance of several kilometers, a special event, yet no tilt events were associated. Numerous tilt events occurred during rainless and windless days. With one exception the stability of the sites appeared to be good. Several of the sites were in laharic breccias which appeared to be very competent. The site near the parking lot at the summit appeared to be partially unstable, ocassionally giving indications of downslope flowage, however; this problem abated and useable data was

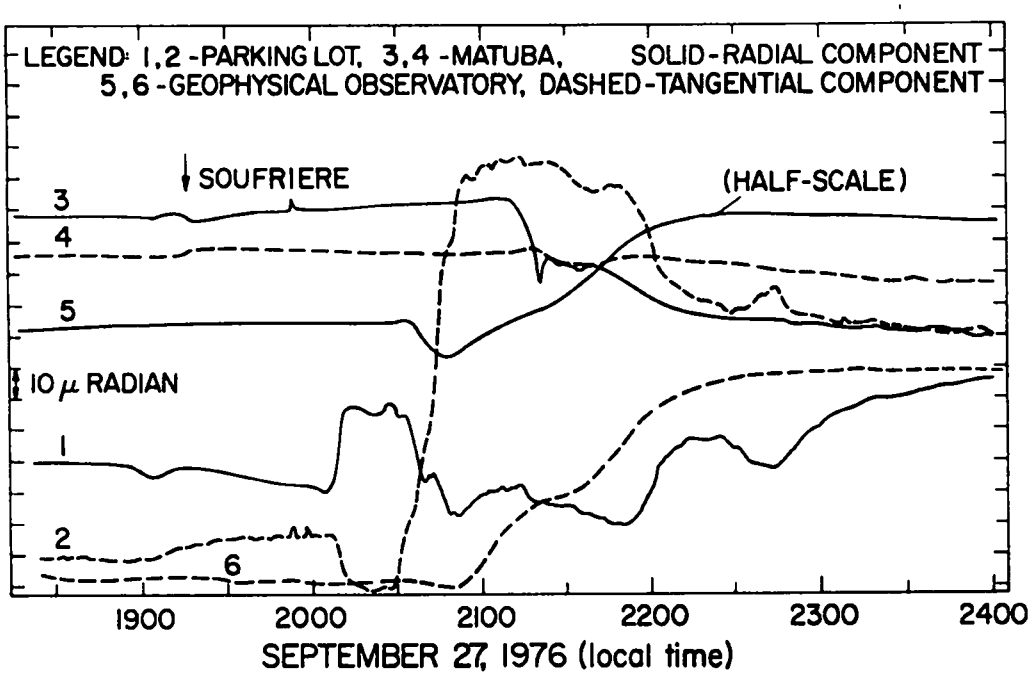


Fig. 4.
Tilt events of September 27, 1976.

recorded for a number of tilt events. The Geophysical Observatory and Matuba stations, which were midway down the volcano slopes, gave no geologic evidence of instability. The cane field station was about 1.5 km from the coast and close to central Basse Terre, a location that is hopefully not unstable; yet rapid type tilt events were recorded at the site. The sudden changes in tilt direction, including tilt reversals, do not fit any common concepts of soil instabilities. The obvious association of some tilt events at several stations with eruptions would seem to indicate the genesis of the tilt as volcanic activity.

IV. DISCUSSION

The tilt events observed were usually more complex than simply inflation or deflation, both in character and orientation. The character of the tilt was quite variable, ranging from uniform gentle rates of tilt to rapid time-dependent rates of tilt.

The character of many of the tilt events recorded is similar to curves typical for the flow of fluids through a porous media which suggests a possible relationship between surface deformation and the groundwater environment of La Soufrière. Intuitively, phenomena commonly related to the flow of water and steam should be expected during phreatic volcanic eruptions. Perhaps phreatic eruptions should be regarded as much hydrologic as volcanic.

Changes in the groundwater piezometric surfaces due to changes in the loading of the aquifer, such as barometric changes, earth tides, and even trains starting or stopping have been noted for a number of years. Surface deformation accompanying the changes in the piezometric surface were first observed only about a decade ago[3]. The withdrawal or injection of water from a shallow artesian aquifer caused a simultaneous deformation of the land surface. Typical of flow of fluids through a porous media much of the change in piezometric surface occurred linearly with the logarithm of time and so did the deformation of the land surface, approximately. Bodvarsson[4] has proposed utilizing this stress-pressure relationship exhibited by confined fluids in an artesian aquifer as an indicator of strain. Possible natural manifestations of confined fluids acting as strain meters are the variations of geyser activity[5] and the triggering of volcanic eruptions[6]. It is well known that the migration of lava in volcanoes such as Kilauea[7] and Mt. Etna[2] causes surface deformation. In view of the relative violence of phreatic volcanic events compared to the extrusion

of lava, it is reasonable to expect associated surface deformation and that it have a character like it's source--rapid and substantial. However, the large difference in viscosities of 10^3 to 10^{11} poise for lavas[8] and 10^{-3} to 10^{-4} poise for steam or water portend a difference in the character of the fluid flow and hence the related surface deformation.

Nakamura[9] has suggested that hydraulic fracturing plays an important role in the volcanic process. Hydraulic fracturing of a rock occurs when the effective fluid pressure overcomes the tensile strength of the rock and any confining pressures. This is expressed[10] as $P_b = T + 3\ \sigma_3 - \sigma_1 - P_o$ where P_b is the formation breakdown pressure of rock of tensile strength T at a pore pressure P_o in a compressive stress field of σ_3, the greatest and σ_1 the least principal stress. Once a hydraulic fracture is induced and the source of pressurization is cutoff, the pressure usually decays linearly with the logarithm of time. In the absence of large tectonic stress fields, most hydraulic fractures induced as a permeability enhancement technique in the oil fields are found to be near vertical[11,12]. Near vertical hydraulic fracturing is proposed for the formation of ore veins[13] and flank eruptions on volcanoes[9]. If at moderate depths the hydraulic pressure exceeds the pressure due to overburden, a horizontal hydraulic fracture may be formed. Intrusive sills and lopoliths may be examples of this type of fracturing. The character of surface deformation associated with hydraulic fracture operations varys somewhat depending on the viscosity of the fracturing fluid. When a grout was used[14] to inflate a hydraulic fracture in a shale, the surface deformation tended to vary linearly with time. In recent experiments, which utilized surface deformations to detect the orientation of vertical hydraulic fractures induced using water,[15] the surface deformation occurred in concert with pressurization of the fracture and both appeared by inspection to vary linearly with the logarithm of time. The appreciable difference in the viscosities of the fracturing fluids, grout and water, suggests that the character of the induced surface deformation may be influenced by the viscosity of the fluid used for fracturing.

The viscosity of the fracturing fluid also plays a role in the pressurization necessary to induce fracturing and in some cases affects the orientation of the fracture[16]. Fluids with a low viscosity, such as steam, have a greater ability to influence the pore pressure P_o. Increasing P_o reduces the pressures necessary for fracturing. Higher viscosity fluids have less of a tendency to raise the pore pressure and thus may require a higher apparent breakdown presure

especially if the fluid is non-penetrating. Zoback et al.[16] found that high viscosity fluids induce fractures with an orientation predicted by theory, i.e. parallel to the maximum principal stress, also that these fractures would not follow existing fractures if the orientation was different from the maximum principal stress. Low viscosity fluids were able to open existing fractures even if their orientation was other than parallel to the maximum principal stress.

It was found[16] that the rate of pressurization also affected the breakdown pressure; a high rate of pressurization resulting in an anomously high breakdown pressure. As the rate of pressurization increases, in a volcano, the mode of deformation may change from viscous to plastic and then to elastic, at high rates of pressurization. Low rates of pressurization may allow the presumably well-jointed volcanic rocks to act essentially as a granular media lubricated by the clays formed by fumarolic alteration. Medium rates of pressurization may cause the shear or thixotropic strength of the clay in the joints to produce something of a plastic deformation. Rapid deformation may allow some measure of dilatant hardening to produce more of an elastic response. Viscous lavas, probably tend to produce only slow rates of pressurization, whereas phreatic events probably produce low or high rates of pressurization depending on the hydrologic environment. The rate of pressurization is dependent on hydrologic source boundary conditions such as having an instantaneous planar source (hydraulic fracture), a line source (central conduit) or a combination (orthogonal fracture system). Each of the modes of deformation probably has a characteristic type of tilt curve.

Two explanations are suggested for the tendency of some tilt events to recover toward the original state of tilt, elastic rebound and the oscillation of an underdamped hydraulic system.[17]

V. CONCLUSIONS

The similarity of character of tilt events recorded at La Soufrière and those observed during the injection or withdrawal of fluids from a porous media and hydraulic fracturing operations, are believed to be more than simple coincidence. On the contrary if tilt events with some of the characteristics normally attributed to hydrologic processes were not observed during phreatic activity, it would be enigmatic. The characteristics of surface deformation

related to volcanic activity are influenced by the rate of pressurization and changes in pore pressure, both being dependent on fluid viscosity.

It appears that phreatic eruptions generated by low viscosity fluids potentially have a much broader range of phenomena than do high viscosity fluids. Low viscosity fluids of phreatic activity permit tilt events to occur in a matter of minutes, whereas events produced by high viscosity fluids (lava) may require times on the order of days (see Fig. 4 of Kinoshita,[7] for event days November 6 to 8, 1967). That low viscosity fluids tend to generate more semilogarithmic time events than linear time events is merely a reflection of the fluid viscosity, the converse being the case for high viscosity fluids. We feel that the deformations observed reflect the gamut of possible responses described above and in particular those expected from hydraulic fracturing. The multiple tilt events observed fit the statement of Phillips[13] "that the build-up of excess pressure at the top of a reservoir of fluid of low viscosity, may lead to the extension of the fracture by periodic episodes of explosive hydraulic fracturing and brecciation."

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