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A Tilt and Seismicity Episode in the New Hebrides (Vanuatu) Island Arc

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Tilt and seismicity have been monitored in the central New Hebrides island arc since 1978 using bench mark arrays, long tube water tiltmeters, borehole tiltmeters, and a local seismometer network. Releveling of the bench mark array on Efate island in late November 1986 revealed a 10 μrad tilt up to the NNW since the previous leveling in April 1986. The tilt event was preceded by a magnitude 5.9 thrust event that occurred on October 25, 1986, at a depth of 48 km and about 11 km NW of the tiltmeter instruments. Six days later, a shallow (<20 km) swarm of earthquakes occurred 12 km NNW of the tiltmeter instruments and 5 km north of the epicenter of the magnitude 5.9 earthquake. Closely coincident in time with the swarm, a 5 μrad tilt up to the NNW that occurred over a period of 5 days was recorded on both the 100 m baseline water tube tiltmeter and the borehole bubble level tiltmeter. A composite focal mechanism of 191 earthquakes selected from the swarm indicates a thrust mechanism with some component of strike slip. Calculations show that the seismic slip associated with a swarm of this magnitude is apparently inadequate to cause the observed surface deformation. Two similar shallow swarms in November 1987 and July 1988 have occurred within 15 km of the 1986 swarm but with no apparent surface deformation. The most likely explanation, supported by simple modeling, is that the swarm and tilt are the result of a magmatic intrusion from island arc volcanism. An alternate hypothesis is that both the seismicity and the tilt are due to an episode of largely aseismic creep in the upper crust.

Introduction

Seismicity and crustal deformation have been monitored in the central New Hebrides island arc since the late 1970s in an effort to identify potential earthquake hazards. The seismicity has been recorded by a local seismic network installed in 1978 [*Isacks et al.*, 1981; *Chatelain et al.*, 1986] and the crustal deformation measured using geodetically levelled bench mark arrays [*Bevis and Isacks*, 1981], borehole bubble level tiltmeters [*Marthelot et al.*, 1980; *Isacks et al.*, 1978], and a two-component, long tube water tiltmeter. The monitoring is a cooperative project between Cornell University and the Institut Francais de Recherche Scientifique pour le Development en Cooperation (ORSTOM).

After 10 years of monitoring, the first clear tilt event was observed in October-November, 1986 when a large (at least 5 μrad) tilt was clearly recorded by all three instruments measuring crustal deformation on Efate island. This tilt event coincided in time and direction with a shallow (< 20 km) swarm of small ($M_L \leq 4.0$) earthquakes centered 12 km northwest of the tilt monitoring instruments. Six days prior to the swarm and the tilt event, an M_S 5.9 thrust earthquake occurred at a depth of 48 km just off the west coast of Efate island. The hypocenter of this preceding earthquake was 38 km below the center of the swarm.

The purpose of this paper is to document the spatial and temporal relationship of the initial thrust earthquake, the tilt event, and the shallow seismicity. This paper will also illustrate the use of a long tube water tiltmeter for crustal deformation measurements. Thus, we shall first briefly review the tectonics of the region, then describe the instrumentation and crustal deformation observations, and finally discuss the relationship of the tilt and seismicity.

Tectonics, Seismicity and Geology of Efate

The island of Efate lies in the central part of the New Hebrides island arc, which extends roughly from the Solomon trench at latitude 11°S to the Hunter Fracture Zone at latitude 22°S (Figure 1). This arc marks the subduction of the Australian-Indian plate under the North Fiji Basin at a convergence rate of approximately 11 cm/yr with a slip direction of N75°E [*Isacks et al.*, 1981; *Pascal et al.*, 1978; *Dubois et al.*, 1977]. The resulting Wadati-Benioff zone is steeply inclined with an average dip of 70° to the east and is continuous along the length of the arc. However, within the upper plate, the structure is anomalous in the central portion of the arc where the islands of Malekula and Santo occupy the expected position of the trench. The disruption of the upper plate is believed to be due to a combination of late Miocene rifting and Quaternary interaction with the subducting D'Entrecasteaux Fracture Zone (DFZ) [*Isacks et al.*, 1981; *Chung and Kanamori*, 1978]. Efate is located to the south of this disruption, near the northern end of the Southern New Hebrides Trench (Figure 2).

Seismicity along the central New Hebrides arc varies greatly but is especially distinctive in the Efate region. More specifically, in the 10 years of local network monitoring, the Efate segment has consistently shown the highest rate of seismic activity. This seismicity displays well-defined zones of repeated seismic activity and extensive clustering of earthquakes, with the highest amount of seismicity taking place between the island and the trench axis. This area has a high rate of background activity and is repeatedly activated by clusters of earthquakes, often associated with foreshock and aftershock sequences [*Chatelain et al.*, 1986]. Moderate events ($5.5 < M_S < 7.0$) are relatively frequent in the Efate segment, but few large events ($M_S > 7.0$) have occurred.

Most of the earthquakes in the Efate region occur along the intraplate boundary, and in the 8 years of monitoring before

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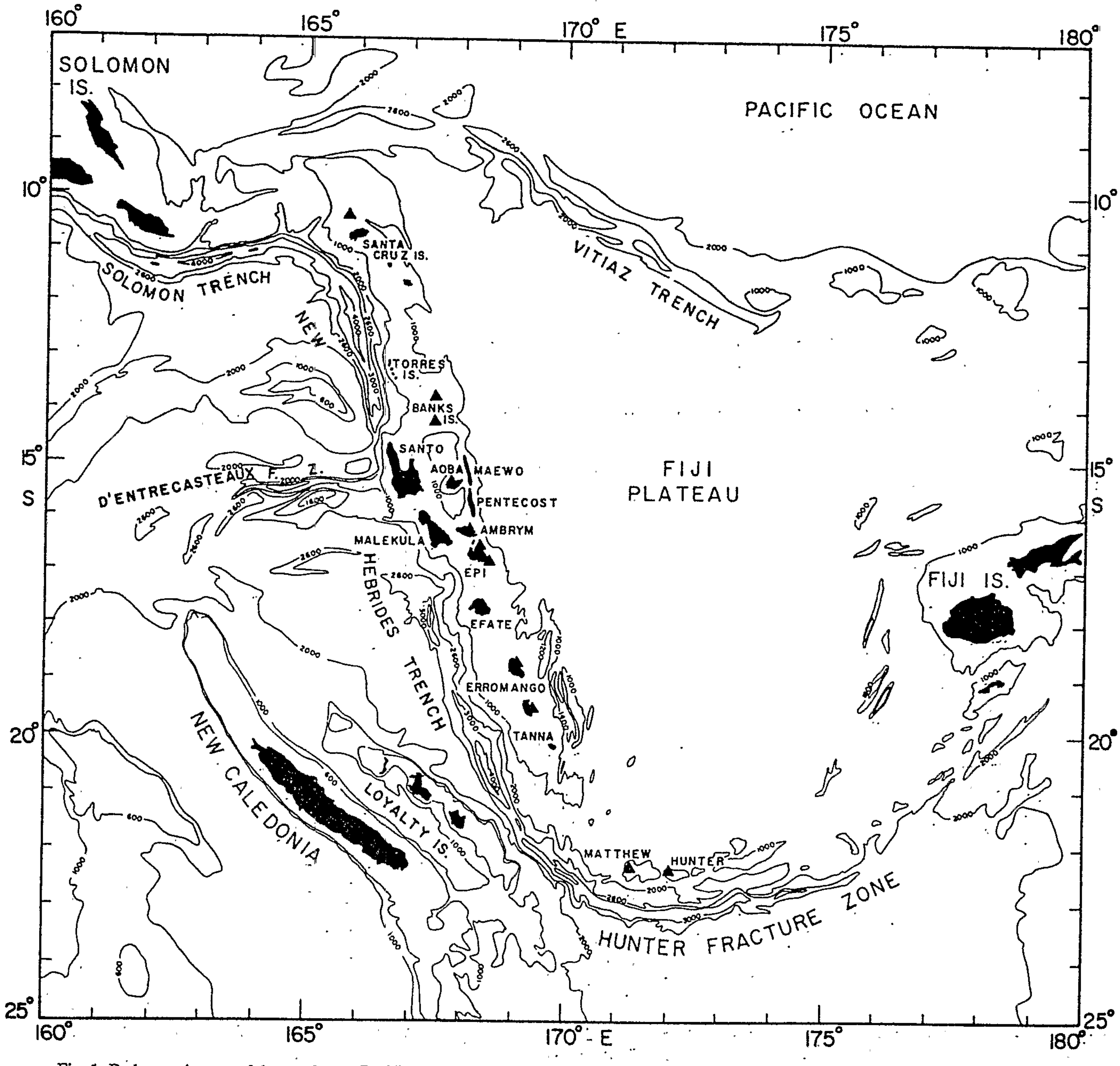

Fig. 1. Bathymetric map of the southwest Pacific region showing the New Hebrides island arc. Triangles represent Quaternary volcanic centers. The contours are in fathoms (1 fathom = 1. 829 m). Adapted from *Isacks et al.* [1981].

1986 only one small cluster had been located on Efate island itself. However, between 1986 and 1988, three unusual shallow swarms occurred on the island of Efate but were situated well above the interplate boundary. The largest swarm, in October and November 1986, was coincident in time with deformations recorded by tiltmeters on the island. Before 1986, in 8 years of monitoring, only one small group of shallow earthquakes had been located on Efate island.

The geology of Efate consists of a core of Plio-Pleistocene submarine volcanics partially covered by Holocene coral limestone (Figure 3). The volcanics consist of breccias and tuffs overlain by younger basalts [*Ash et al.*, 1978; *Carney et al.*, 1984]. The volcanism was centered in the north central part of the island but continued on the small nearby islands to the north after ceasing on the main island. Subaerial basalts found on these small islands appear to range in age from the Late Pleistocene to Recent. These ages were inferred from an uppermost Late Pleistocene age for a superficial tuff found on Efate (from dated coral limestone) and by the state of preservation of the volcanic structures [*Ash et al.*, 1978].

The Holocene coral limestone on Efate is faulted and uplifted, often forming dramatic terraces created by the interaction of sea level variations with the uplift. Dating of the terraces using high-precision thorium 230 ages indicates an uplift rate of approximately 1 mm/yr for the last 200,000 years. [*Bloom et al.*, 1978; *Edwards et al.*, 1987, 1988]. The terraces are most obvious on the western side of Efate.

Currently, geothermal activity is present in at least four places on Efate. The largest area is located near the site of the most recent volcanism on the extreme north end of the island. This

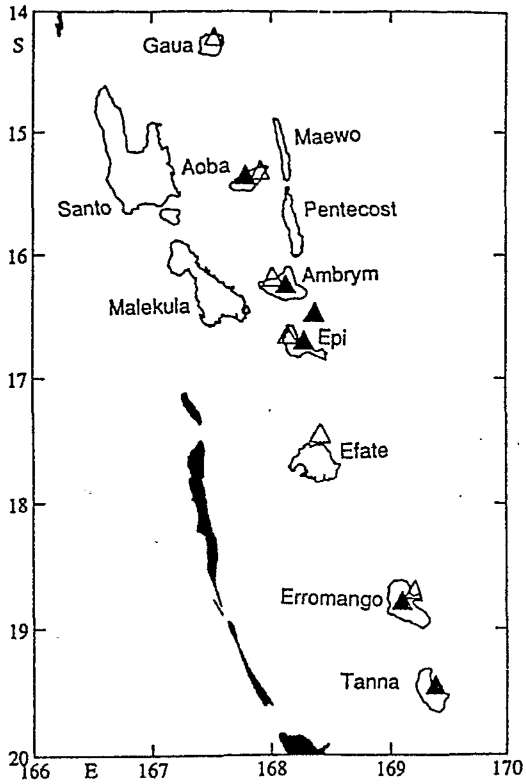

Fig. 2. Map of the central New Hebrides island arc. The solid triangles denote active volcanic centers, and the open triangles denote Quaternary volcanic centers. The shaded region denotes areas deeper than the 6000 m contour of the trench.

area is characterized by hot springs, fumaroles, and high ground temperatures. The other three areas of geothermal activity occur in the central and eastern parts of the island and are characterized by thermal springs with water temperatures up to 58°C [*Mallick*, 1972].

DESCRIPTION OF THE TILTMETER INSTRUMENTATION

Three separate systems for monitoring tilt are deployed on Efate island. Each recorded a tilt during October-November 1986. These systems consist of a periodically leveled bench mark array, a two-component long tube water tiltmeter, and two bubble level borehole tiltmeters (Figure 4). A full description of the bench mark array has been given by *Bevis and Isacks* [1981] and the borehole tiltmeters were discussed by *Marthelot et al.* [1980].

Bench mark array. The leveling array consists of 11 bench marks located within an area 1 km square that is releveled by professional surveyors using first-order procedures at intervals of 6 months to a year (Figure 5). During releveling, the difference in relative elevation is measured between pairs of benchmarks. The change in relative elevation from one survey to the next, divided by the distance between the bench marks, gives the tilt along the azimuth of the bench mark pair. A planar tilt is then determined for the independent pairs using an unweighted, least squares scheme and then expressed in terms of two vectors, a north-south component and an east-west component [*Bevis and Isacks*, 1981]. The resolution is about 1-2 μrad [*Isacks et al.*, 1978]. Apparent tilts can be caused by bench mark instability, measurement error, and loading due to ocean tides [*Bevis and Isacks*, 1981; *Beavan et al.*, 1984]. However, since the leveling procedure requires several observations along the same lines, loading due to tides tends to cancel out [*Bevis and Isacks*, 1981]. An estimate of the error is provided by the standard deviation of the fit of the planar tilt.

Long tube water tiltmeter. The second element in the tilt monitoring system is two orthogonal long tube water tiltmeters installed in 1978. One component is oriented parallel (N20°W) to the strike of the island chain, and the other is perpendicular (N70°E) to the strike. Each tiltmeter consists of a 100 m long, 10 cm diameter PVC pipe half filled with water and buried about 1 m in a trench cut into recrystallized coral bedrock. Detector end pots are anchored to concrete piers set in the underlying recrystalized coral. The water level at each end of the tube is measured using a probe fixed to a float that moves unimpeded in the bore of a fixed linear variable differential transformer (LVDT) body. The LVDT voltage is proportional to the float displacement and is recorded broadband time compressed on Rustrack recorders and band-pass filtered on clock-driven Esterline Angus strip chart recorders.

Because a tilt produces a change in water level that is in opposite direction at each end of the tube during a tilt, tilt signals can be effectively separated from changes caused by thermal and evaporation effects that cause identical changes at each end. This anticorrelation between the water level signals at each end distinguishes tilt from the long-term drift evident in the yearly record. This drift is believed to be caused primarily by evaporation, condensation, or secondary thermal effects. These effects have been decreased by conditioning the surface of the water with oil, but the ENE-WSW tube still exhibits considerable drift, recently shown to be caused by a minor leak in the system. A degree of redundancy is provided by performing first-order geodetic releveling on the piers of the long tube tiltmeter at the same time as the benchmark array. The accuracy of the long tube is very good for short-term events (less than a few days) but decreases with time as the long-term drift is difficult to identify and constrain. The tilt caused by tidal loading [*Marthelot et al.*, 1980; *Isacks et al.*, 1978] is clearly observed. The long tube is also surprisingly sensitive to apparent crustal loading due to tsunami signals near the resonant frequency of the underdamped half filled tube of water (about 6 min). Surface deformation due to rainfall and groundwater effects appears to be minimal, as no anomalous tilt has been observed in periods of extreme rainfall during hurricanes or after controlled pumping of local wells normally used for agricultural purposes.

Borehole tiltmeters. The third element of the tilt monitoring system consists of two Kinemetrics TM-B1 borehole bubble level biaxial tiltmeters installed in steel jacketed boreholes at 2 m depths and coupled to Rustrack recorders [*Isacks et al.*, 1978; *Marthelot et al.*, 1980]. The two borehole tiltmeters on Efate are located at Devil's Point near the long tube water tiltmeter and within the leveling array and at Tukutuku 5 km NW of Devil's Point. Again, the two components of measured tilt are N20°W and N70°E. The results from these instruments are fairly reliable for periods up to a few days but suffer from drift probably due to soil effects from thermal changes and root growth [*Isacks et al.*, 1978; *Wyatt and Berger*, 1980; *Wyatt et al.*, 1988].

Seismometers. The five seismic stations on Efate are part of the 19 station telemetry network operated by Cornell and ORSTOM since 1978. A sixth three-component intermediate

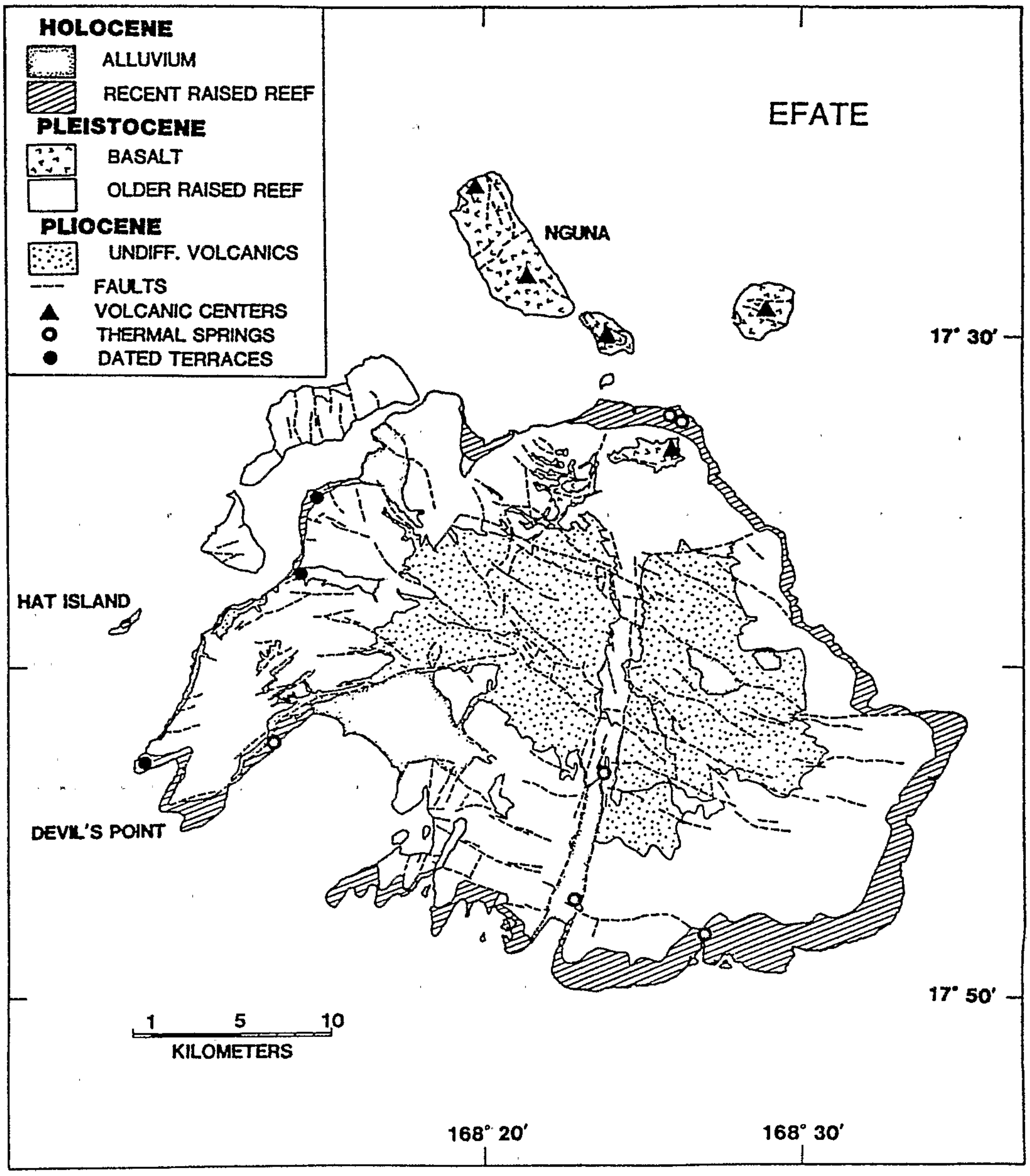

Fig. 3. Geologic map of Efate island. Adapted from *Ash et al.*, [1978] and from *Bevis and Isacks* [1981].

band station, PVC, is operated separately at Port Vila by ORSTOM. Three of the stations (NGA, RTV, MBV) record the vertical component only, while DVP and PVC each record a horizontal (E-W) and a vertical component. A low-gain station, CAV, operating at the base station at Port Vila, is added to the signals from the local network, and the signals are recorded there in both digital and analog form. Earthquake locations are derived using HYPOINVERSE [*Klein*, 1978] from manually picked phases. Magnitudes are determined from a local scale based on coda length and tied to the teleseismic m_b scale by *Chatelain et al.* [1986] from events reported in the Preliminary Determination of Epicenters (PDE) according to the method described by *Tsumura* [1967].

TILT AND SEISMICITY OBSERVATIONS

Prior to the October-November 1986 event, the only possible tectonic tilt recorded was a gradual 6 μrad tilt from 1976 to 1984 registered by the bench mark array at Devil's Point [*Bevis and Isacks*, 1981; *Chatelain et al.*, 1986]. This tilt was believed to be caused by a creep episode along the plate boundary, as no association with major earthquakes was apparent.

Tilt. In October and November 1986, however, a clear and unambiguous tilt episode was recorded by the instruments on Efate island. The first indications of this tilt event were observed upon analysis of the data from the November 26, 1986, leveling of the DVP array. An unprecedented amount of tilt had occurred between the April and November 1986 leveling. Upon the arrival and examination of the long tube tiltmeter and borehole tiltmeter data, it became clear that the deformation coincided with the unusual shallow seismicity recorded on Efate island from October 30 to November 5.

Analysis of the bench mark array data using a best fitting planar tilt calculated from the benchmark movement indicated a tilt of about 9-10 μrad up toward the north since the April 1986 leveling (Figure 6). It was initially suspected that the tilt was the

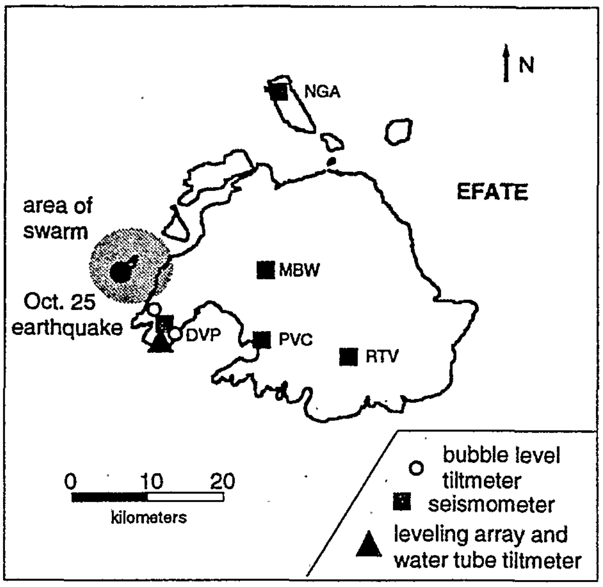

Fig. 4. Map of Efate showing the location of instrumentation and the location of the October-November 1986 shallow swarm. The solid circle is the epicenter of the October 25, 1986, magnitude 5.9 earthquake.

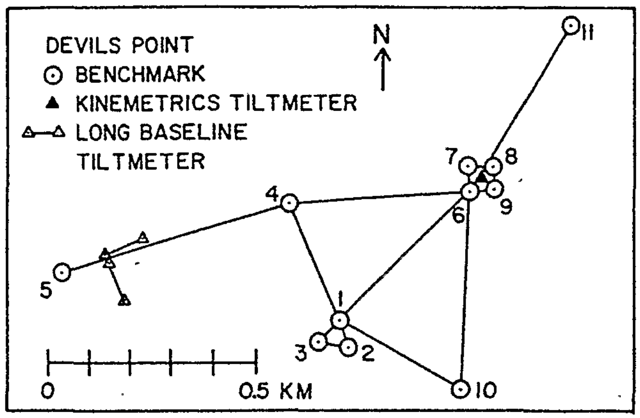

Fig. 5. Diagram of benchmark array. Taken from *Bevis and Isacks*, [1981].

result of bench mark instability, but further analysis of the leveling data showed that the tilt was relatively coherent over the array. The standard deviation of each bench mark observation was within previously recorded values, which argued against sudden bench mark instability. Subsequent relevelings in April and November 1987 appear to confirm the continued stability of the bench marks. Inspection of the data also revealed no misclosures or evidence of blunders in the surveying, implying that the tilt was real and extended over the width of the array. Also, no significant change in precipitation occurred during this period. Even if the maximum resolution error of 2 μrad is assumed on both April and November levelings, the resulting tilt is still at least 6 μrad.

Examination of the records from the long tube water tiltmeter confirm a clear 5 μrad tilt up to the NNW between November 1 and November 9 on the NNW-SSE component (Figure 7). The ENE-WSW component shows a slight amount of tilt (about 0.5 μrad) up to the west but instrumental recording problems and varying sensitivity in the west end of the ENE-WSW instrument prevented a clear estimation of tilt on this component. The long tube recordings also show evidence of a smaller tilt before the larger event. Close examination of the east end of the ENE-WSW long tube data appears to show a slight tilt down to the WSW on October 30 before the larger tilt on November 2 up to the NW, but the lack of a clear corresponding signal on the west end prevents verification.

Examination of the data from the long tube and the bench mark array illustrates two other observations. One is that the majority of the tilt occurs in a NNW-SSE direction. Very little tilt is observed on the ENE-WSW component. The amount of tidal loading on the long tube water tiltmeter is also greater on the NNW-SSE component. Examination of the instrument calibrations indicates that this is probably not instrumental bias

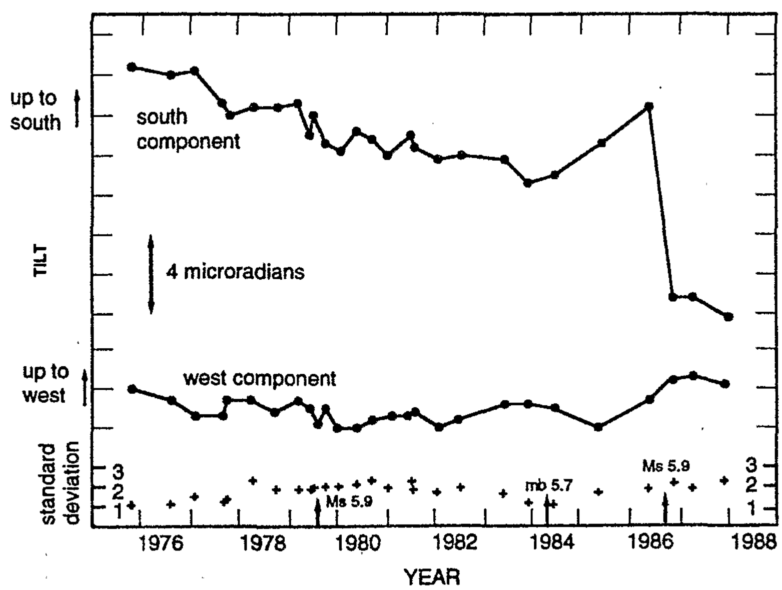

Fig. 6. North-south and east-west components of the planar tilt as calculated from the releveling of the bench mark array. The arrows mark the occurrence of larger earthquakes near Efate island. The small crosses mark the standard deviation of each set of data.

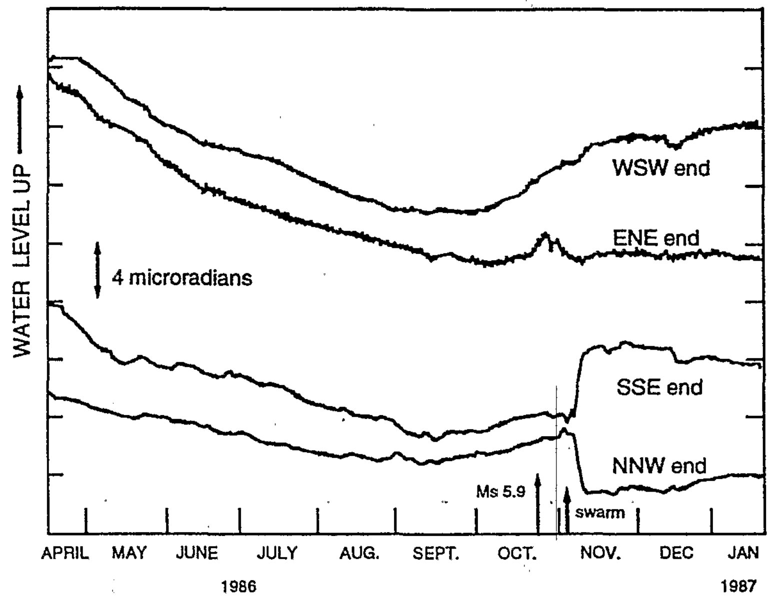

Fig. 7. Yearly record of the water level at each end of the two long tube tiltmeters. The calibration in microradians refers to the tilt as measured separately at each end. The SSE-NNW component has been filtered to remove the effects of tidal loading.

but appears to reflect actual tilt. The other observation is that the tilt as measured by the leveling array appears to follow a progressive tilt toward the north except for the two measurements immediately before the April-November 1986 event. This trend continues after the 1986 measurements. This may reflect a continuation of the tilt reported by *Bevis and Isacks* [1981].

Leveling observations are also made using the bench marks on the four water tube piers, but these measurements are not included in the calculation of tilt from the bench mark array. The measurements indicated a tilt of 5.5 μrad up to the north on the NNW-SSE tube piers and a tilt of 2.7 μrad up to the west on the ENE-WSW piers. Although the tilt measured by the NNW-SSE component agrees well with the calculated 5.5 μrad tilt up from the releveling of the N-S long tube piers, the range of error of these measurements is much greater than that of the bench mark array as the measurements are not redundant, have a short stability history, and have a short baseline.

The data from the borehole tiltmeter at Devil's Point confirms a tilt to the northwest (Figure 8), but an independent magnitude was difficult to determine due to a lack of adequate calibration and high noise levels. Unfortunately, the recorder associated with the borehole tiltmeter developed a problem on November 4 and the traces were truncated on that date. Nevertheless, a strong signal is observed on the NNW component that begins on November 1 and reaches a magnitude of roughly 4 μrad by

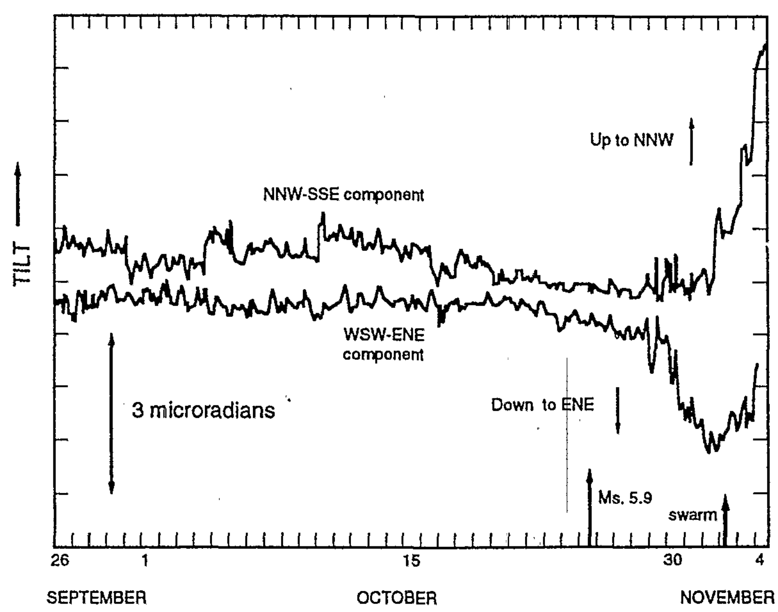

Figure 8. Relative tilt as measured by the borehole bubble level tiltmeter located in the leveling array at Devil's Point. The end of the data is due to instrumental problems.

November 4. This closely matches the signal recorded by the long tube tiltmeter. The ENE component of the borehole tiltmeter shows a 2 μrad excursion that begins on October 30 but largely reverses itself by the time the trace ends. This tilt transient on the ENE could be ground or instrument noise. We believe that the NNW trace reflects a real tilt excursion because of its magnitude and persistance but are not sure about the ENE component trace. The record from the other tiltmeter north of Devil's Point was badly contaminated by diurnal thermal drift, and it was impossible to detect any evidence of the episode.

Seismicity. Two separate seismic events occurred near the time and place of the measured crustal deformation. The first was an interplate thrust earthquake at a depth of 48 km 5 days before the start of the tilt. The second was the shallow swarm at a depth of about 12 km that occurred simultaneously with the tilt.

The initial earthquake, a M_S 5.9 thrust event (PDE, CMT solution) at 2047 UT, October 25, was located by the PDE at a depth of 31 km off the west coast of Efate almost directly below a small island (Hat Island) (Figure 4). The location calculated from the network data using HYPOINVERSE placed it farther south although this location was badly constrained (a large rms error) due to saturation of the S arrival and interference from another event. A re-location using both the local network P arrivals and the PDE teleseismic data with a teleseismic location program shifted the location just to the south of the island at a depth of 48 km. This depth is well constrained by the local P readings. This hypocenter is close to several apparent aftershocks which were well located by the network (as both S and P phases were clearly recorded). This depth places the earthquake hypocenter close to the presumed interplate boundary [*Chinn and Isacks*, 1983], which, along with the thrust-type focal mechanism, suggests strongly that it is an interplate event (Figure 9). This earthquake was followed by only a few aftershocks which is characteristic of events at that depth in the Efate area [*Chatelain et al.*, 1986].

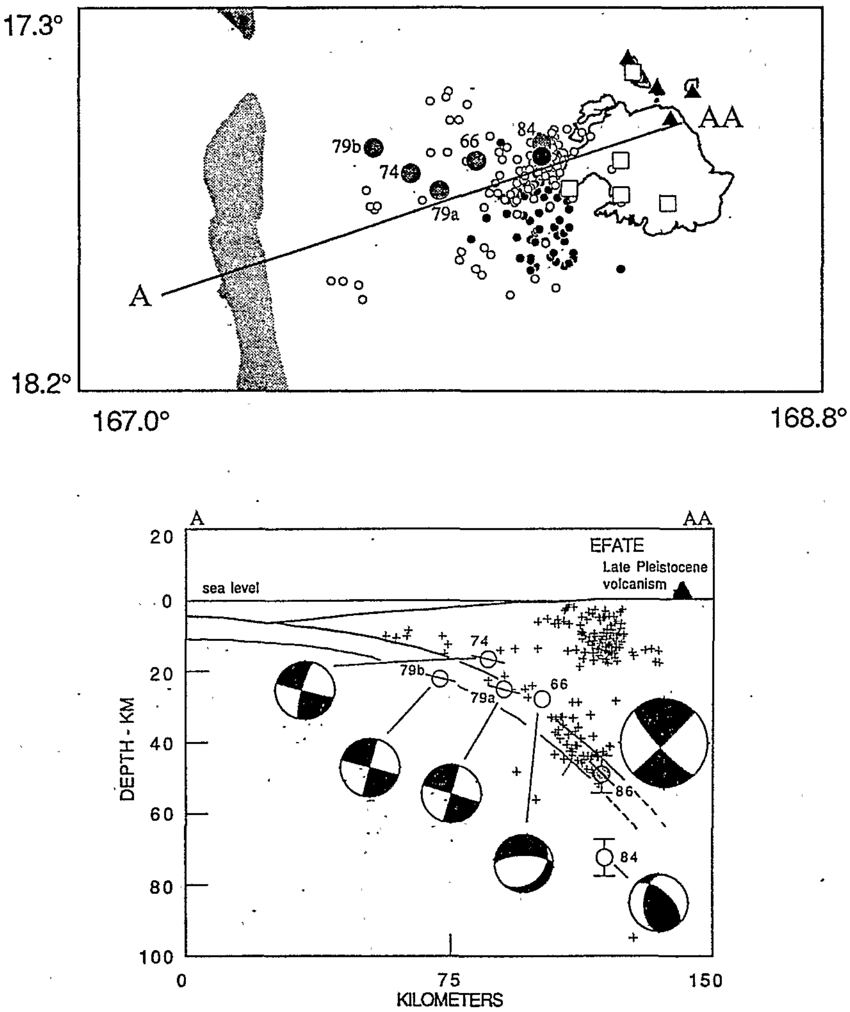

Fig. 9. Map of Efate island and cross-sectional view of the same region. The 6000 m contour is shaded. The squares are seismometers, and the solid triangles are Pleistocene volcanic centers. The small circles denote events in the seismic swarm with the hypocenters deeper than 30 km darkened. Larger circles are the epicenters of large, well-located earthquakes with the October 25, 1986, event shaded. In the cross section, only the well-located swarm events are shown (pluses). The short lines through events 79a, 79b, and 74 show the presumed fault plane orientation. The topography and inferred plate boundary are marked. Focal mechanisms are seen in cross section and the numbers correspond to the year in which they occurred. The 1966, 1974, and 1979 locations and mechanisms are from *Chinn and Isacks* [1983] and the 1986 and 1984 depths are from this study. The mechanisms for the 1986 and 1984 events are the Harvard centroid moment tensor solutions from the PDE. Error bars indicate the range of error on the depth of events 86 and 84.

The shallow seismic swarm consisted of 191 located earthquakes that occurred between October 30 and November 5, with a peak rate of 71 events per day on November 2. The center of the swarm was located beneath Hat Island, 5 km NW of the west coast of Efate and 12 km NNW of the tilt measuring instruments. No distinct main shock occurred during the swarm and the largest event was M_L 4.0. Total moment release was approximately 2.3 X 10^{23} dyn cm (calculated using log M_0 = 1.5 M_L + 16.1 [*Hanks and Kanamori,* 1979]). Of the 14 earthquakes larger than magnitude 3.5, 12 were between 5 and 15 km deep. Eighty percent of the remaining earthquakes were less than 20 km deep with a median depth of 10 km, well above both the interplate boundary and the hypocenter of the October 25 earthquake. Consequently, this swarm does not appear to be a simple aftershock sequence to the October 25 earthquake, as it was delayed by 6 days and was located at a much shallower depth. The restricted azimuthal distribution of the four stations (and the rest of the network) prevented determination of a useful focal mechanism for any one earthquake, although a composite focal mechanism was generated (Figure 10). Only one focal plane is reasonably well constrained and defines a predominantly thrust solution with an unconstrained component of strike slip.

No reliable shape or trend to the swarm is apparent, although the range of error of the hypocenters would have obscured any fine structure. The well-located (vertical and horizontal errors <5 km, rms <0.2 s) events define a volume of about 250 km^3 located below Hat island.

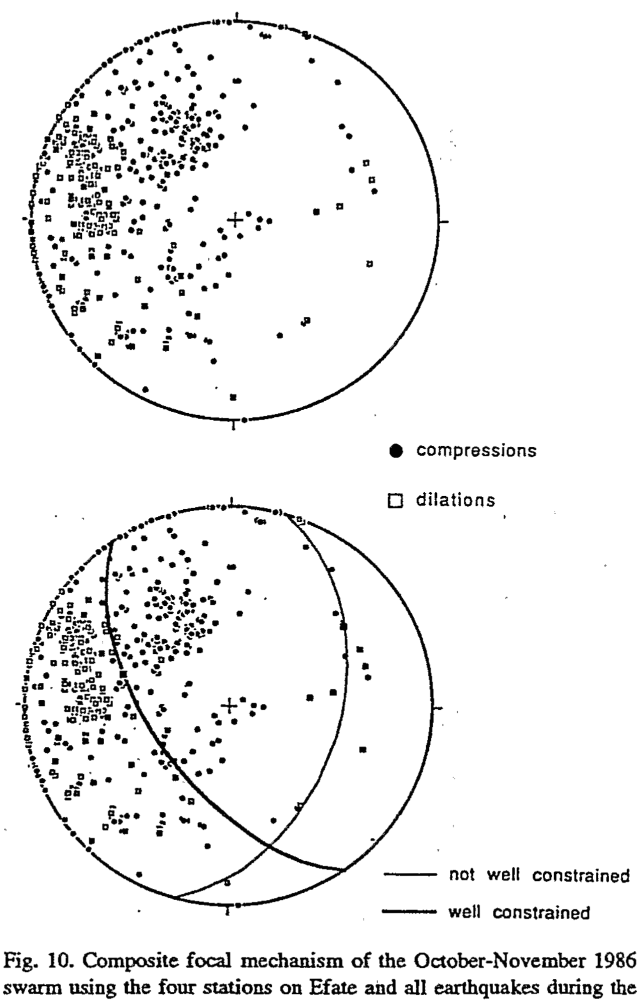

Fig. 10. Composite focal mechanism of the October-November 1986 swarm using the four stations on Efate and all earthquakes during the swarm with depth less than 30 km. The bottom figure shows a possible solution.

In the previous 10 years of recorded seismicity, no other shallow swarms similar to this one had been recorded on Efate. Only one small swarm, of much smaller magnitude, had been recorded on Efate itself, in December 1981. However, in the two years since the October-November 1986 swarm, two other swarms, in November 1987 and July 1988, have occurred. These were similar in character but smaller in size (<120 earthquakes). All lacked any definite main shock and were located at shallow depth in the upper plate. The November 1987 swarm is spatially more compact than the others, although this may be due to better constrained hypocenters as it is located almost directly below the DVP station. Due to the smaller size of the two other swarms and reductions in station coverage, composite focal mechanisms were much less well constrained, although the first motions as recorded at the station DVP were compressional for most events in both the October-November 1986 and the November 1987 swarms. None of the other swarms were associated with either tilt or larger earthquakes.

This swarm-type seismicity centered on Efate island appears to be distinct from previously recorded seismic activity in several ways. First, the majority of the earthquakes located prior to the Efate swarms were deeper and occurred close to the presumed interplate boundary. The interplate seismicity centered between Efate and the trench is characteristically at depths of 20-30 km. Second, many of the previous earthquake clusters were clearly either foreshock or aftershock sequences. The October-November 1986 swarm, although associated with a larger event, does not appear to be an aftershock sequence of the October 25 event as there is no evidence of a migration of events either spatially or temporally between the large event and the swarm.

A number of larger (M_s > 5.5) and well-located earthquakes have occurred in the immediate area, and four of these have occurred after the advent of the local network and the deformation monitoring program. None, except for the October 1986 event, are associated with any shallow seismicity or tilt.

DISCUSSION

Relationship of tilt and seismicity. The tilt and seismicity were very closely related in both direction and time (Figures 11 and 12). Figure 11 shows that the direction of the tilt vector as measured by the leveling array and the long tube tiltmeter agrees well with the direction of the seismicity. The reason for the difference in magnitude between the deformation measured by the two instruments is not as clear. One possibility is that a cumulative 10 µrad tilt did occur between April and November 1986 but was masked in the long tube data by the long-term drift. Since the discrepancy between the measured deformation is not much larger than the sum of the standard deviation of both instruments, it may also be explained in a large part by instrumental error.

The precise timing between the two events is shown by Figure 12. Interestingly, the deformation is not precisely contemporaneous with the swarm. The tilt and cumulative moment curves are quite similar in shape, but the tilt curve appears delayed by 2 or 3 days relative to the peak earthquake activity. The similarities in the time scale and waveform do suggest an intimate connection between the two phenomena.

The delay indicates that the tilt may not be due solely to seismic deformation. A rough, first-order calculation of the

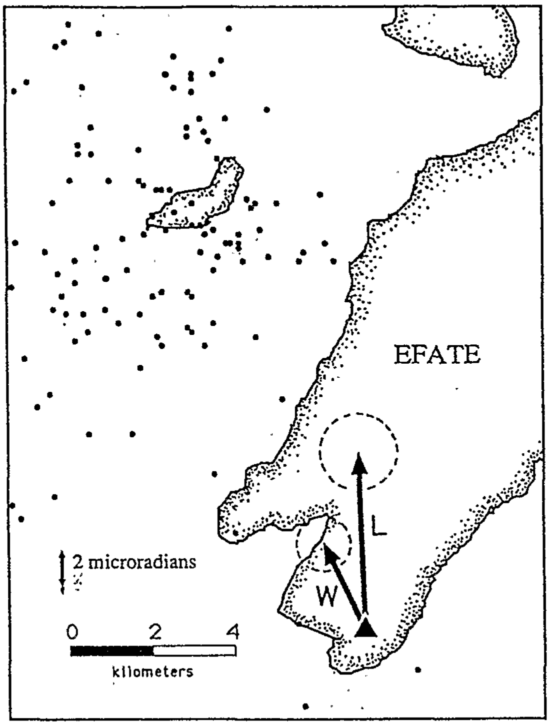

Fig. 11. Comparison of the tilt vectors showing direction of ground uplift as measured by the leveling array (L) from April to November 1986 and by the long tube water tiltmeter (W) from October 31 to November 5, 1986. Circles indicate the approximate range of the standard deviation of the measurements. The triangle marks the location of the tiltmeter instruments and earthquakes occurring between October 30 and November 5 are marked by small solid circles.

expected surface deformation from the swarm agrees with this observation. The total moment release of the swarm is about 1.32×10^{23} dyn cm, and if the rupture is modeled as occurring on a circular fault, the area of faulting can be calculated using the relationships

$$M_0 = \mu S D$$

and

$$\Delta s = \frac{7\pi\mu D}{16 a}$$

where M_0 is the moment, μ is the shear modulus, D is the average slip, a is the radius, and Δs is the stress drop [*Kanamori and Anderson,* 1975]. A shear modulus of 3×10^{11} dyn/cm^2 was used, and the calculations were made using stress drops of 10 and 100 bars. These parameters resulted in a fault varying in size from 2 km^2 with a slip of 18 cm (at 100 bars) to a fault 10 km^2 in size with 4 cm slip (at 10 bars). From these parameters, the surface deformation can be calculated by the method of *Savage and Hastie* [1966]. The faulting was modeled as a dislocation in an elastic half-space at a depth of 10 km. The depth was taken from the median depth of the larger earthquakes in the swarm. The dislocation was assumed to be centered in the swarm region, and the dip and fault dimensions were varied in order to maximize tilt at a point 12 km away (the distance from the center of the swarm to the instruments at Devil's Point). Using these parameters, the maximum modelled tilt was < 1 µrad and therefore insufficient to explain the observed 5 µrad tilt at Devil's Point. Nor were any of the larger earthquakes located significantly closer to Devil's Point than the swarm. Although these calculations are only a rough approximation, it appears that only a fraction of the deformation can be attributed directly to the seismic swarm.

Cause of tilt and seismicity. We believe that the most likely explanation appears to be a magmatic intrusion, possibly triggered by the October 25 interplate earthquake. An alternate explanation would be a largely aseismic creep event related to interplate slip following the earlier thrust event.

Several lines of evidence support a magmatic origin. First, the seismicity is typical of that associated with volcanic activity. Volcanic swarms usually lack a single definite main shock and often exhibit a symmetric temporal histogram [*Hill,* 1977; *Savage and Cockerham,* 1984]. This matches the characteristics

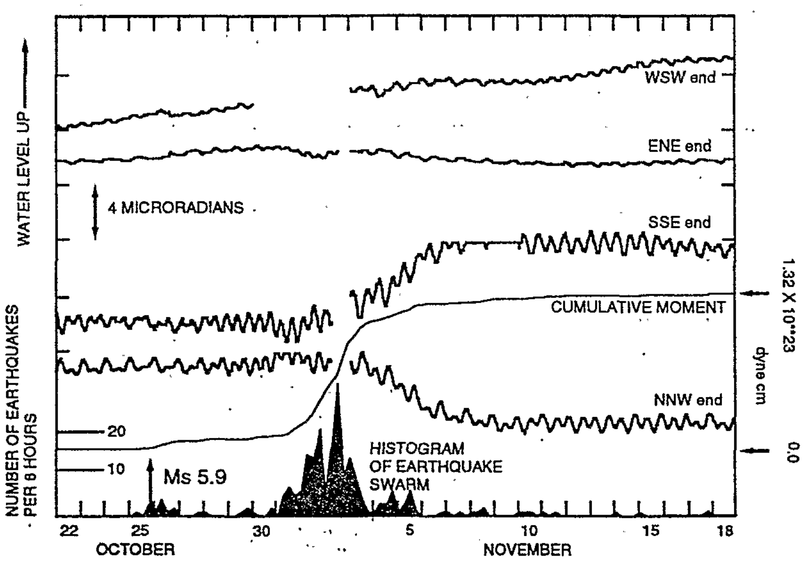

Fig. 12. Short-term record of long tube tiltmeter. Relative water level in both components of the long tube water tiltmeter over the time of the October 25 earthquake and the shallow swarm. The gaps in the data are due to the analog recorder running out of paper. No offset occurs during these periods. The shaded curve is a histogram of the number of earthquakes per 6 hours in the area of the swarm. The cumulative moment curve measures the summed moment of the swarm earthquakes but does not include the October 25 M_S 5.9 earthquake.

of the three Efate swarms, as none had any single larger shock and all displayed a sharp rise and decline in rate of seismicity over time. The pattern of repeated swarms in November 1986, November 1987, and July 1988 is also typical of seismicity in volcanic regions. Swarms and deformation have been observed in other clearly volcanic areas, notably at Long Valley Caldera [*Savage and Cockerham*, 1984], the Taupo volcanic zone in New Zealand [*Grindley and Hull*, 1986; *Otway*, 1986], and Campi Flegrei in Italy [*DeNatale et al.*, 1987]. The timing and duration of the swarm and tilt closely resemble those observed by *Shimada et al.* [1990] on the Izu peninsula in Japan near Teishi volcano. The lack of any observed harmonic tremor could possibly be explained by the distance of the stations and depth of the intrusion. The largely aseismic deformation following the peak of the seismicity has been noted in other volcanic areas and can be explained by dike inflation after the initial seismogenic crack propagation [*Rubin and Pollard*, 1988; *Jachens and Roberts*, 1985]. Although seismicity in volcanic regions is generally characterized by strike-slip or normal faulting, thrust focal mechanisms have been observed in other volcanic regions [*Savage and Cockerham*, 1984] so the thrust type focal mechanism does not necessarily refute a volcanic origin. Finally, a volcanic origin is consistent with the geology of the area. An extensive late Pleistocene-Recent volcanic complex is present on the the island of Nguna 40 km to the northeast of the swarm area. Fumaroles and hot springs occur on the coast of Efate opposite Nguna, and several hot springs are scattered over the rest of Efate.

A simple test of this idea was made using the approach of *Mogi* [1958], which assumes inflation of a spherical source in an elastic half-space. Although other geometries are clearly possible [*Dieterich and Decker*, 1975; *Larsen et al.*, 1986], the distribution of the seismicity tends to support a relatively compact source. Provided that the magma chamber has a radius that is small compared to its depth then the surface uplift and tilt fields are completely characterized by the depth of the chamber and the amplitude of surface uplift directly above the chamber. (This last quantity is simply related to the product of the chamber's volume and the hydrostatic pressure change responsible for its inflation). We find that if the chamber had a depth of 10 km and was located in the vicinity of the earthqauke swarm, then an inflation of 13 cm directly above the chamber would produce a 5 μrad tilt at Devils Point. Since maximum uplifts of this magnitude are believed to be fairly common just before and during volcanic eruptions (this uplift is more than an order of magnitude smaller than the better constrained uplifts seen in Hawaii, Rabaul, and Campi Flegrei), we conclude that a magmatic intrusion is a viable explanation of the observed tilt.

The relationship between a possible intrusion and the initial interplate earthquake is not as clear. The interplate boundary is about 50 km deep at the location of the swarm, which is unusually shallow. Normally, magmatism is at least about 100 km above the descending plate [*Gill*, 1981] but the steep dip of the subducting plate in the New Hebrides places the 100 km deep contour of the descending plate under the east side of the island. *Thatcher and Savage* [1982] suggested that several large interplate eathquakes were triggered by increased stress due to an inflating magma body on the Izu peninsula, and it may be possible that decreased stress after an earthquake may have triggered the intrusive activity. A number of other studies have attempted to relate deeper seismicity and volcanism, but few definite links between subduction zone seismicity and volcanic activity have been conclusively established [*Acharya*, 1987; *Carr*, 1983].

An alternative explanation of the tilt and seismicity is that they may be the result of processes related to subduction, possibly a creep episode at the interplate boundary associated with upper plate deformation following the October 25 earthquake. The close timing between the earthquake and the swarm supports this hypothesis, and the thrust-type focal mechanism of the swarm earthquake appears to be more consistent with this explanation. Both *Chatelain et al.* [1986] and *Taylor et al.* [1990] suggest that a portion of the interplate movement in the Central New Hebrides arc may be accommodated by aseismic slip. Modeling (using the method of *Savage and Hastie*, [1966] as before, with a stress drop of 20 bars) indicates that a large amount of interplate slip (at least equivalent to a magnitude 6.0 earthquake) in addition to the upper plate deformation attributed to the swarm would be necessary to produce the observed tilt. This amount of interplate slip seems large. Therefore, a significant amount of aseismic deformation would be required in the upper plate as well, simultaneous with the swarm. Significant coseismic deformation exceeding that calculated from the seismic moment (by about 25%) has been reported elsewhere [*Wyatt*, 1988], but a much greater difference would be required here. Therefore, an aseismic slip event seems unlikely, but possible.

Conclusion. A correlated tilt and seismicity episode was observed on Efate island in the central New Hebrides island arc in October and November 1986 six days after a magnitude 5.9 interplate earthquake. The swarm consisted of nearly 200 small earthquakes centered well within the upper plate. Simultaneous with the swarm a 5 μrad tilt was recorded 12 km away from the center of the swarm. The episode took place over a period of several days and was recorded by three different tiltmeters and the local network of seismometers. Since November 1986, two similar shallow swarms have occurred on Efate Island but with no observed tilt. The amount of measured deformation exceeds that generated seismically which indicates that much of the deformation was aseismic. The most likely cause of the tilt and seismicity is a magmatic intrusion, but it may have been caused by an episode of aseismic creep following the larger earthquake. Simple modeling supports the intrusion hypotheses.

APPENDIX: PROCESSING OF THE TILTMETER DATA

Long tube water tiltmeter data. The long tube water tiltmeter data is recorded on Efate on a Rustrak & Esterline Angus strip chart recorder. These charts record the change in water level over time as a continuous line along the charts. The position of the line relative to the center of the strip is directly proportional to the vertical movement of the water surface. Each chart usually consists of a approximately a month of data and has the local time marked on them at approximately two week intervals. The data is recorded in two ways, one as time compressed broad band (DC to 5 s) and the other as non-compressed band pass filtered (5 s to 1000 s). The broadband charts are then combined onto large 70 mm film spools which usually consist of three months of data. Because the data are in analog form, and the paper strips are several meters long, the data are processed to produce a digital and time compressed unity gain analog record to allow more manageable manipulation and analysis. In contrast to the usual digitizing procedure, where a pointer is moved along the data trace, this device scrolls the strip of paper past a pointer.

Two channels are recorded, one for the tilt signal and one for time marks and the nearby earthquake signals. Sampling is done at 15 hertz on the paper record, a rate which oversamples most tilts observable on the record but allows precise location of earthquake signals.

The digital records are then in a form suitable for further processing. The major task is to make the time base constant. The motors operating the recorders on Efate run off batteries which lose power gradually over time. This causes the recorders to operate at varying speeds. Since the batteries do not lose power equally, the amount of paper used by the different components varies considerably (up to 30%) which affects the actual real time between each digitized sample point of the tilt signal. The transformation to a set time base was performed by multiplying discrete segments (usually a few days) of the data by a constant. This constant was determined separately for each segment by using all available time data, including the time marks, earthquake signals, and tidal fluctuations. After converting to a fixed time base, the signals were calibrated to a constant vertical scale using the data from a calibration on September 18, 1986. The calibration involved adding a liter of water to each component and noting the amount of change measured by each instrument, an amount that varyed slightly due to differing instrument sensitivity. These calibration offsets were removed from the record, as were offsets due to re-centering of the instruments, in order to enhance the visibility of any tilt signal. A running average with a window of several hours was taken over the long term NNW-SSE component to remove the daily tidal fluctuations as they obscured the longer period changes.

Borehole bubble level tiltmeters. The data from the biaxial borehole bubble level tiltmeters is band pass filtered, amplified, and time compressed and then recorded with the time base enhanced on two Rustrak strip chart recorders. The compressed version of the Devils' Point record was digitized on a digitizing table and plotted versus time. Rainfall is also recorded on the strip of paper.

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