MEASUREMENTS OF TILT IN THE NEW HEBRIDES ISLAND ARC

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INTRODUCTION

The New Hebrides island arc, part of a seismically active zone of lithosphere subduction, has several features which make it an attractive area to "catch" a large earthquake. The shallow seismicity associated with the boundary between the convergent plates is characterized by the frequent occurrence of clusters of moderately large earthquakes rather than by the infrequent occurrence of great earthquakes such as in the seismic zones of Chile, the Kuriles, and Kamchatka. In the central New Hebrides, islands accessible to instrumentation are located unusually close to the zone of thrust faulting where the major shallow earthquakes are generated. To take advantage of these and other favorable factors, Cornell University and the French Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM) are working with agencies of the New Hebrides government, the Direction des Ressources Minerales and the Service Topographique, in a program of earthquake studies which includes monitoring tilt in the central region of the New Hebrides.

The New Hebrides is an area where field conditions do not favor sophisticated instrumentation requiring constant and special attention. Thus the bubble-level borehole tiltmeters developed by the U.S. Geological Survey (USGS) and built by Kinemetrics seemed a reasonable choice, although we felt from the beginning that the extremely short baseline of the instrument would be a problem in respect to long term stability. Accordingly, a leveling technique was adapted to cover the long term effects and to measure tilt over a significant baseline. In August 1975 measurements of tilt began with the installation and leveling of two arrays of bench marks. These arrays have dimensions of the order of a kilometer and have been releveled at intervals of approximately 6 months during a nearly three year period. In July and August of 1976 a network of tiltmeters of the borehole, bubble-level type commenced operation and now includes eight stations. The releveling results and the tiltmeter recordings comprise the data discussed in this paper.

So far the central New Hebrides has been remarkably quiet. No earthquakes with magnitudes (mb) greater than 5.4 have occurred within the network, while two events with magnitudes (Ms) of 6.5 and 6.9 occurred about 140 km north and 350 km south of the network, respectively. No clear and unambiguous signals have been associated with the earthquake sources. Co-seismic offsets, changes in slope, and exponentially decaying offsets are observed, but the data suggest that these are effects near the stations of the large amplitude seismic waves. However, the search for possible pre- or post-seismic signals reveal characteristics of the noise levels and sensitivity of the monitoring system. In addition, evidence is found for a tilt signal of marginal significance that may be related to a time-space migration of seismicity in the central region. This signal is produced by the leveling method, but some evidence for it is found in the tiltmeter recordings.

MONITORING TILT IN THE CENTRAL NEW HEBRIDES

Tiltmeter Network

Ten tiltmeters were obtained from Kinemetrics through the USGS in the Spring of 1976. One was eventually found to be defective (the bubble lost its liquid) and eight have been installed in the central New Hebrides. These units have nominal outputs of 40 millivolts per microradian and are recorded with Rustrak strip chart recorders at sensitivities all within 50% of about 2 mm/microradian. Chart speeds are 0.5 in/hr. Beginning in the latter part of 1977 tilt has also been recorded on a second Rustrak recorder operating at chart speeds of 1-2 in/day. Rainfall at the site is also recorded on the slow speed Rustraks.

The locations of the stations were chosen as a compromise among several factors. Necessary conditions included topographic and subsurface characteristics thought to be favorable to instrumental performance and reasonable accessibility. Fortunately, these two factors turn out to be positively correlated in the New Hebrides. The flat coral terraces, the best terrain for tiltmeters, are also favored as locations for coconut plantations, and have thus been cleared and are reasonably accessible. Additional factors in the locations included nearness to the zone of shallow earthquakes, coverage of a large area of the seismic zone to increase the chances of catching an event, and spacing between stations which provide some possibility of correlations among the recordings.

The resulting locations are shown in Figure 1. The relationship of these locations to the main zone of earthquake generation is shown in Figure 2. The islands south of Efate are located too far east of the shallow zone of earthquakes to be useful sites. The Torres Islands, located north of Santo Island and close to the shallow earthquake zone, are relatively inaccessible but are still possible sites for future stations if sufficient logistic support can be managed. The west coast of Santo Island is also difficult logistically.

The stations are located on level and well-drained terrain with a water table well below the three-meter depth of the tiltmeter borehole. Clay-rich soils were avoided, particularly the dense, sticky clays developed in the volcanic ash deposited on the older, high coral terraces. Five of the sites are located on relatively young uplifted coral terraces, two in soil, and one in sand. In the last case (Southwest Bay) the tiltmeter site was built up into a broad circular mound around the tiltmeter enclosure in order to keep the bottom of the borehole casing well above the ground water level. The sites on coral terraces are in semi-consolidated coral material which at some sites could be broken easily with a pickaxe or shovel but at other sites required a jackhammer. This material is generally very well drained and contains no clay. The older terraces at Port Olry and Malapoa are covered with a near-surface layer of clay soil, but the borehole and lower part of the enclosure are completely within the clay free coral material.

The installation procedure is basically similar to that developed by the USGS, but was modified to provide additional protection against moisture. Aged iron pipes with six inch diameters were used to case the holes and were sealed at the bottom and capped at the top to keep moisture away from the tiltmeter tube. Cleaned, sieved and oven-dried coral sand was used to pack the tiltmeter tubes' within the iron pipe casing. The sand was packed by tapping the iron pipe while monitoring the tiltmeter output and mechanically centering the tube for zero outputs on both channels. The iron pipe is itself initially set into the borehole with sandy backfill from the excavation. After completion, one can move about in the enclosure right next to the top of the iron pipe casing without causing more than a few tenths of a microradian disturbance.

The fiberglass enclosure was buried above the cased sand-packed tiltmeter tube as shown in Figure 3. Styrofoam sheet planks cut into circular forms were installed in the enclosure to provide thermal insulation. The fiberglass tops were fitted with rubber gaskets and bolted down to the enclosure to prevent any moisture leakage. Condensation is minimized by placing a styrofoam plank very close to the top of the enclosure. A polyethylene sheet is fitted over the pipe and sealed to it and to the bottom of the fiberglass enclosure to exclude water vapor entering the enclosure from the bottom.

The recording system, housed in a second enclosure, is shown in Figure 4. The records obtained from the tiltmeter stations are summarized in Figure 5. Many of the record gaps were due to problems with the Rustrak recorders. Modifications to the recording system and the addition of a second Rustrak (as shown in Figure 4) has significantly improved the continuity of the recordings obtained.

Tilt Determined By First Order Releveling of Benchmark Arrays

During July-October 1975, two networks of benchmarks were established near the sites where the Devil°s Point and Ratard tiltmeter stations are now operating. These networks are shown in Figure 6. The Devil°s Point tiltmeter was located near but not within the original leveling network. The network was expanded in 1976 to include the tiltmeter by the addition of a small array of four benchmarks installed around the tiltmeter (PD 6-9 in Figure 6). In 1977, three more benchmarks were added to strengthen the array in the north-south direction.

Each benchmark consists of a marine-grade stainless steel rod (3/8" or 1/2" diameter) about 0.5 to 1 m long embedded in a buried concrete pier. The dimensions and shape of the pier vary but occupy a volume of approximately 0.15 cubic meters. Typically, the pier is poured into a hole excavated in semi-consolidated coral deposits. It is then reinforced and is further anchored by rods driven into the ground before the concrete is poured. The stainless steel rod upon which the leveling staff is placed is attached to cross-pieces and embedded in the pier. It has its upper end filed to a smooth rounded surface. The upper end is protected with a plastic pipe and a cap.

The leveling is done by standard first order techniques. Zeiss Ni-1 self-leveling instruments and Wild invar rods with 1 cm gradations and steel rod supports are used. The initial leveling of the Ratard array in 1975 was done with foot plates as turning points, but all subsequent levelings of both arrays were done with permanently installed turning points. These are galvanized pipes driven into the ground or set into concrete on rocky terrain. The permanent turning points significantly reduce closure errors and increase the speed and ease of the leveling work. The leveling of an array takes about three to four days. Since 1975 each array has been leveled 6 times, with intervals between levelings varying between about 1 to 11 months. Since 1976 the intervals have been between 5 and 8 months.

Both the Devil°s Point and Ratard arrays include small clusters of three or four benchmarks spaced close enough together to be leveled with one central instrument setup. The spacings between the benchmarks are typically about 70 m. The purpose of the small arrays is to check benchmark stability and to provide a means to determine large tilts very rapidly. As shown in Figure 7a, the relative movements of two benchmarks as determined for two successive levelings, are mostly within the noise levels of the leveling technique. The small Ratard array R-1, 2, and 3 shows a grouping of values between 0.3 and 0.5 mm which are slightly larger than the errors expected from the closures(0.1-0.3mm). For a given pair of benchmarks these movements oscillate between plus and minus values for successive levelings so that little or no net movement has accumulated. These fluctuations are mostly small, however, and do not indicate a serious problem of benchmark stability. The Devil°s Point benchmarks appear to be more stable, especially R 6,7,8 and 9.

The errors in determining movements between the more widely spaced benchmarks of the entire array are indicated by the closures obtained in the double run lines between two benchmarks. The closure is taken as the difference between the relative elevations determined by the forward and backward runs between two benchmarks. Of the closures thus far obtained, 75% are less than 1 mm, 93% less than 2 mm, and all are less than 3 mm. The closures depend on the length of the lines, which vary from about 350 to 900 m. In Figure 7b, a histogram of the closures is given in terms of the equivalent tilt, i.e. the tilt calculated by dividing the closure by the length of the line. This histogram gives an indication that sensitivity of the method could be about 1-2 microradians. Tilt change in time is determined by subtracting the results of successive levelings, which increases the error, and by combining the redundant results of the several lines in a given array to determine two components of tilt, which reduces the error. The determinations of tilt changes described in a later section of this paper indicate that the resolution of the leveling method is close to 1-2 microradians.

TILTMETER PERFORMANCE: ENVIRONMENTAL AND INSTRUMENTAL NOISE

The processing of the Rustrak records includes detailed examination of the original records, digitization of the records at intervals of 1 hour, and computer re-plotting of the data with several different time scales. At the most compressed time scale a low-pass filter is applied to the data to remove tidal oscillations. The filtered plots are then composited into a single record for each component after electronic offsets, etc. are removed. Otherwise, further processing into tilt vectors, derivatives, etc. is avoided. We feel that the interpretations at this stage are best done as close to the original data as possible.

The data is illustrated in plots with several time scales in Figures 8 to 10. These plots show the general character of the data as well as give examples of several types of noise signals that have been identified.

Periodic Noise: Tidal Loading and Diurnal Thermal Oscillations

Signals with tidal periodicities are clearly recorded at Malapoa, Devil°s Point, Lamap, and Ratard, which are all located at distances less than 1 km from the nearest coastline. Tidal signals are barely perceptible or not recorded at Olry, Sarmet, Southwest Bay and Tukutuk. Olry and Sarmet are located at distances of 1.5 to 2 km from the coast. The last two are located on narrow strips of land nearly halfway between two nearby coastlines, and are thus in positions where the loading effect on tilt would tend to cancel out. These facts, in addition to detailed calculations of the loading of the ocean tides at Malapoa and Devil°s Point (Marthelot et al., in preparation), show that the tidal signals observed on the records are probably largely due to the load of the ocean tides as applied within a distance of a kilometer or less of the station. Marthelot et al. show that the effect can be explained by a Boussinesq-type model which is modified to include a low rigidity near-surface layer. Malapoa, located only 100 m from the nearest coast, is most affected by the low-rigidity layer and records a very large tilt of 3.5 microradians per meter of water load (see Figures 9d-e). Devil°s Point, located 700 m from the shore, records only 0.5 microradians per meter of water load(also Figures 9d-e), while the more distant stations from the coast record smaller signals. The estimate of the thickness of the low rigidity layer obtained by Marthelot et al. is 0.5 to 1 km.

These tidal signals are quite useful in monitoring instrument performance and sensitivity. In one case, analysis of the tidal signal led to the detection of an error in instrument polarity. However, at Malapoa the effect is so large that the tilt recorded there may be significantly coupled to variations in sea level and thus to vertical tectonic motions. Data from a tide gauge operating across the bay from the station can be used to separate the tilt from the loading effects. Both instruments record a 25 minute seiche in the bay at about the same amplitudes relative to the tidal signal.

Several of the stations have recorded a strong diurnal oscillation which is inferred to be a thermal effect. At Southwest Bay the effect seems to be a thermoelastic response of the small mound of earth around the tiltmemeter. The oscillations can be significantly reduced by covering the mound and nearby area with coconut fronds. This treatment works well at Southwest Bay, Ratard and Lamap, but has had less success at Sarmet and Tukutuk. The cause of the oscillations at those two stations is not clear. The amplitudes have "spontaneously" decreased to a reasonable level at Sarmet, while Tukutuk has not changed since the inception of recording. Tukutuk is sited in a very level area. It is not clear why there should be a thermoelastic effect there larger than at several of the other stations. The effect continued unchanged after replacement of the tiltmeter electronics and continued to be associated with only one of the components. The oscillation may be due to a very thermally sensitive component within the borehole unit itself.

Rainfall Effects

Rainfall is one of the most important sources of noise on the tiltmeter records. The susceptibility of the tiltmeters to rainfall, however, varies quite remarkably. Devil°s Point shows virtually no effect at all. Other stations, such as Malapoa, Southwest Bay, and Olry, show characteristic signals of up to about 4 microradians associated with the heaviest rainfalls (which can be 10-20 cm within a day) but are not otherwise seriously affected. The signals are exponential-like steps, in the case of Olry and Southwest Bay, and unipolar transient waveforms approximated by the function T*exp(-T/To), in the case of Malapoa. The time constants involved are about one day. Long period effects with time constants of the order of 10 days are also visible at Malapoa, but these are small. At Ratard a long period bay-like disturbance with time constants of the order of 10 days is associated with heavy rainfall. The susceptibility seems to be somewhat worse than the aforementioned stations. The bay-like signals account for much of the character of the filtered record shown in Figure 10b. The worst stations in terms of rainfall effects are Lamap and Sarmet. Both short and long period effects can be large, i.e. tens of microradians. The records have been repeatedly driven offscale and several times the tiltmeter tube itself had to be reset in order to recenter the instrument. However, during relatively dry periods the instruments operate at reasonable noise levels.

The rainfall effects are most likely related to the various factors affecting runoff and percolation of rainwater in the immediate vicinity of the tiltmeter installation, and to possible dilatant effects on clay material. The two worst sites, Lamap and Sarmet, are both sited in brown soil which is not entirely clay free, while at the other sites the iron tube is buried in clay free and fairly well-drained porous coral material (or sand in the case of Southwest Bay). In respect to rainfall, Devil°s Point is the best station and has the most level local topography. It is speculated that the varying responses among the moderate to good stations depends upon heterogeneities in the percolation of rainwater near the installation. The unipolar transient signals may represent a localized loading effect due to temporary concentration of water within the non-uniform porosity of the coral rock, while the steps represent a kind of settling of the iron tube or the surrounding area as a result of the flow of water. This complexity of response could account for the puzzling occurrence of rainfall steps on different components at different times at Olry, as illustrated by the steps during December 1976 and June 1977.

Long Period Noise

Figure 10 shows the tiltmeter data filtered and plotted at the most compressed time scale. Over the 20 month period sampled, the records show an overall drift of as little as several microradians to as much as several tens of microradians in the case of the Devil°s Point ENE component. In some cases the two components show some correlations while in others they do not. The Devil°s Point record, for example, shows a large drift during the first half of the period on the ENE component which does not appear on the other component, while the second half of the record is dominated by a large bay-like excursion apparent on both components. It is interesting that the bay-like excursion with a similar period and phase is observed also on the Malapoa ENE component (see also Figure 11).

The results of releveling the Devil°s Point benchmark array, however, do not show the large excursions indicated by the tiltmeter (see Figure 11). The results from the large array and from the small four point array surrounding the tiltmeter (PD 6,7,8,and 9) both do not yield the large tilt excursions shown by the Devil°s Point tiltmeter. Neither array shows a tilt change greater than about 2 microradians between successive levelings. Thus the large tiltmeter drifts must be instrumental in origin or reflect tilting over dimensions significantly smaller than the 70 meter dimension of the small array surrounding the tiltmeter. An instrumental problem is suggested where there is no correlation between the two components, as in the case of the large drift on Devil°s Point ENE at the end of 1976. Replacement of the electronics and experiments with recording with a resistive network in place of the tiltmeter sensor at Devil°s Point have shown that the large drift of the ENE component is not due to defective components external to the tiltmeter tube. On the other hand, the large bay-like excursion seen during the second half of the Devil°s Point record and also at Malapoa may be a seasonal effect on the sites.

EARTHQUAKES MONITORED BY THE TILTMETERS

The earthquake activity for a period during which the tiltmeters operated is shown in Figure 12. Since the inception of tilt measurements in August 1975, no shallow earthquake with a body-wave magnitude greater than 5.4 has occurred in the central New Hebrides. Three events recorded at Olry, one event at Ratard and two events at Devil°s Point and Malapoa had magnitudes (mb) between 5.0 and 5.4 and were located at (straight-line) distances from the hypocenters to the stations of between 30 and 65 km. In the entire arc, the largest event occurred on August 2, 1976 about 350 km south of the tiltmeter stations on Efate island. This event has a thrust-type focal mechanism, and a magnitude (Ms) of 6.9. On September 4, 1977 a magnitude (Ms) 6.5 event occurred north of Santo island about 140 km from the nearest tiltmeter on Santo (Olry). These events are probably too far away from the tiltmeter stations to produce any strong effects.

Nevertheless, the data are examined for these events as well as the largest of the earthquakes which occurred within the network of observations. The data are plotted with three different time scales in Figures 8-10. The copies of the original records cover periods from minutes to nearly one day (Figure 8). Time-compressed plots of unfiltered data cover periods from several hours to about one month (Figure 9), and plots of filtered data which cover periods from about several days to nearly two years (Figure 10). The leveling data are also plotted with the long time base in Figures 11 and 15.

The tiltmeter data show two characteristic signals which can be clearly associated with the occurrence of earthquakes, or rather with the passage of seismic waves. The first is a simple offset in the trace which has been recorded for both local and more distant regional events. The second type of signal is an exponential recovery following a co-seismic offset. Most of the local events produce an exponentially decaying signal with a time constant appropriate to the overloading of the electronic low-pass filters in the system. However, the larger events sometimes produce a signal with a significantly longer time constant, of the order of 10 minutes, which cannot be explained as an electronic effect (see Figure 8). These signals are quite similar to the "tilt impulses" described by McHugh and Johnston (1977) for the central California tiltmeter network. The New Hebrides results are similar also in respect to the lack of consistency and regularity in the observations. This is illustrated, for example, in Figures 8c-e by the recordings of events by the Devil°s Point and Malapoa tiltmeters. These stations are located only 11 km apart and 55 to 70 km from the sources. A step is recorded by Devil°s Point but not the Malapoa tiltmeter in one case, but in another the reverse is true for an "impulse". These data support the conclusion that the signals are effects of the passage of the large amplitude seismic waves at or near the tiltmeter rather than effects near the source.

Rapid changes in drift rate, seen as corners or kinks in the tiltmeter plots, sometimes occur near the times of local events. The most remarkable case is recorded at Ratard for the large earthquake of September 4, 1977 located 217 km north of the station (see Figure 10b). The coincidence of the change in drift rate and the earthquake is quite close. However, the Olry tiltmeter, located about 77 km closer to event, shows no similar change in drift rate (see Figure 10a). Changes in drift rate can be seen at Ratard for the earthquakes of December 6, 1976 and February 5, 1977 (Figure 9a), but are not evident for local events recorded by Olry (Figures 9b-c). Changes in drift rate are also recorded at Malapoa and Devil°s Point. Both stations record a change in the same sense on the ENE components near the time of the November 9, 1976 event, although the change is small and the timing resolution poor (see Figure 9d). A remarkable change in drift rate on the ENE component of Devil°s Point begins about one day after the October 10, 1976 event (see Figure 10e). This change is correllatable with much smaller but resolvable changes on the SSE component of Devil°s Point as well as on the ENE component of Malapoa (see Figure 10d). In general, the leveling data do not support the large drift rates seen on the Ratard and Devil°s Point tiltmeter records. This evidence, in addition to the lack of correlation between Olry and Ratard for the September 4 event, suggest that the changes in drift rate may again be site or instrumental effects of the large amplitude seismic waves reaching the stations.

Further examination of the records reveals no other signals which can be clearly associated with the earthquakes. The bay-like signals recorded at Ratard that appear to be associated with the earthquakes of December 1976 and February 1977 (see Figure 9a) are probably associated with rainfall. At that time the nearest rain gauge operated 17 km away. However, similar signals have been observed since then which are clearly related to local rainfall as recorded at the site. In general, the search for effects related to the earthquakes has demonstrated to us the absolute necessity for having rainfall recorded continuously at the station along with the tilt.

TILT RECORDED BY RELEVELING: A REAL SIGNAL AT RATARD?

In Figure 13 the releveling results are shown in terms of changes of relative elevations between two benchmarks as a function of time. The tilt change is obtained by dividing the elevation change by the length of the line. Thus each line measures the component of tilt in the direction of the line, and the array can be thought of as a multi-component tiltmeter. This method of presentation remains close to the original data and also yields a plot directly comparable to a tiltmeter recording. Coherence of the "records" of two independent but nearly parallel lines is a good test that a real tilt is being observed. In Figure 13 the lines are grouped accordingly.

The Devil°s Point array shows relative stability, with a suggestion of small drift in the sense of a tilt downwards to the WNW or towards the trench. These results, if not merely errors of measurement, indicate a rate of about one microradian per year. The drift appears on both the lines PD6-PD1 and PD4-PD5. As mentioned above, the leveling results do not substantiate the large excursions exhibited by the tiltmeter.

The Ratard results indicate what appears to be a real tilt signal which is coherent over the dimensions of the array. The signal is marginal in the sense that it is represented by a single releveling. This tilt occurs between the August 1976 and April 1977 relevelings and is approximately recovered in the next interval terminated by the October 1977 releveling. The relationship of the measurements along individual lines to the overall tilt is shown in a simple graphical form in Figure 14.

The dashed lines in Figure 14 give an approximate eyeball fit to the data. In addition, a least squares procedure was used to calculate the tilt. In this calculation the tilt is taken as the slope of a plane which best fits the data on changes in the relative elevations of benchmarks. In double-run levelings of four benchmarks, for example, six lines can be measured and yield 12 data on changes in relative elevations of the six pairs of benchmarks.

For the Ratard array the least squares solutions yield tilt changes with magnitudes of 0.8, 3.5, 3.5 and 0.4 microradians, respectively, for the four successive intervals covered by the relevelings during the period 1975-1977. The same analysis applied to the results from the Devil°s Point array yields magnitudes of tilt all less than 1.5 microradians for all successive intervals. In the case of the October, 1977 to April, 1978 interval, at Ratard, where all 6 lines were measured in both levelings, the 12 data yield an estimate of 3.5 ± 2.9 microradians, where the plus/minus value is the 95% confidence interval. This estimate, in addition to the consistently low magnitudes of tilt for the first and last interval at Ratard aand for all the intervals at Devil°s Point, suggest that the tilt signals illustrated in Figures 13 and 14 represent real tilt signals which are coherent over the dimensions of the Ratard array.

The tilt is 3.5 microradians downward toward the southeast during the first interval, July 1976-April 1977, and then is approximately recovered during the following interval, April 1977-October 1977, with a tilt of 3.5 microradians downward toward the NNW. The tilt directions are approximately parallel to the strike of the island arc and subduction zone.

The tilt determined along one of the lines approximately parallel to the estimated tilt excursion is plotted together with the appropriate tiltmeter component in Figure 15. The average trend of the SSE component of Ratard is approximately linear during two periods: (1) December 1976 to the rainfall signal of April 1977, and (2) May 1977 to the middle of August 1977. If these two trends are extrapolated throughout the period covered by the three levelings in 1976 and 1977, i.e. if the rapid drifts prior to December 1976 and after August 1977 and the rainfall signal of April 1977 are eliminated, then the agreement between the leveling and the tiltmeter data is excellent. This is encouraging, but the tiltmeter data alone would be considerably uncertain.

The pattern of seismicity in the region around the Ratard leveling array reveals an interesting feature possibly related to the tilt event. The seismicity in the New Hebrides is in general characterized by a strong degree of clustering in time and space. The pattern of occurrence near the Ratard array during the three year period is shown in Figure 15. A cluster occurs first in Malekula. After this the two relatively isolated events located close to the Ratard array occur in December 1976 and February 1977. Then in the Spring and Summer of 1977 a cluster occurs in northern Santo. Finally, the large event of September 4, 1977 occurs north of Santo. The tilt excursion inferred from the releveling data could thus be related to the northward progression of seismicity. One can speculate that a propagating stress pulse, perhaps of the type discussed by Elsasser (1969) and others, passed northward along the strike of the arc and produced the tilt excursion.

The small arrays at Ratard apparently do not have the resolution to detect the signal. The closure errors of 0.1-0.2 mm for a given leveling of the small arrays imply a tilt error of 1.4-2.8 microradians. The elevation changes between successive levelings are somewhat larger than this, as discussed in a previous section, (see Figure 7a), and yield tilt changes with magnitudes up to 5-6 microradians. However, the tilts do not agree with those determined for the larger array either in magnitude or direction. Although these results could be interpreted as an indication of small wavelength irregularities in the tilt field, it is more likely that larger tilts determined by the small arrays arise from errors in measurements or small movements of the benchmarks. All that is required to produce tilts of observed amounts is an additional few tenths of a millimeter above that indicated by the closures.

The data indicate that the resolution of the large arrays approaches 1-2 microradians, while that of the small triangular arrays of Ratard and the one at Devil°s Point is probably not better than about 5 microradians. The small four-point array around the Devil°s Point tiltmeter, however, seems quite stable and has a resolution approaching that of the larger arrays.

CONCLUSIONS

The bubble-level borehole tiltmeters are relatively noisy instruments which appear best adapted to monitor in the short period part of the spectrum of transient deformations. As illustrated by the original records, the noise levels are small in the range of periods between minutes and hours, and the sensitivity in this range can approach 0.1 microradians. Rainfall signals are an important source of noise at periods of hours to weeks, but the rainfall transients are fairly easy to identify. However, rainfall must be monitored at the site. At periods of days to weeks, the sensitivity is probably of the order of a microradian at the better stations where rainfall effects are not too serious and are carefully monitored. At longer periods the sensitivity decreases to probably the order of 10 microradians although certain components of certain stations may have significantly better sensitivity. In general, as period increases the performance of the instrument is degraded by long period effects of rainfall, instrumental noise, and possibly other effects in the siting (which are poorly understood), in addition to the problems of maintaining an accurate baseline for the complex electronic recording system over a long period of time. In contrast, with the leveling technique a sensitivity of the order of a microradian is preserved at long periods. In retrospect, the leveling system has provided the best data on tilt so far in the New Hebrides.

Although the leveling method could be applied at weekly intervals, for example, practical considerations limit it to longer intervals. More frequent levelings will be made temporarily after a large earthquake. Nevertheless, there is a gap in the measurements provided by the tiltmeters and the leveling. The gap includes approximately the range of periods between days and months in which the tiltmeter records show increasing noise but which is too short to be easily covered by the leveling method. We think that the best way to cover this gap is with a long-baseline liquid level tiltmeter. This type of instrument is simple and in our opinion has the best chance to achieve long term stability and sensitivity. We are now installing a system of about 100 meters length near the Devil°s Point site. The terrain is flat enough to use a half filled, buried tube (Beavan and Bilham, 1977), so that thermal problems will be minimized. A simple sensing technique will be used to obtain a sensitivity of 0.1 microradians.

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FIGURE CAPTIONS

Figure 1. Presently operating network in the New Hebrides. Most of the seismograph stations shown were parts of temporary networks operated for periods of 1-2 months. The heavy line with filled triangles shows the trace of the zone of thrust fault contact between the subducted oceanic plate to the west and the island arc, as inferred from seismic studies.

Figure 2. Vertical cross section through New Hebrides Subduction Zone showing locations of tiltmeter stations. The dotted area shows the most active zone of thrust type earthquakes along the convergent plate boundary.

Figure 3. Tiltmeter installation.

Figure 4. Tiltmeter recording system in use now. The digital recorder is still under development. The original system included only Rustrak B.

Figure 5. Tiltmeter records obtained and analyzed for this paper. The stations have continued to produce records through to the present. The gaps in records are due mainly to recording problems, primarily paper jams or records running out.

Figure 6. Map view of Devil°s Point and Ratard bench mark arrays. The elevation variations within the arrays vary from tens of centimeters to about 5 meters. See Figure 1 for the locations of these arrays in the New Hebrides. Both are located on young coral terraces.

Figure 7a. Histograms of changes in relative elevations between pairs of bench marks within the small arrays in the Ratard and Devil°s Point arrays. These are changes between successive relevelings.

Figure 7b. Histogram of closure errors expressed in terms of microradians of tilt. These data are for the long lines within the Ratard and Devil°s Point arrays.

Figure 8a. Ratard tiltmeter records for two earthquakes. The distances given are straight line distances between hypocenter and station. The vertical lines indicate half hour intervals. The vertical scale for this and following records is close to about 2 Rustrak units/microradian or 25 microradians full scale. Top: Dec. 6, 1976, depth=29 km, distance=38 km, mb=4.8. Bottom: Feb. 5, 1977, depth=39 km, distance=34 km, mb=5.2, Ms=4.6. In this figure, the solid trace is the ENE component (down on the record equals tilt downward to the ENE) and the dashed component is the SSE component (down on the record equals tilt downward to the SSE).

Figure 8b. Olry records of three earthquakes. Top: May 21, 1977, depth=35 km, distance=46 km, mb=5.2, Ms=4.6. Middle: June 18, 1977, depth=37 km, distance=51 km, mb=5.4, Ms=4.8. Bottom: Aug. 25, 1977, depth=35 km, distance=40 km, mb=5.1. The signal about 7 to 4 hours before the June 18 event is seen at other times without earthquakes and is probably an effect of rainfall. In Figures 8b-8e, the solid trace is the ENE component (up on the record equals tilt downwards to the ENE) and the dashed trace is the SSE component (up on the record equals tilt downward to the SSE). This applies to all records except Ratard which has the opposite polarity.

Figure 8c. Devils°s Point records for four earthquakes. The same earthquakes as recorded by Malapoa are shown in Figure 8d. Top: Oct. 10, 1976, depth=22 km, distance=63 km, mb=4.8. Upper Middle: Nov. 9, 1976, depth=32 km, distance=55 km, mb=5.0. Lower Middle: Dec. 14, 1976, depth=68 km, distance=68 km, mb=4.9. Bottom: May 16, 1977, depth=30 km, distance=54 km, mb=5.1, Ms=5.3.

Figure 8d. Malapoa records for the same four earthquakes as shown for Devil°s Point in Figure 8c. Note the large exponentially decaying signal following the Dec. 14 event. Top: Oct. 10, 1976, depth=22 km, distance=70 km, mb=4.8. Upper Middle: Nov. 9, 1976, depth=32 km, distance=55 km, mb=5.0. Lower Middle: Dec. 14, 1976, depth=68 km, distance=70 km, mb=4.9. Bottom: May 16, 1977, depth=30 km, distance=61 km, mb=5.1, Ms=5.3.

Figure 8e. Large regional earthquakes (both shallow depth) as recorded by the nearest stations. The upper two records at Devil°s Point and Malapoa show the Aug. 2, 1976 (Ms=7.0) event located south of Efate Island and the lower two for Olry and Ratard show the Sept. 4, 1977 (mb=6.0, Ms=6.5) event located north of Santo Island. Top: Devil°s Point, Aug. 2, 1976, distance=350 km. Upper Middle: Malapoa, Aug. 2, 1976, distance=350 km. Lower Middle: Olry, Sept. 4, 1976, distance=150 km. Bottom: Ratard, Sept. 4, 1976, distance=215 km.

Figure 9a. In this and in Figures 9b through 9e the tiltmeter data are unfiltered and plotted on the same time scale. The plots are made from hourly digitizations. The rainfall data, given in daily totals, are taken from a rain gauge located 17 km from the Ratard tiltmeter. In Figures 9 and 10 the distance is the straight line distance between the hypocenter and the station.

Figure 9b. Olry records for earthquakes in the Spring of 1977. The large offsets occurring at the end of March in the upper plot are the effects of a magnitude (mb) 5.7 intermediate-depth earthquake (depth=109 km) located northeast of Santo. The rainfall data are obtained from a Catholic Mission located about 3 km from the station.

Figure 9c. Ratard and Olry records for the large Sept. 4, 1977 event located north of Santo (see also Figure 8e). Again rainfall data are taken from a gauge located 17 km from the tiltmeter. The large offsets associated with the Sept. 4 event are removed but the amount of offset is noted in the figure.

Figure 9d. Devil°s Point and Malapoa records for an event in Nov. 1976. A small rainfall transient is illustrated on the left side of the Malapoa records. The rain data for both plots are taken from the Port Vila rain gauge located about 2 km from Malapoa and about 13 km from Devil°s Point.

Figure 9e. Devil°s Point and Malapoa records for the May 16, 1977 event. The downturning of the Malapoa traces following the earthquake is believed to be due to failure of the lead-acid storage batteries being used at the station prior to the Summer of 1977. The rainfall data are from the same source as described for Figure 9d.

Figure 10a. This and Figures 10b-10f are all plotted on the same time scale. The data have been filtered by taking a running 12 hour average of the hourly digitizations of the Rustrak records. Note the step-like transients associated with rainfall in January and June of 1977. The baseline was preserved through the gap in recording in Oct.-Dec. 1977. Rainfall data are taken from a gauge at a distance of about 3 km from the station. The data are given as daily totals in mm according to the scale on the lower left hand side of the figure.

Figure 10b. Filtered data for the Ratard station. Rainfall data are taken from a gauge located 17 km from the station, and are given as daily totals in mm, as indicated by the scale on the lower left hand side of the figure. No rain data are available for March and April 1978.

Figure 10c. Filtered data for Southwest Bay. The rainfall data are taken from the nearest raingauge located at Lamap, a distance of 40 km on the other side of the island. Hence the correlations are very uncertain. The step-like transient in June 1977 associated with the heavy rainfall at Lamap is confirmed by later rainfall data recorded at the Southwest Bay site.

Figure 10d. Filtered data for Malapoa. The rain data are taken from the raingauge in Port Vila located 2 km away from the station.

Figure 10e. Filtered data from Devil°s Point. The rainfall data are taken from Port Vila, 13 km from the station. The baseline was not lost through the gap in records during February-April 1977. The dotted segment there is shown to identify the traces on the left of the gap.

Figure 10f. Filtered data from the station at Tukutuk. The station commenced operation in late September 1977. The large oscillations on the SSE component accompany a large diurnal signal of unknown origin. Rainfall data from Port Vila.

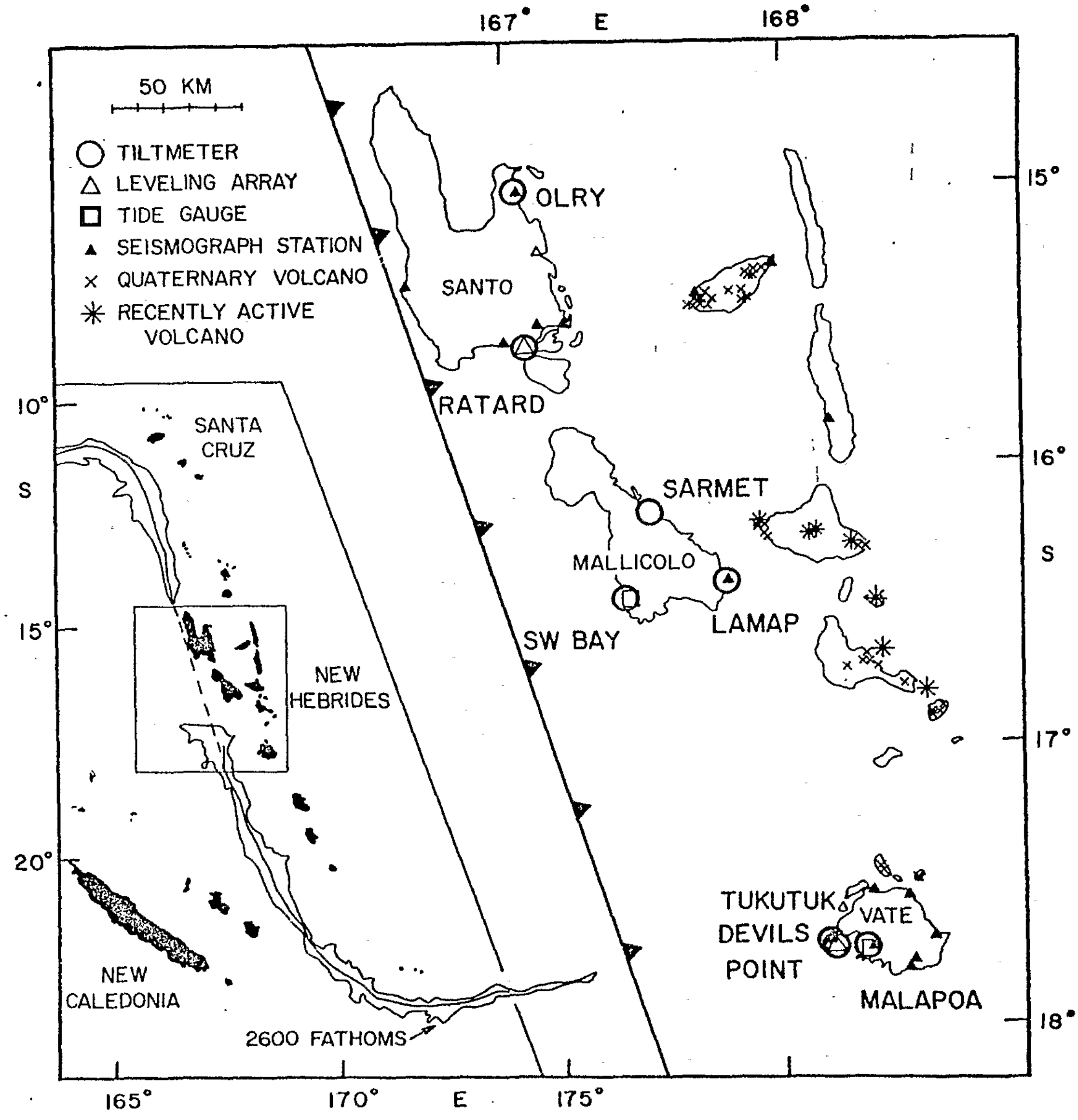
Figure 11. Comparison of leveling data at Devil°s Point and tiltmeter data. See Figure 6 for locations of observations. The leveling results are shown with the same scale of tilt as for the tiltmeters. See Figure 13.

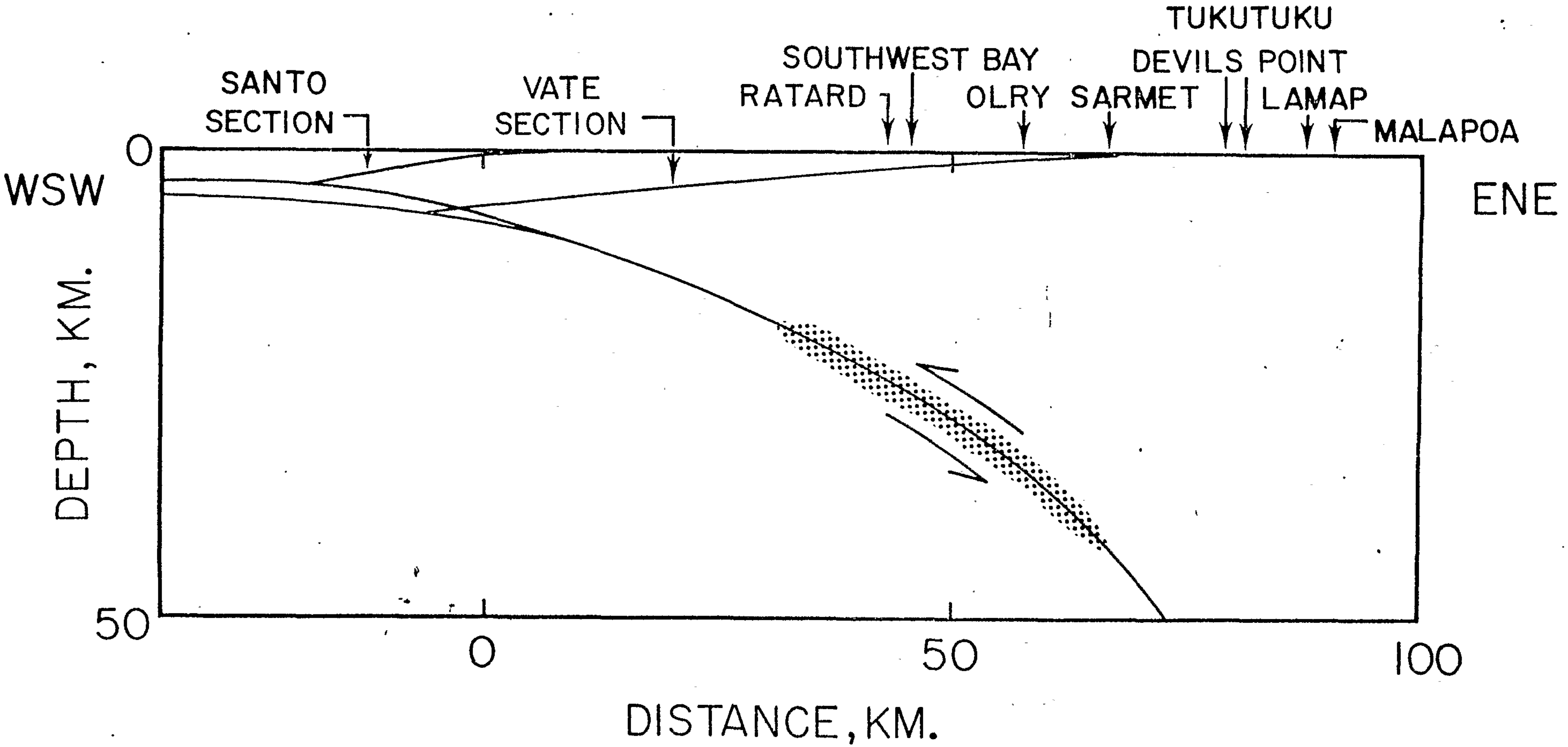
Figure 12. Earthquakes located by the PDE for the period August 1976 - December 1977. The tiltmeter stations are shown by triangles and are identified in Figure 1. Only shallow earthquakes are shown.

Figure 13. Leveling results summarized for each pair of bench marks in the Santo and Efate arrays. The locations of the bench marks are shown in Figure 6. Circles are unadjusted values (average of foreward and backward runs) and triangles are adjusted values.

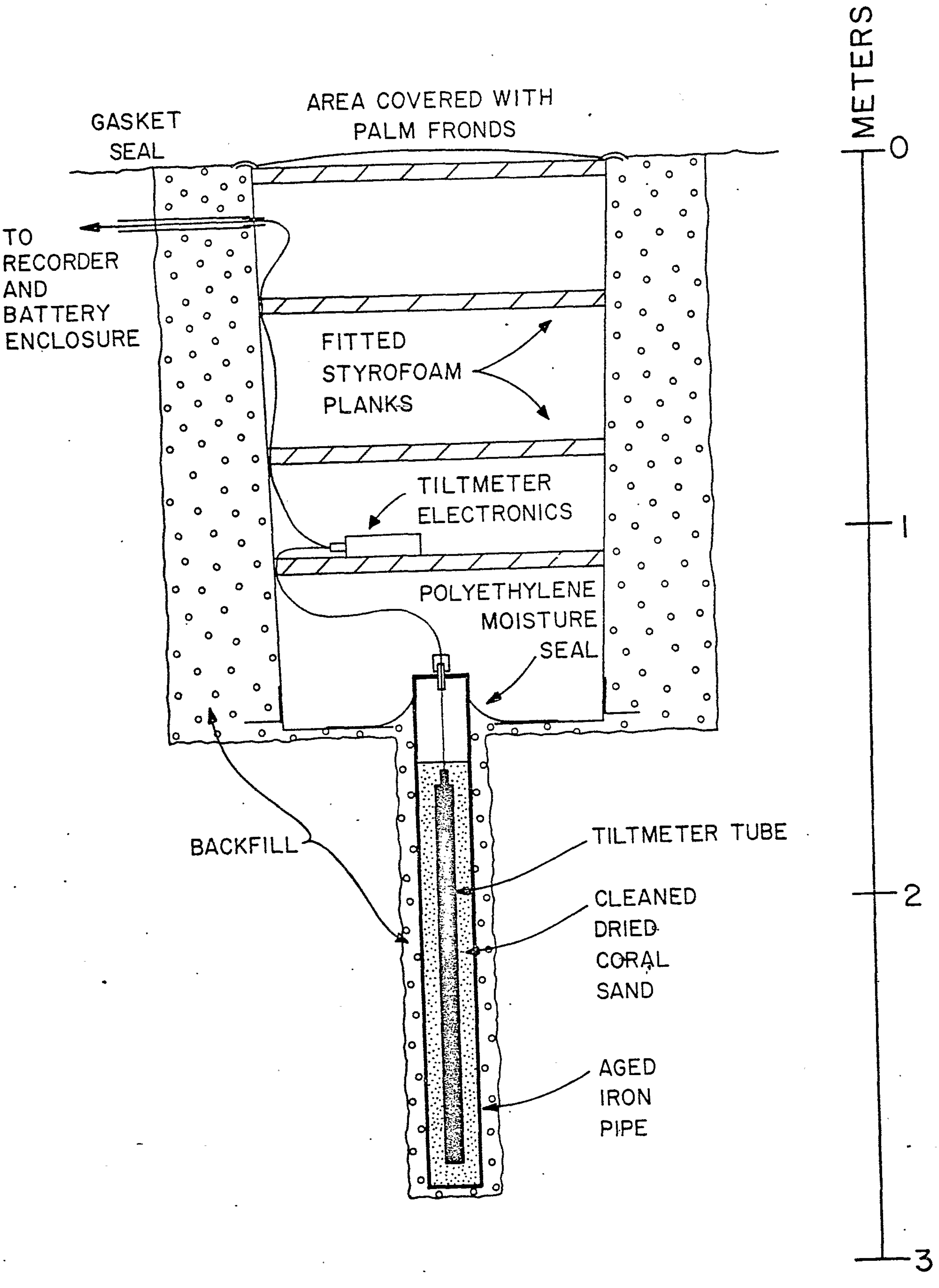
Figure 14. Tilt change along lines between two bench marks plotted as a function of azimuth of the line. The intervals over which the tilt change is computed are shown in the figure. The dashed line is the variation in tilt if the tilt is uniform and coherent over the array, and is a graphical fit to the data. The estimated tilt is 4 microradians along the azimuth of the maximum of the dashed line, or about southwest and northeast, respectively.

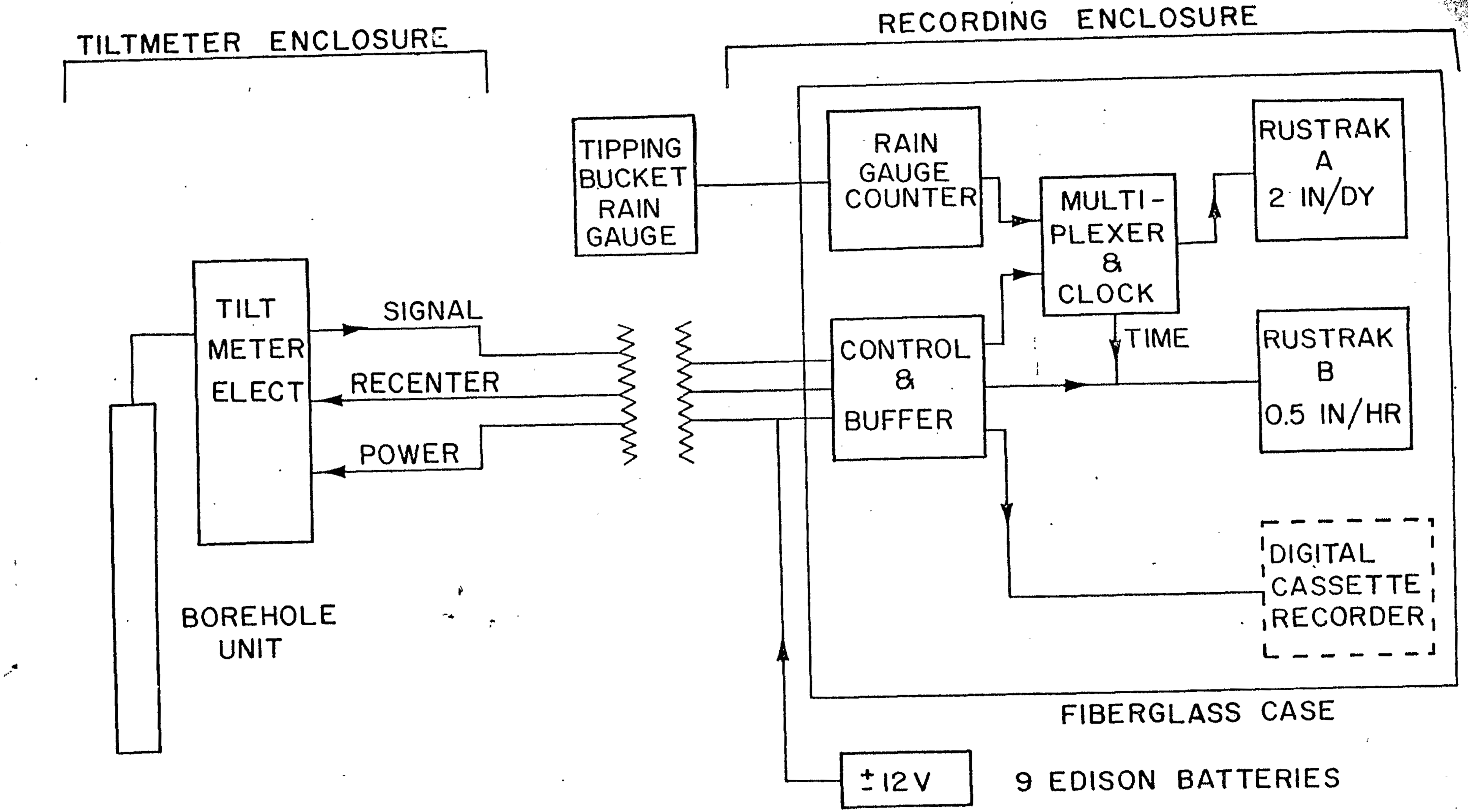
Figure 15. Comparison of leveling data and tiltmeter data for Ratard, as in Figure 11. See also Figures 6 and 13. The seismicity data is taken from the listing of the PDE for the period concerned, and the areas covered shown in the figure.

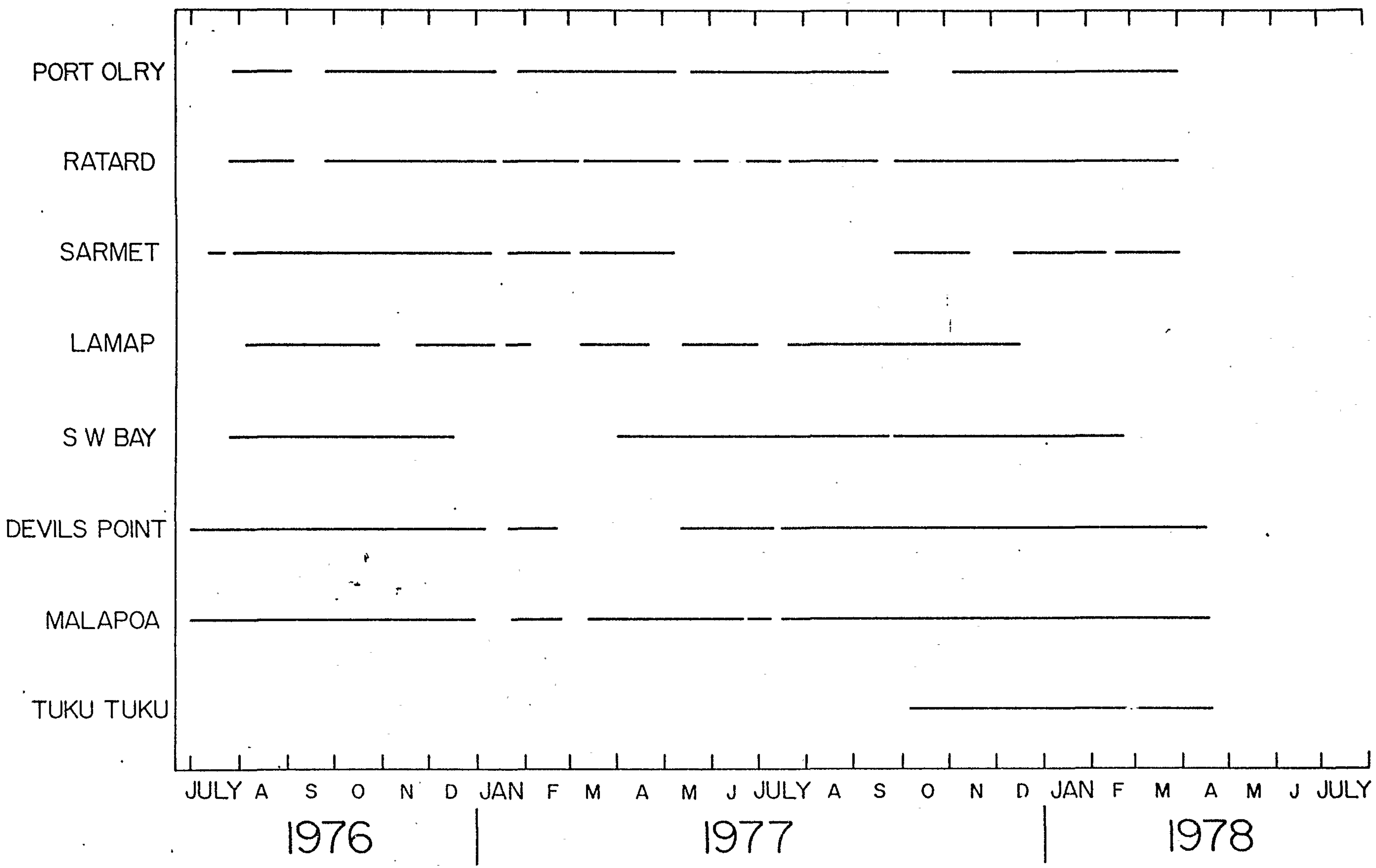

167°
E
168°
50 KM
TILTMETER
LEVELING ARRAY
TIDE GAUGE
SEISMOGRAPH STATION
QUATERNARY VOLCANO
RECENTLY ACTIVE VOLCANO
15°
OLRY
SANTO
RATARD
10°
S
SANTA CRUZ
16°
SARMET
MALLICOLO
LAMAP
S
SW BAY
15°
NEW HEBRIDES
17°
20°
TUKUTUK
VATE
DEVILS POINT
NEW CALEDONIA
MALAPOA
18°
2600 FATHOMS
165°
170°
E
175°

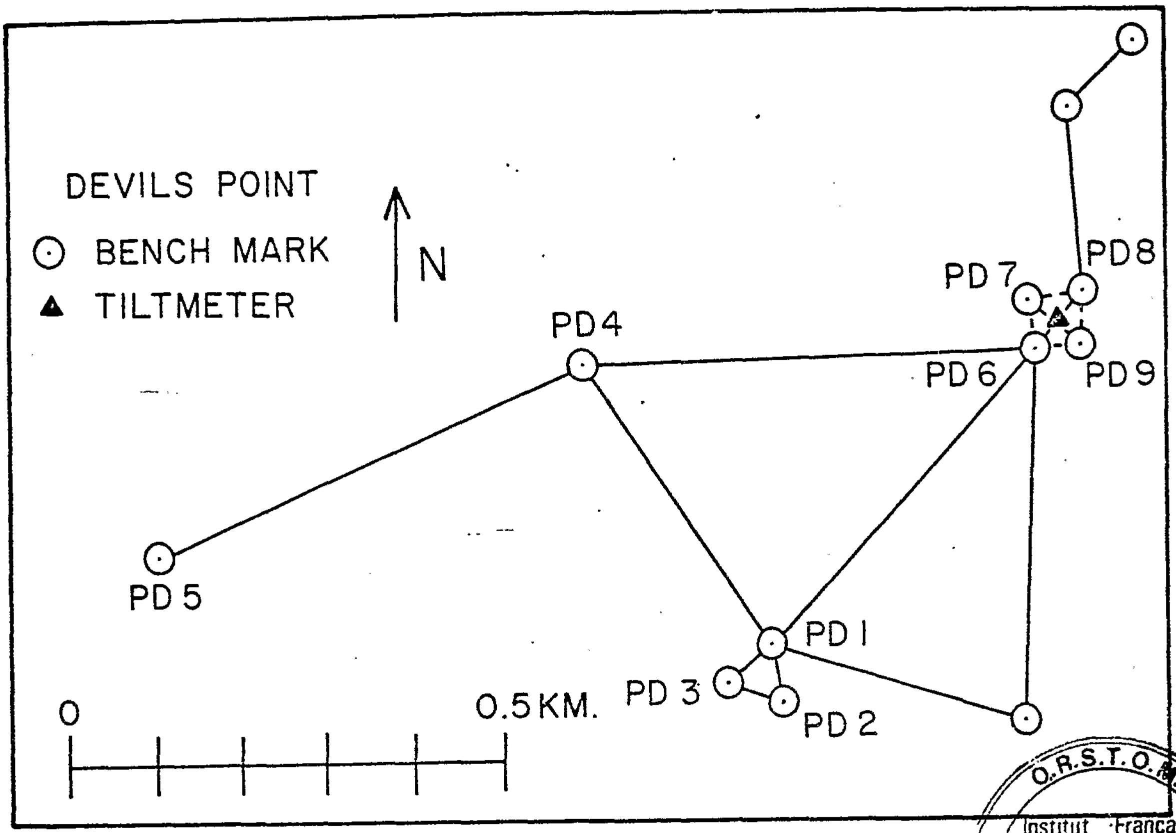


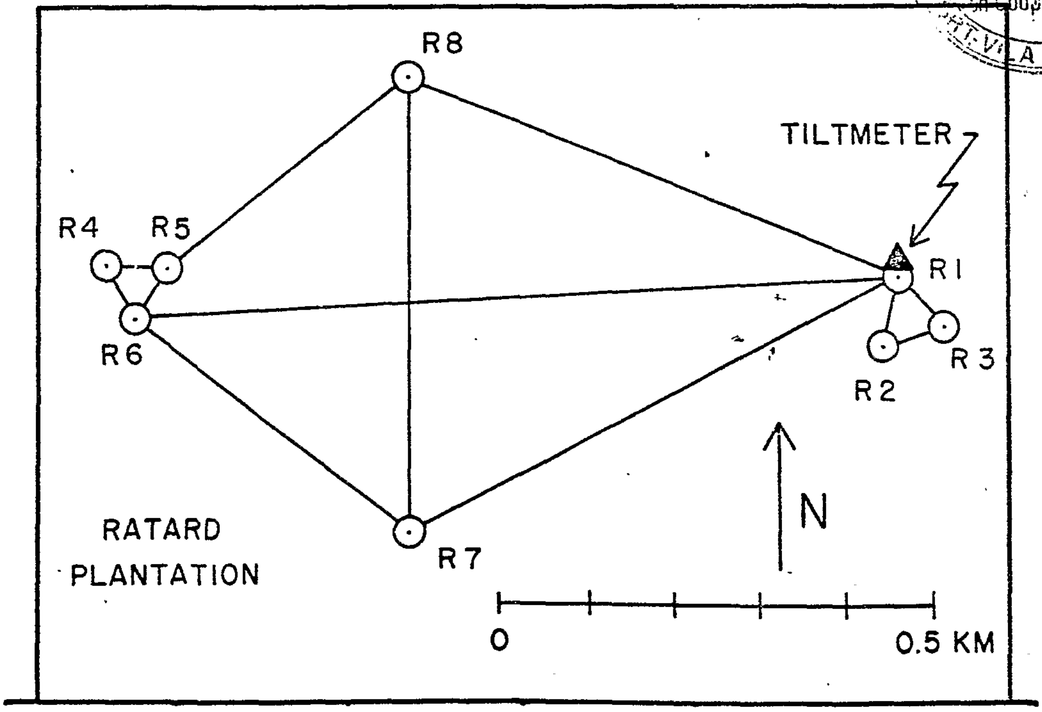
SANTO SECTION
VATE SECTION
RATARD
SOUTHWEST BAY
OLRY
SARMET
TUKUTUKU
DEVILS POINT
LAMAP
MALAPOA
WSW
ENE
0
50
DEPTH, KM.
0
50
100
DISTANCE, KM.

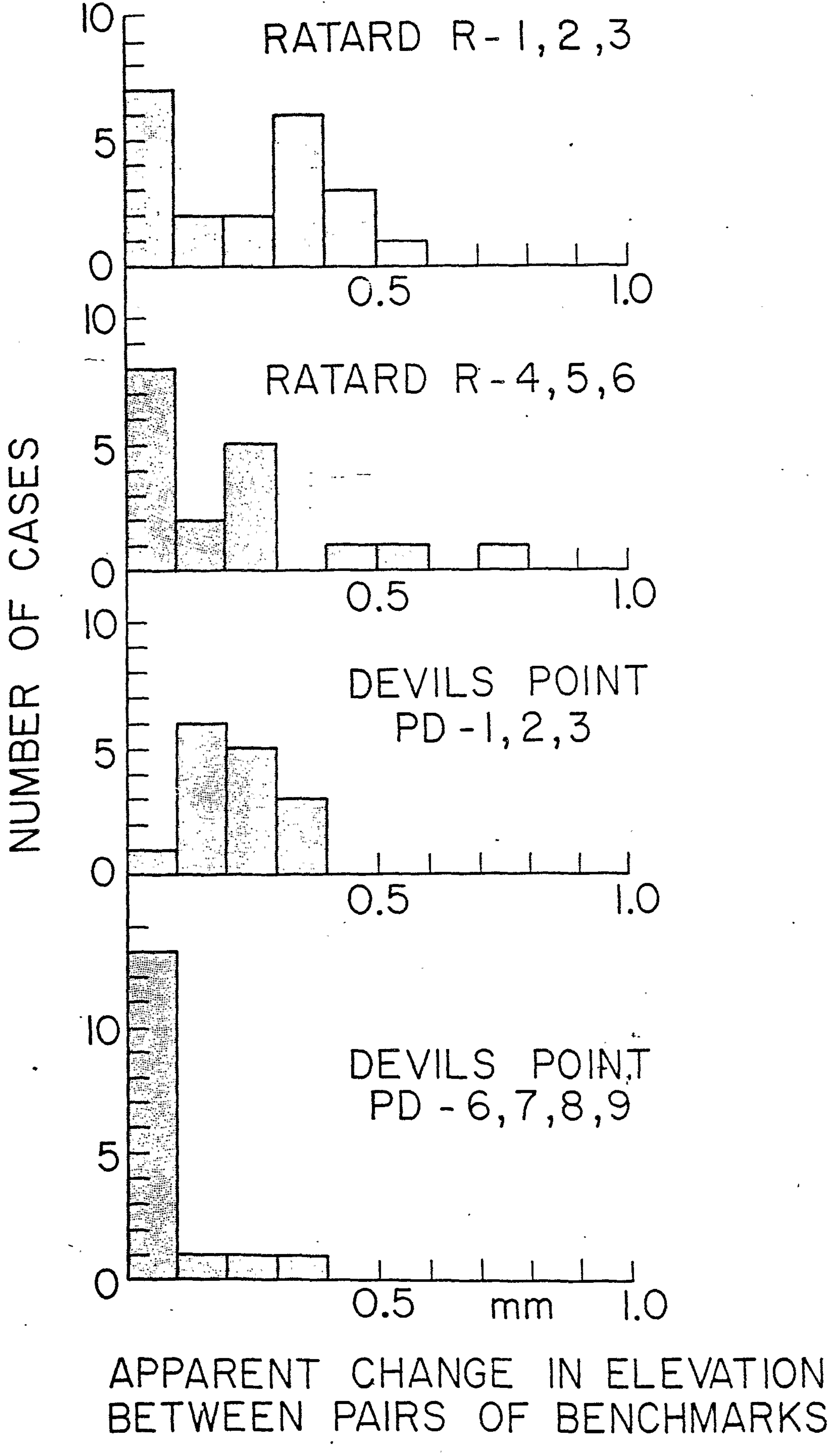

AREA COVERED WITH PALM FRONDS
GASKET SEAL
TO RECORDER AND BATTERY ENCLOSURE
FITTED STYROFOAM PLANKS
TILTMETER ELECTRONICS
POLYETHYLENE MOISTURE SEAL
BACKFILL
TILTMETER TUBE
CLEANED DRIED CORAL SAND
AGED IRON PIPE
METERS
0
1
2
3

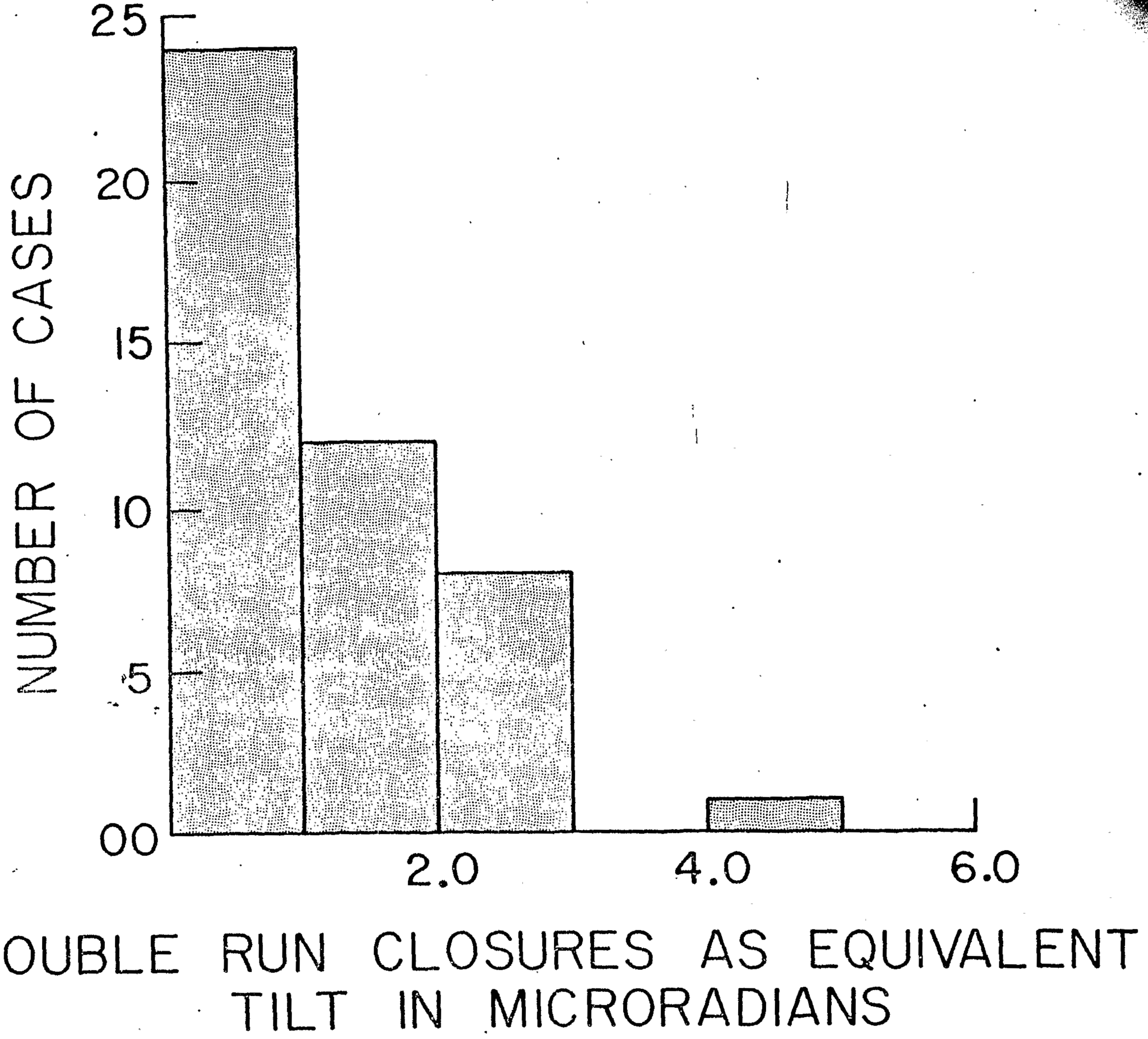

TILTMETER ENCLOSURE
RECORDING ENCLOSURE
TIPPING BUCKET RAIN GAUGE
RAIN GAUGE COUNTER
MULTI-PLEXER & CLOCK
RUSTRAK A 2 IN/DY
TILT METER ELECT
SIGNAL
RECENTER
POWER
CONTROL & BUFFER
TIME
RUSTRAK B 0.5 IN/HR
DIGITAL CASSETTE RECORDER
BOREHOLE UNIT
FIBERGLASS CASE
±12V
9 EDISON BATTERIES

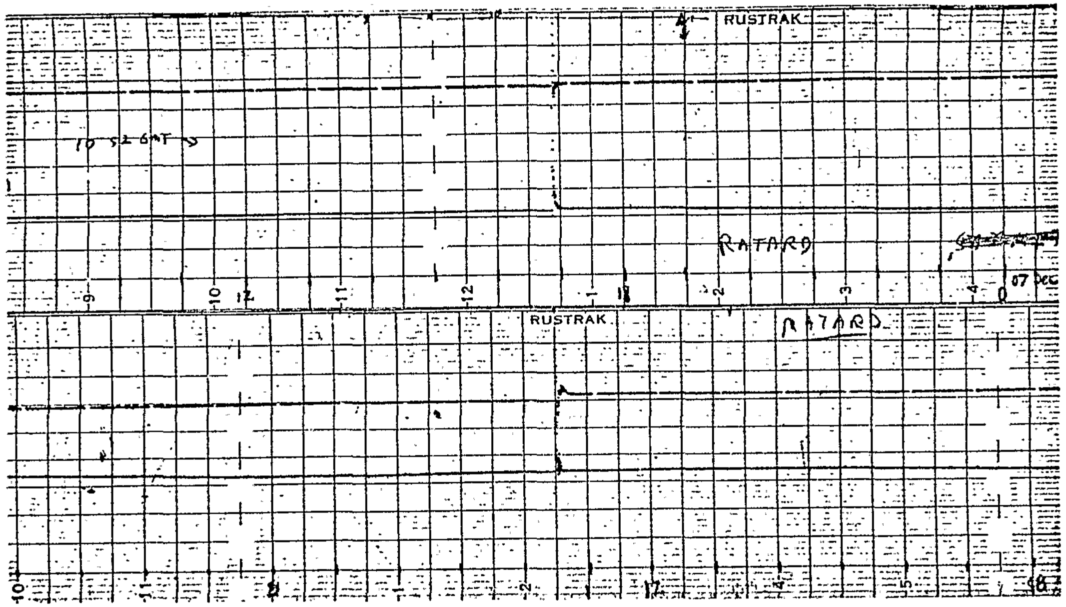

PORT OLRY
RATARD
SARMET
LAMAP
S W BAY
DEVILS POINT
MALAPOA
TUKU TUKU
JULY A S O N D JAN F M A M J JULY A S O N D JAN F M A M J JULY
1976
1977
1978

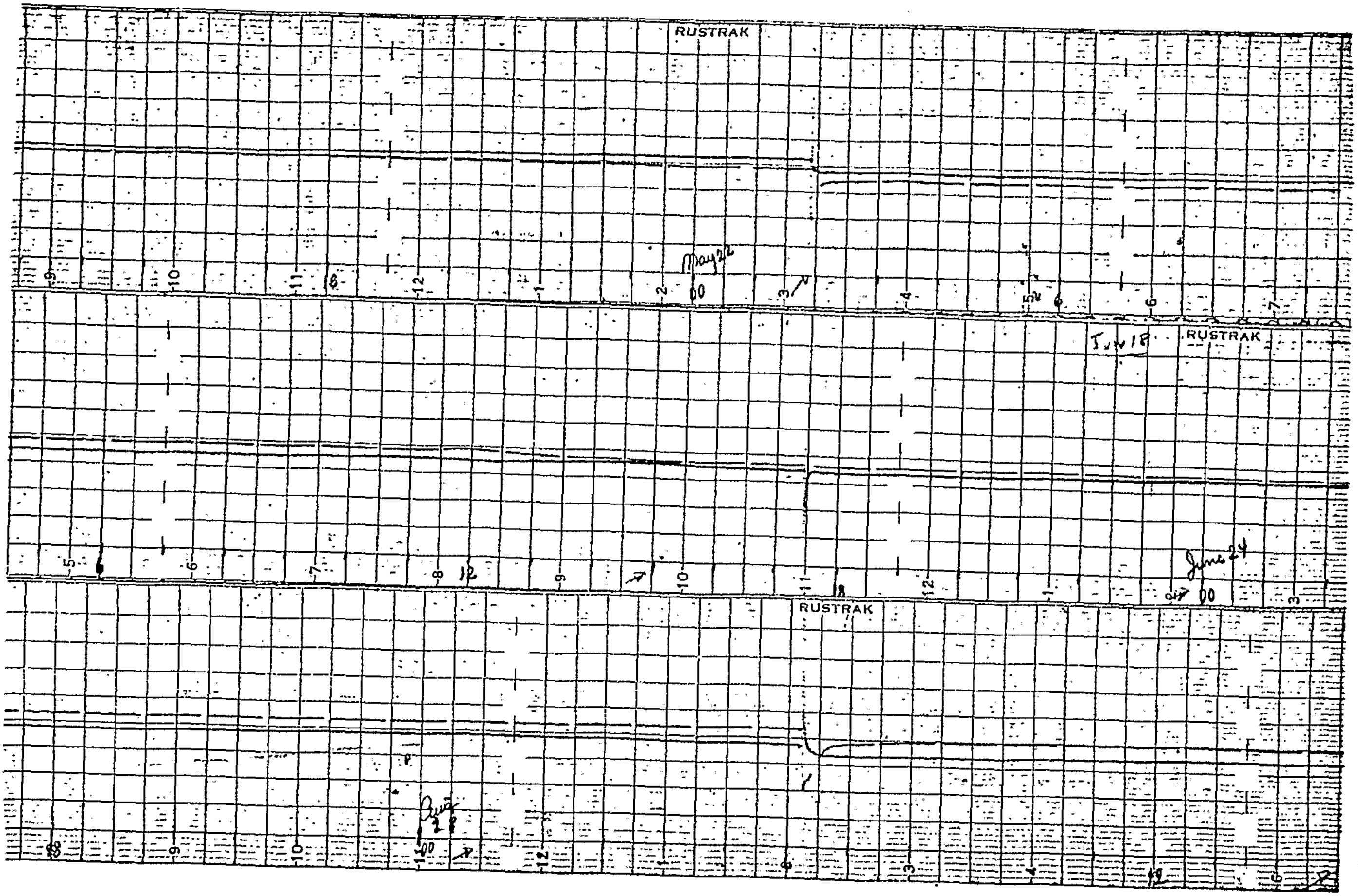

DEVILS POINT
⊙ BENCH MARK
▲ TILTMETER
N
PD4
PD 7
PD8
PD 6
PD 9
PD 5
PD 1
PD 3
PD 2
0
0.5 KM.


R8
TILTMETER
R4
R5
R1
R6
R3
R2
RATARD PLANTATION
N
R 7
0
0.5 KM


RATARD R-1,2,3
RATARD R-4,5,6
DEVILS POINT PD-1,2,3
DEVILS POINT PD-6,7,8,9
NUMBER OF CASES
0
5
10
0.5
1.0
mm
APPARENT CHANGE IN ELEVATION BETWEEN PAIRS OF BENCHMARKS


NUMBER OF CASES
25
20
15
10
5
00
2.0
4.0
6.0
DOUBLE RUN CLOSURES AS EQUIVALENT TILT IN MICRORADIANS

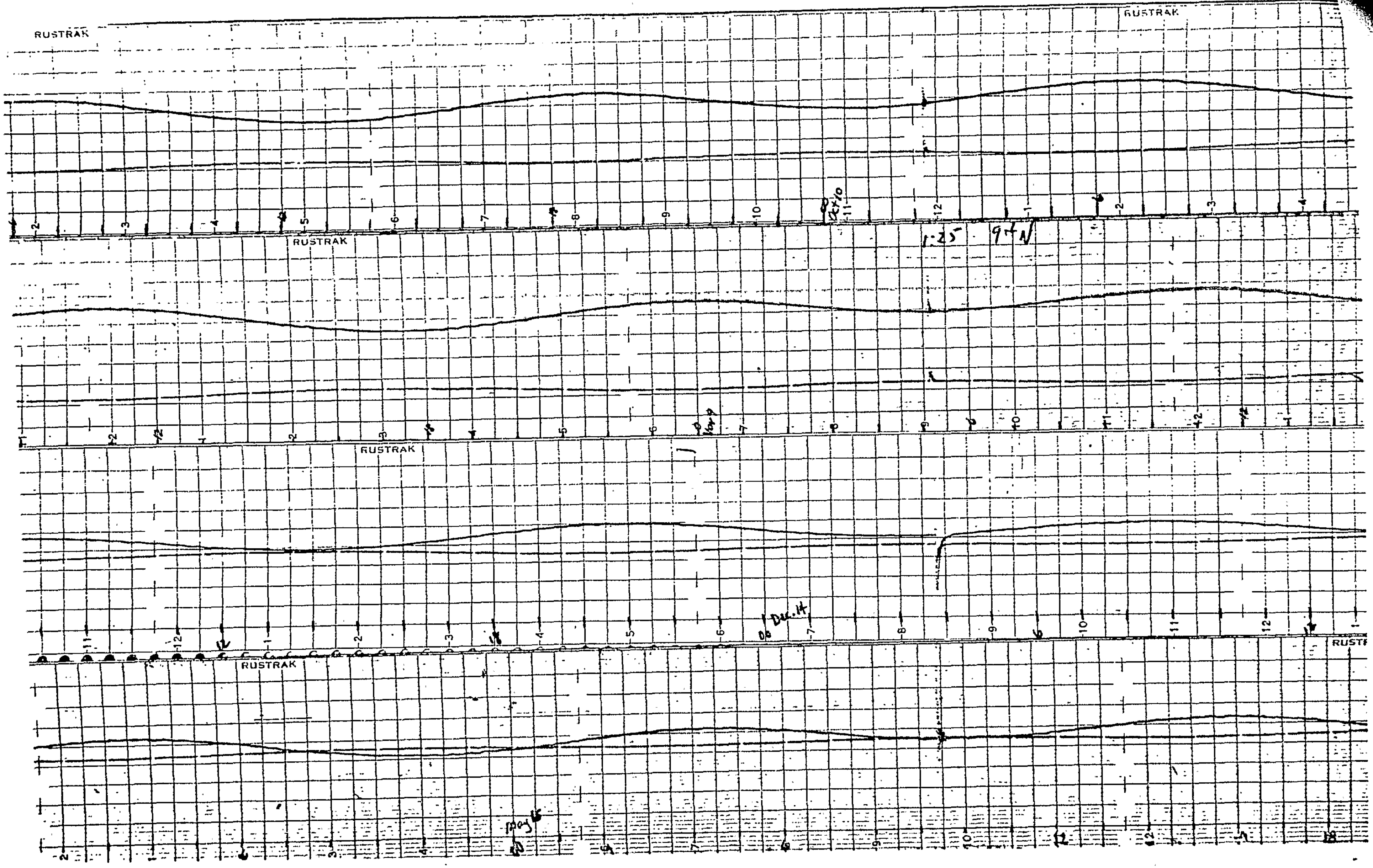

RUSTRAK
10 52 GMT
RATARD
07 Dec
9
10
11
12
1
2
3
4
RUSTRAK
RATARD
10
11
12
1
2
3
4
5

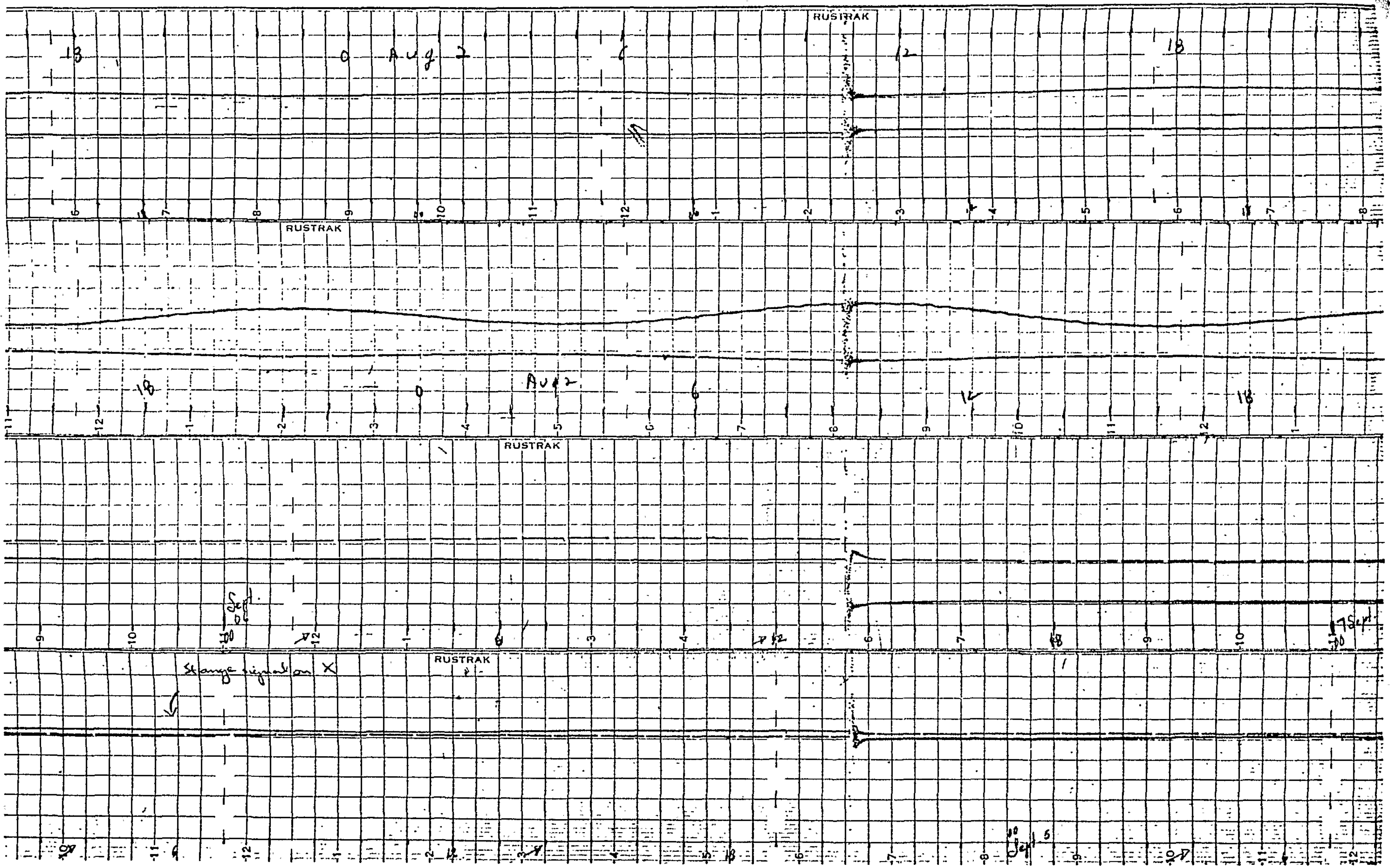


RUSTRAK
May 22
00
Jun 18
RUSTRAK
June 24
00
RUSTRAK
Aug 2
00

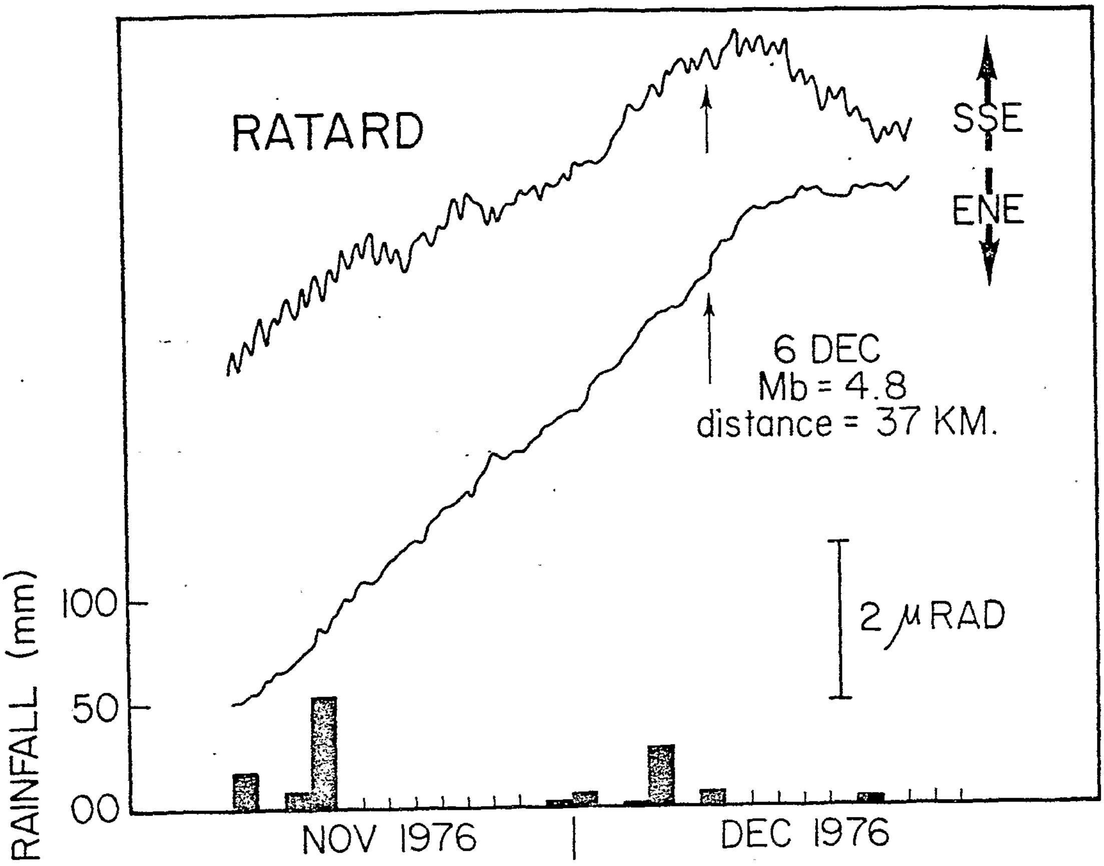
8+GV 12

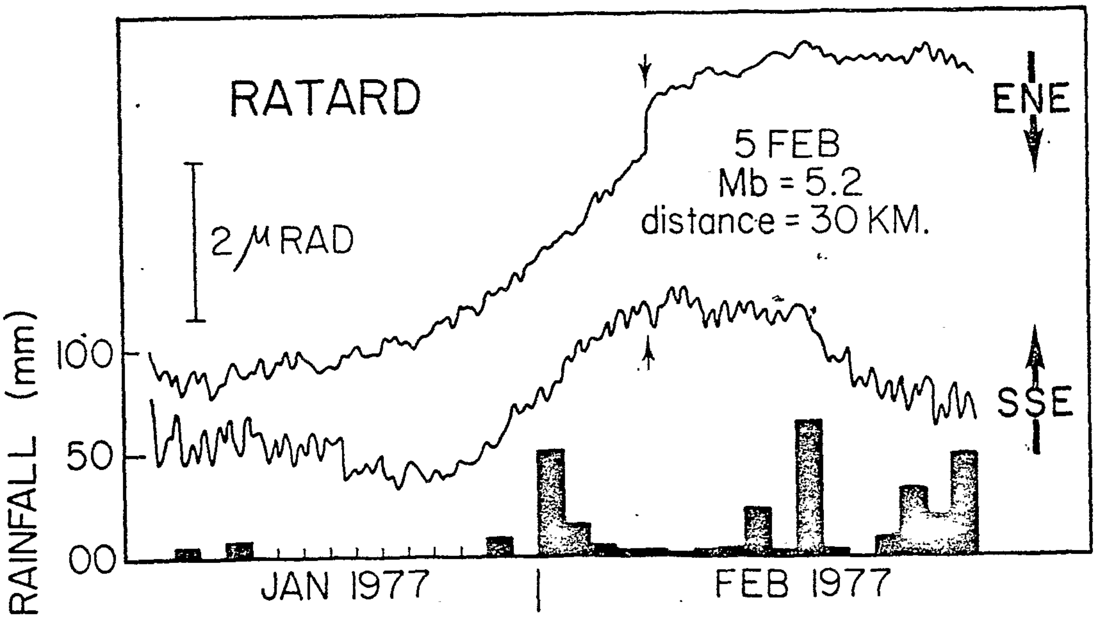

RUSTRAK
Oct 10
Nov 9
12
00
6
12
18
Felt in Port Vila III-IV
P&C 01 25 415 P
25 415
Dec 14
May 16 61 1307 5.1 -10
ms = 6.3
May 17 62 19 36.1 4
17 0244 29.
18 0643 01.
17
00

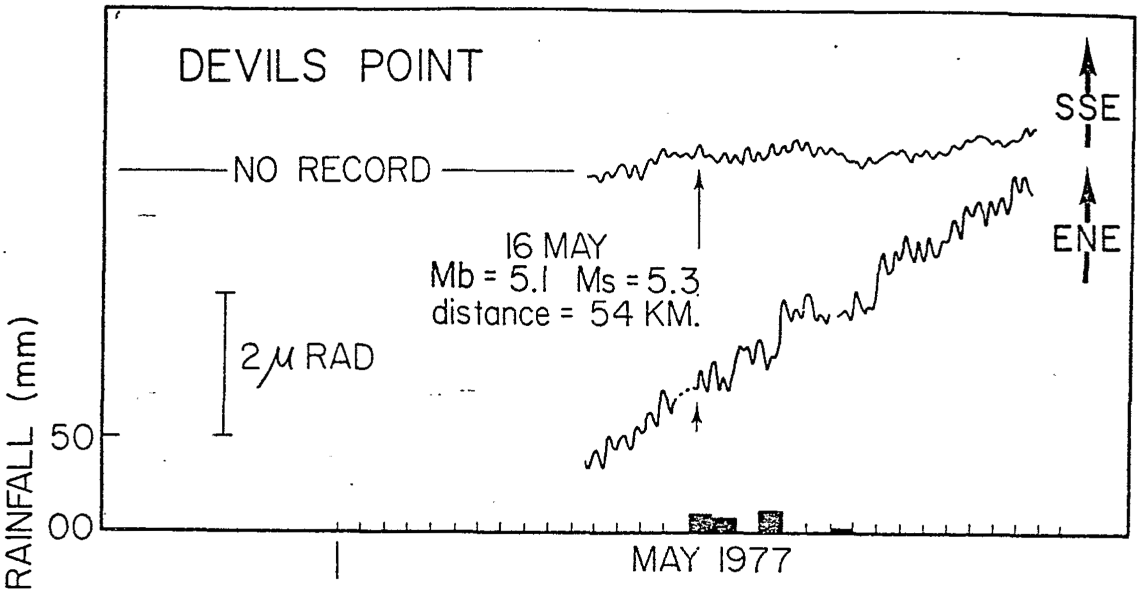

RUSTRAK
8 Oct 10
1:25
9-7 N
RUSTRAK
8 Nov 9
RUSTRAK
08 Dec. 14
RUSTRAK
May 15

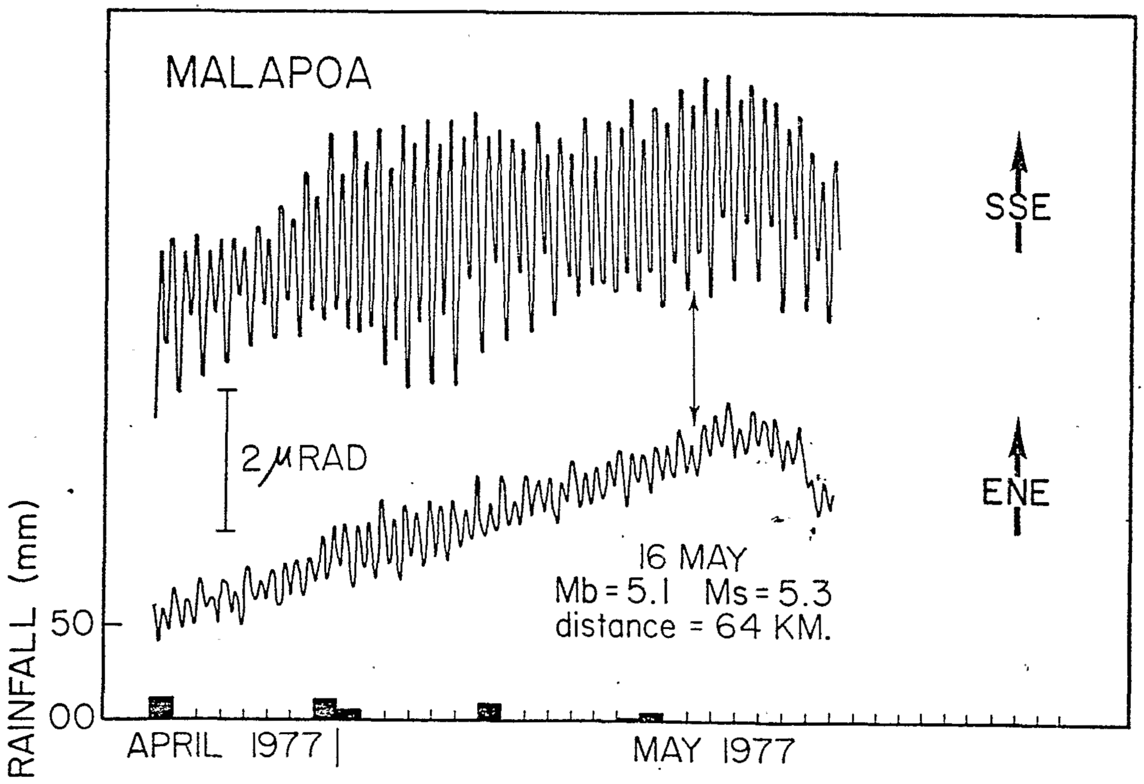


Strange signal on X

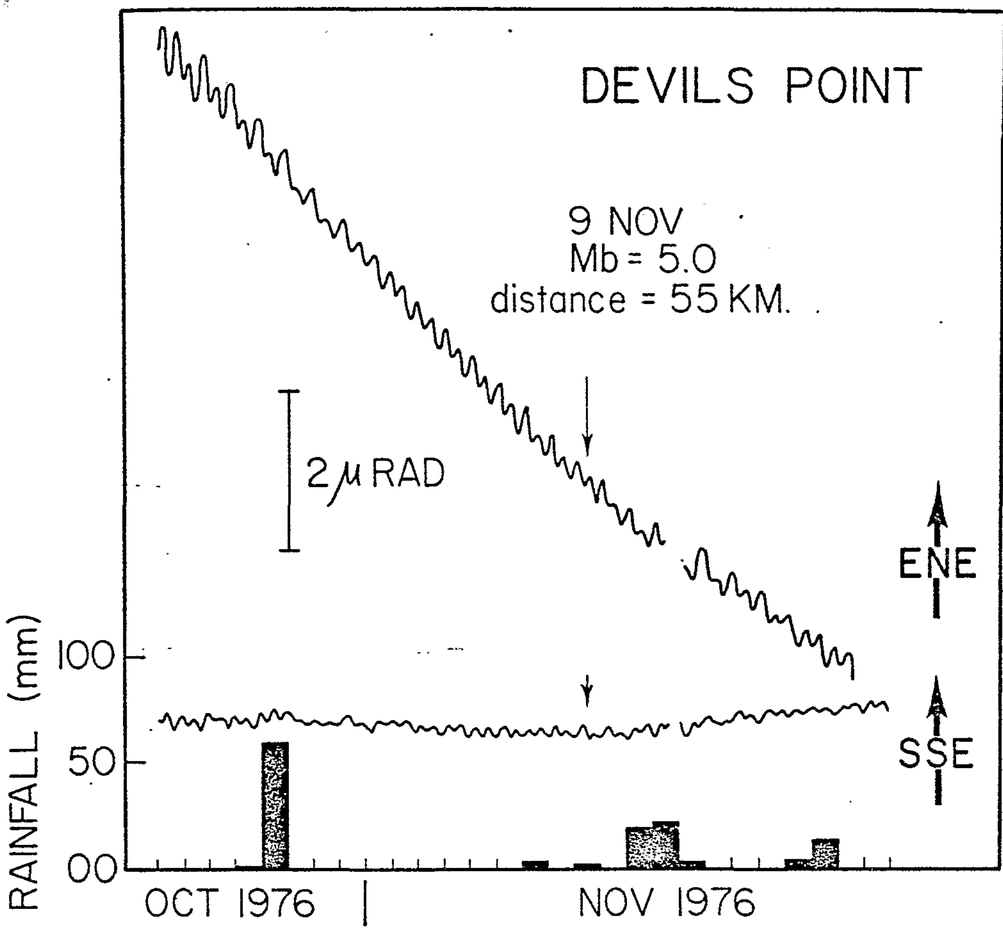

RATARD
SSE
ENE
6 DEC
Mb = 4.8
distance = 37 KM.
2 μ RAD
RAINFALL (mm)
100
50
00
NOV 1976
DEC 1976

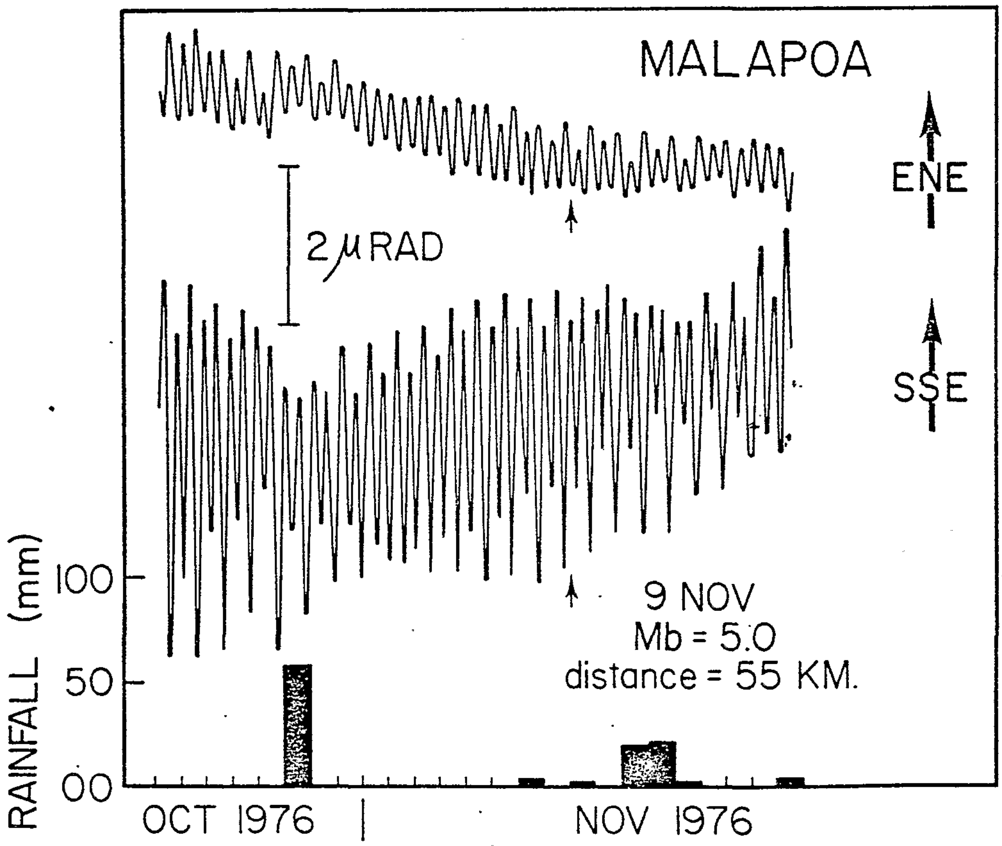

RATARD
ENE
5 FEB
Mb = 5.2
distance = 30 KM.
2 μ RAD
RAINFALL (mm)
100
50
00
SSE
JAN 1977
FEB 1977

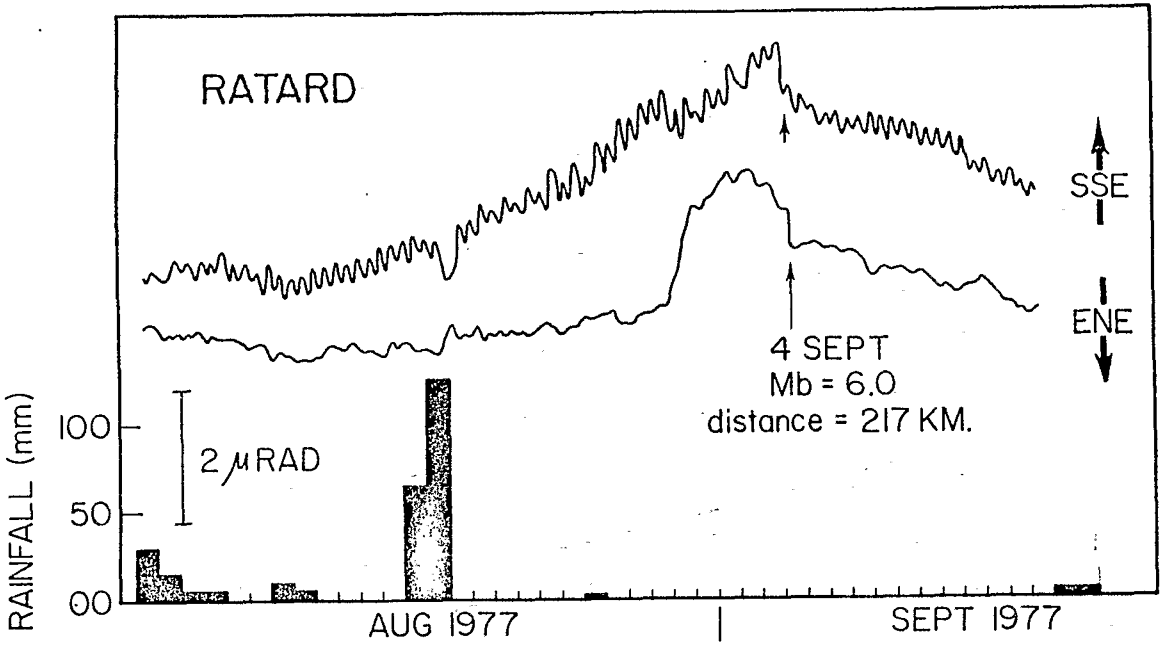

DEVILS POINT
NO RECORD
SSE
ENE
16 MAY
Mb = 5.1 Ms = 5.3
distance = 54 KM.
2 μ RAD
RAINFALL (mm)
50
00
MAY 1977

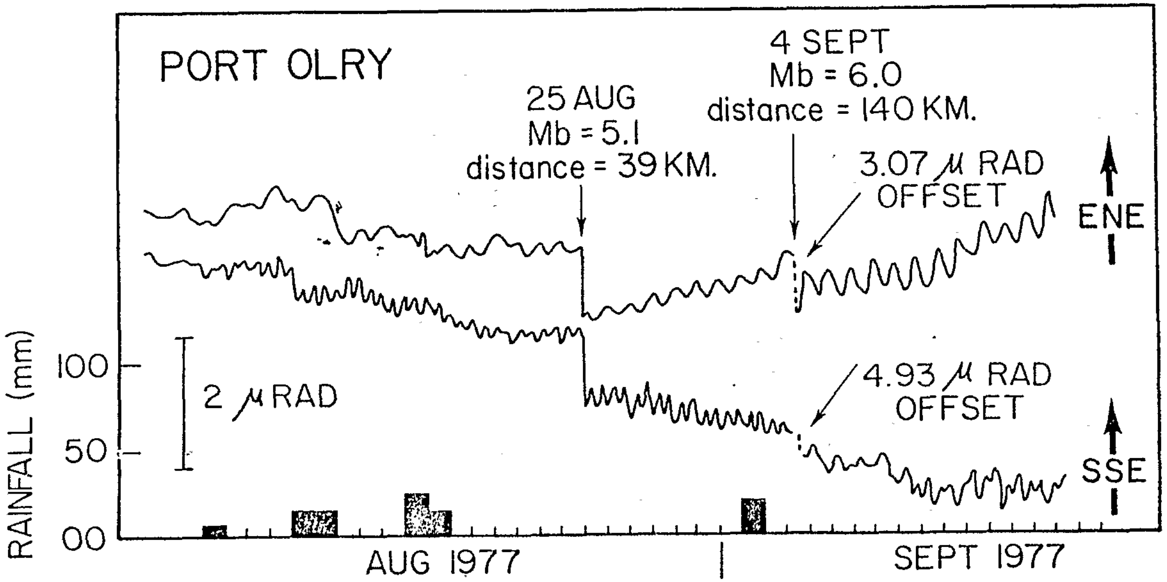

MALAPOA
SSE
ENE
2 μ RAD
16 MAY
Mb = 5.1 Ms = 5.3
distance = 64 KM.
RAINFALL (mm)
50
00
APRIL 1977
MAY 1977

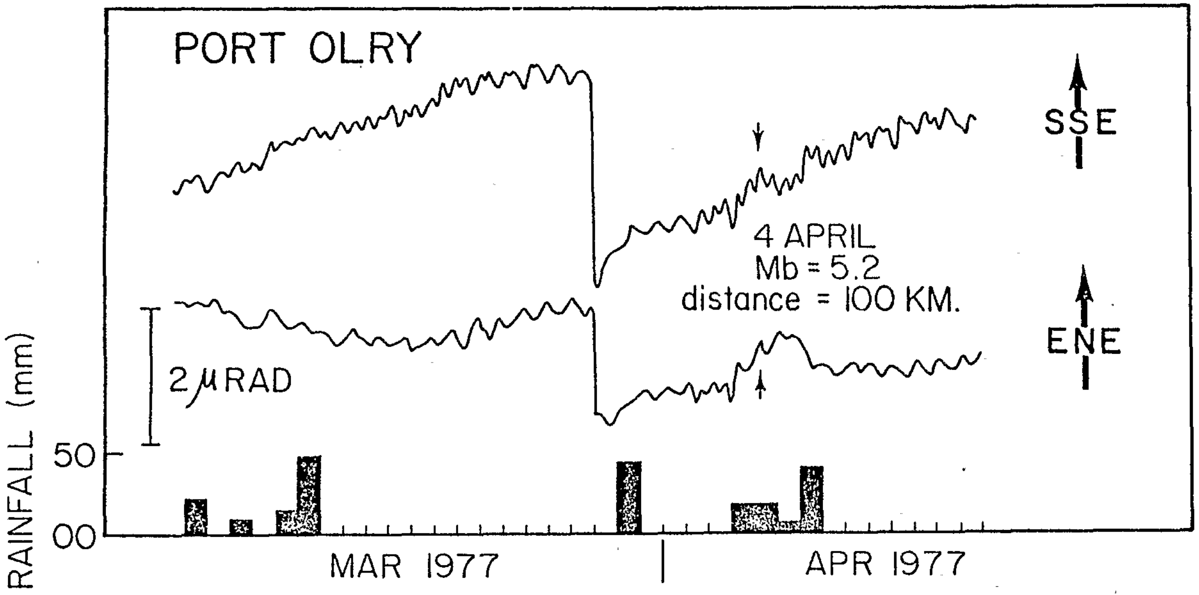
≃ 1978

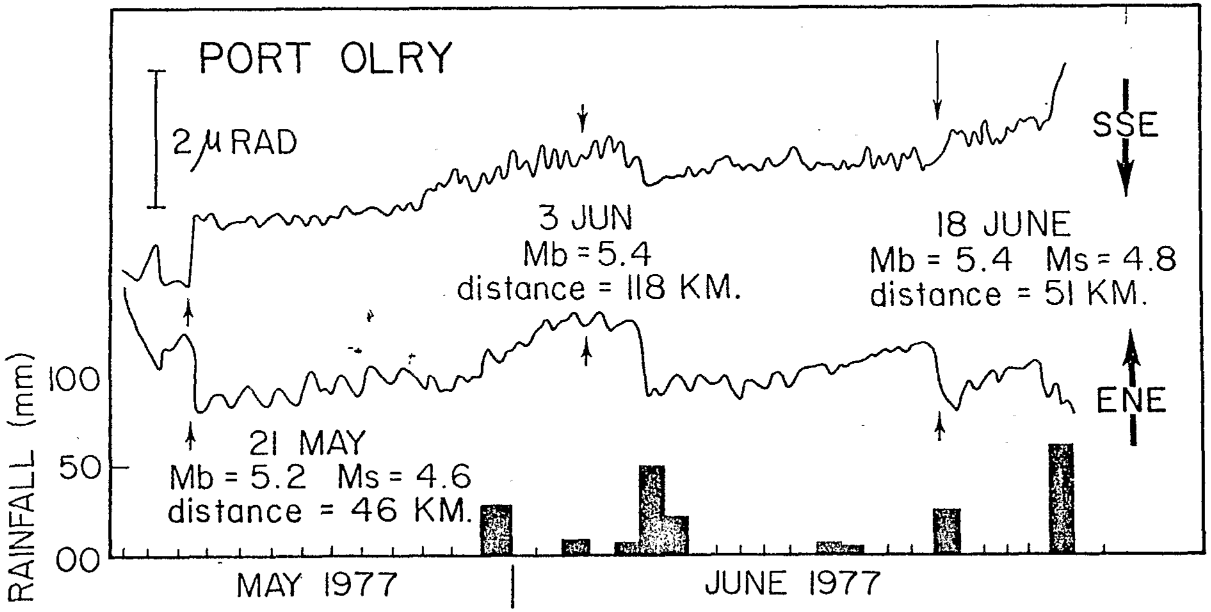

DEVILS POINT
9 NOV
Mb = 5.0
distance = 55 KM.
2 µ RAD
ENE
SSE
RAINFALL (mm)
100
50
00
OCT 1976
NOV 1976

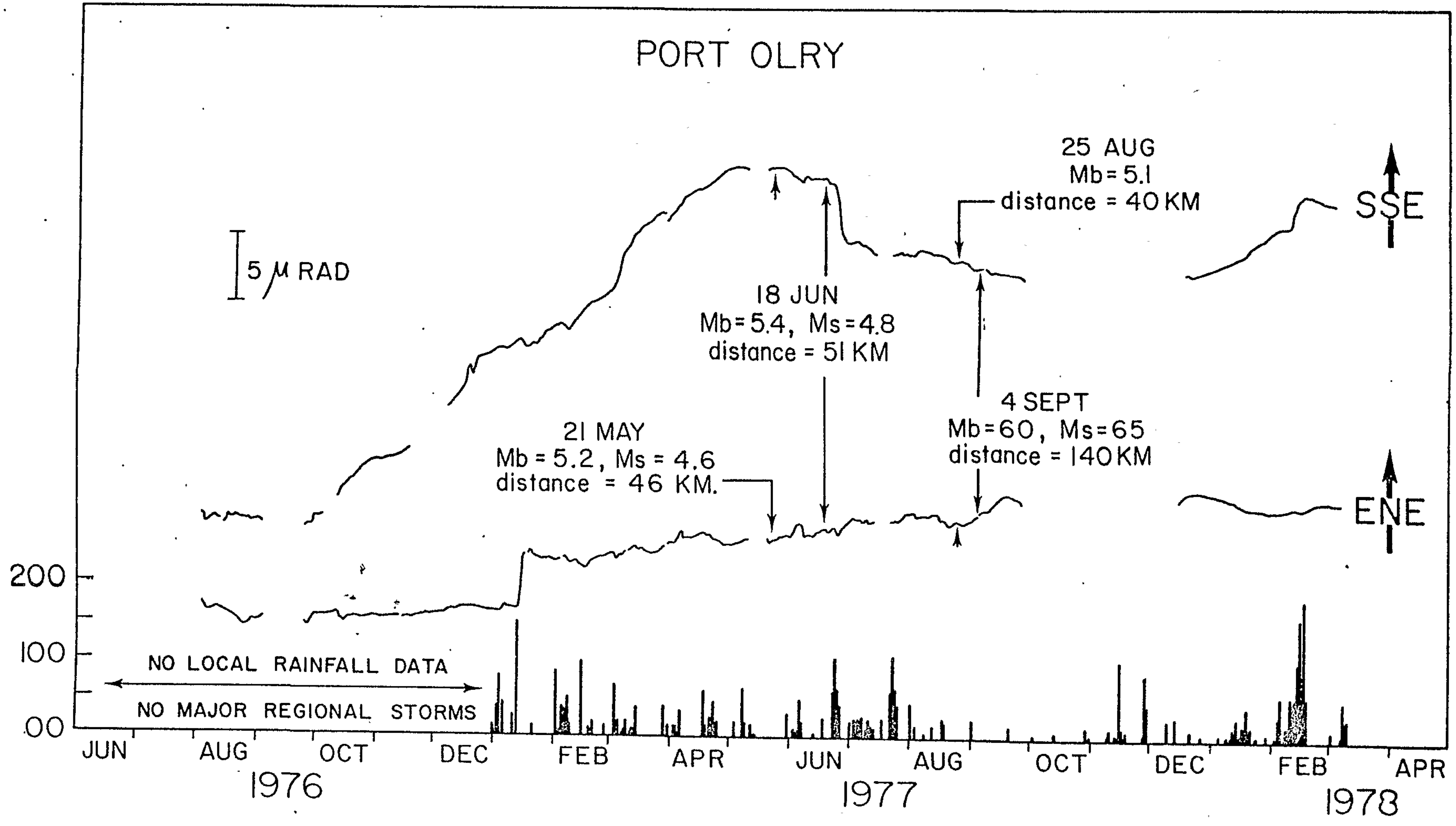

MALAPOA
ENE
2 µ RAD
SSE
RAINFALL (mm)
100
50
00
9 NOV
Mb = 5.0
distance = 55 KM.
OCT 1976
NOV 1976

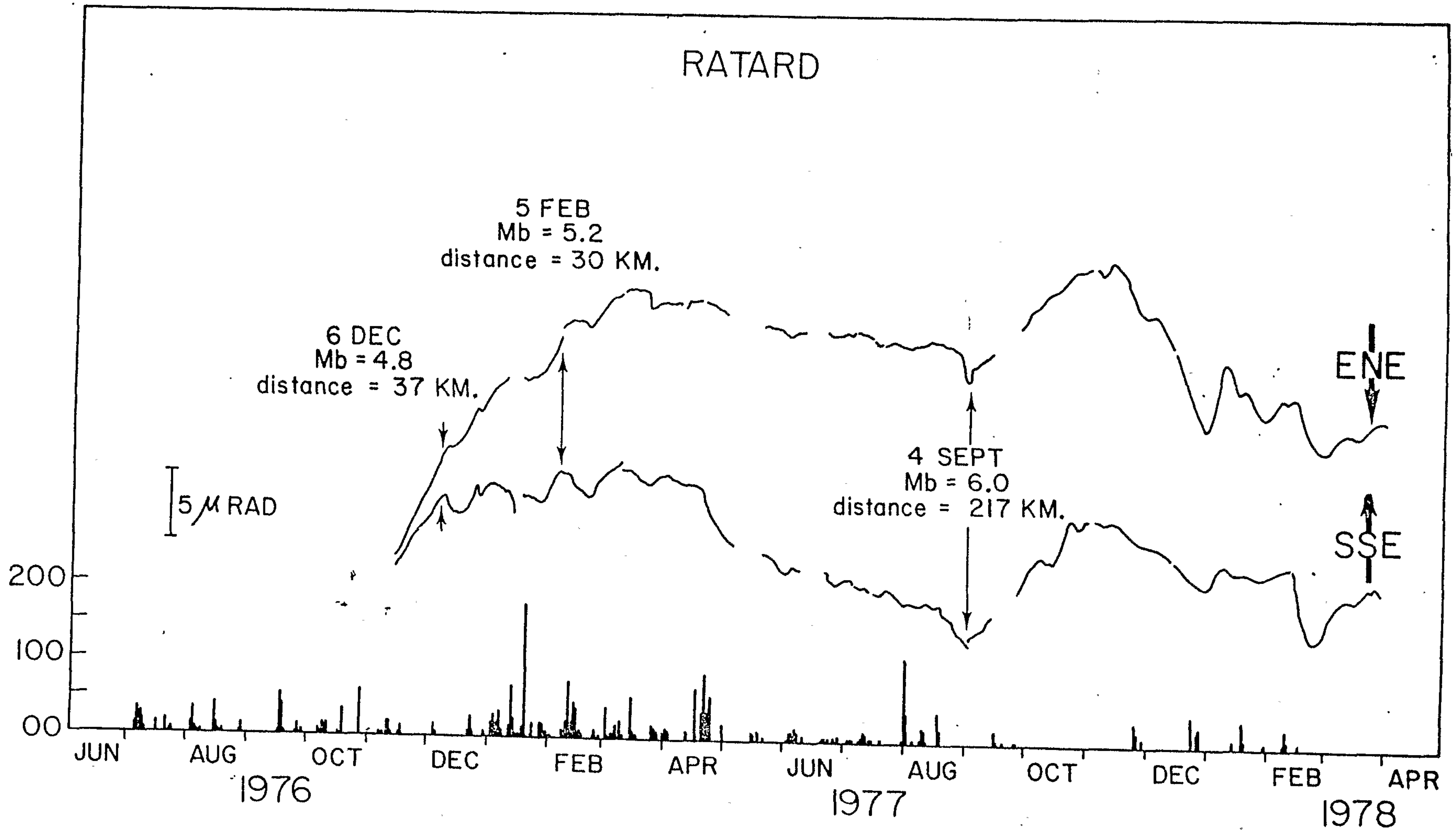

RATARD
SSE
ENE
4 SEPT
Mb = 6.0
distance = 217 KM.
2 µRAD
RAINFALL (mm)
100
50
00
AUG 1977
SEPT 1977

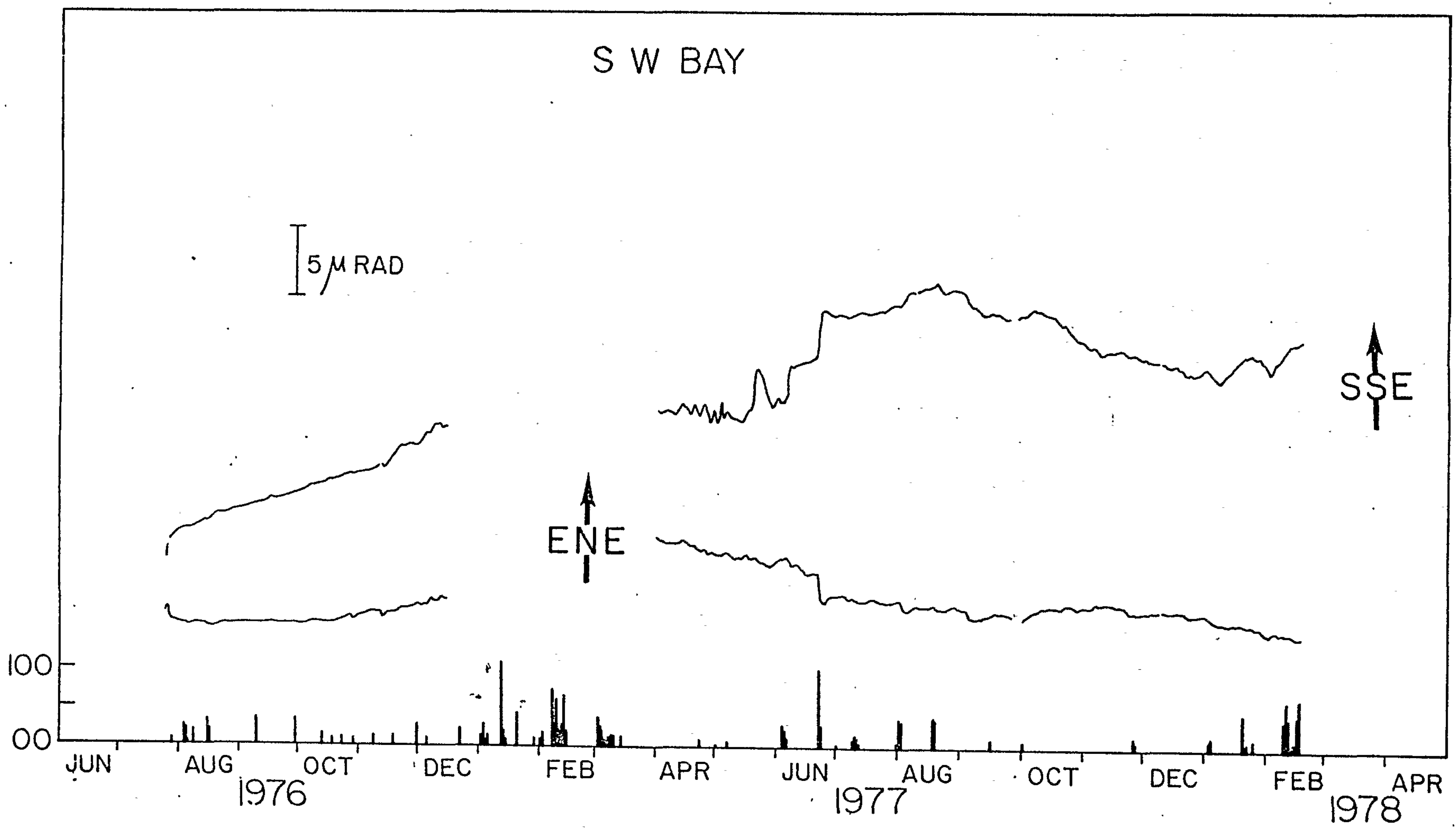

PORT OLRY
25 AUG
Mb = 5.1
distance = 39 KM.
4 SEPT
Mb = 6.0
distance = 140 KM.
3.07 µ RAD
OFFSET
ENE
4.93 µ RAD
OFFSET
SSE
2 µ RAD
RAINFALL (mm)
100
50
00
AUG 1977
SEPT 1977

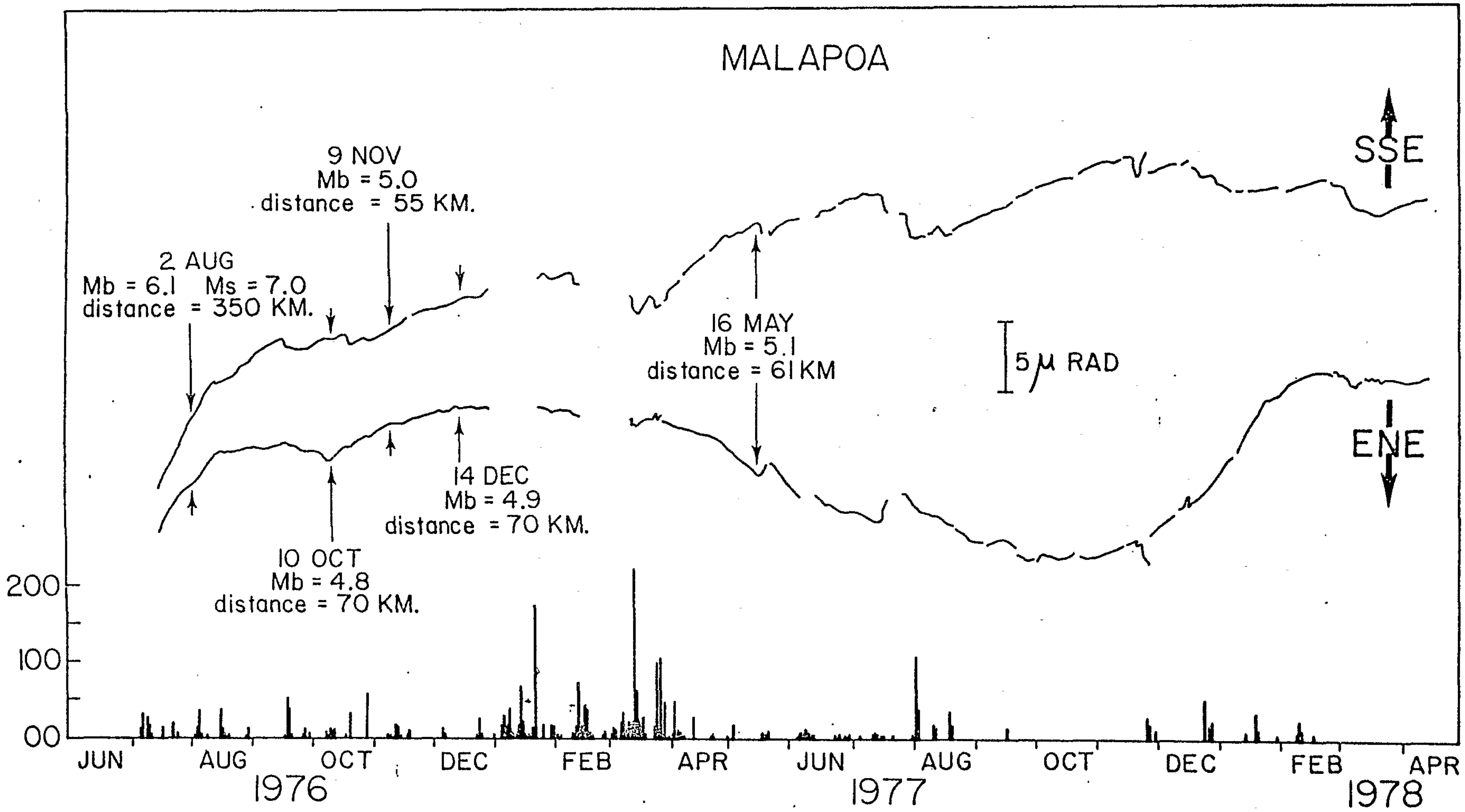

PORT OLRY
SSE
ENE
4 APRIL
Mb = 5.2
distance = 100 KM.
2 μ RAD
RAINFALL (mm)
50
00
MAR 1977
APR 1977

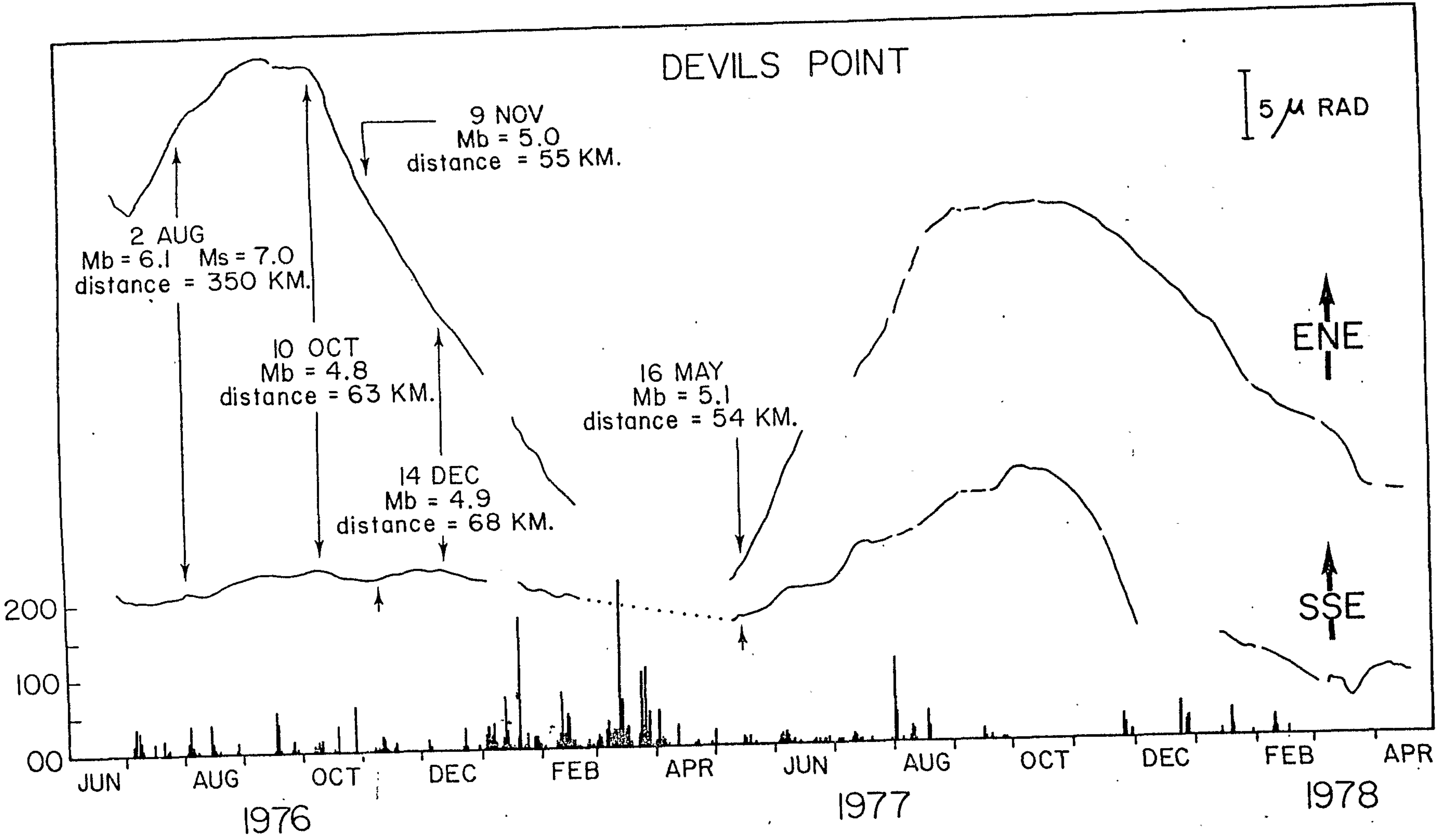

PORT OLRY
2 μ RAD
SSE
ENE
3 JUN
Mb = 5.4
distance = 118 KM.
18 JUNE
Mb = 5.4 Ms = 4.8
distance = 51 KM.
21 MAY
Mb = 5.2 Ms = 4.6
distance = 46 KM.
RAINFALL (mm)
100
50
00
MAY 1977
JUNE 1977

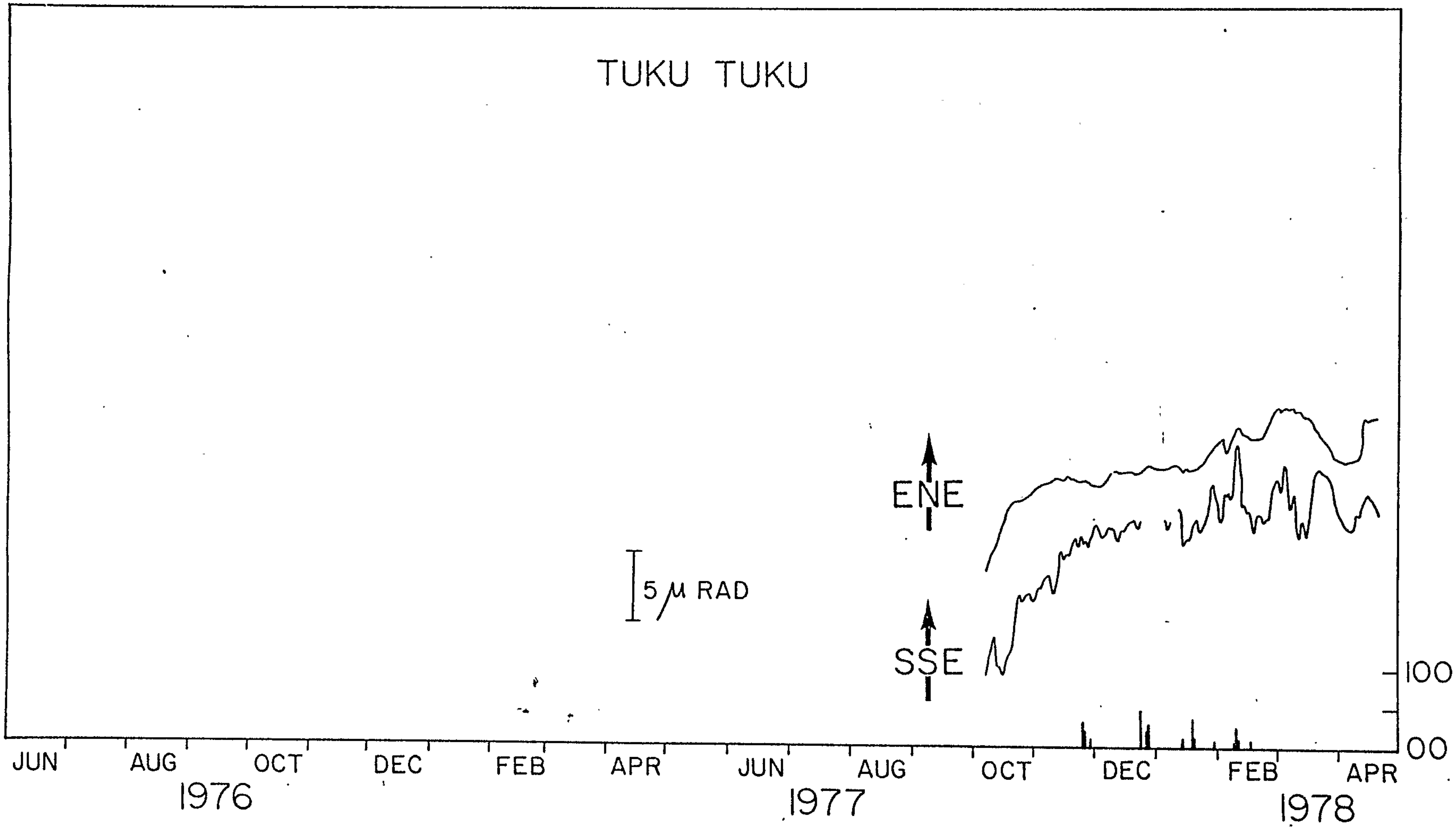

PORT OLRY
5 μ RAD
25 AUG
Mb = 5.1
distance = 40 KM
SSE
18 JUN
Mb=5.4, Ms=4.8
distance = 51 KM
4 SEPT
Mb=60, Ms=65
distance = 140 KM
21 MAY
Mb = 5.2, Ms = 4.6
distance = 46 KM.
ENE
200
100
00
NO LOCAL RAINFALL DATA
NO MAJOR REGIONAL STORMS
JUN
AUG
OCT
DEC
FEB
APR
JUN
AUG
OCT
DEC
FEB
APR
1976
1977
1978

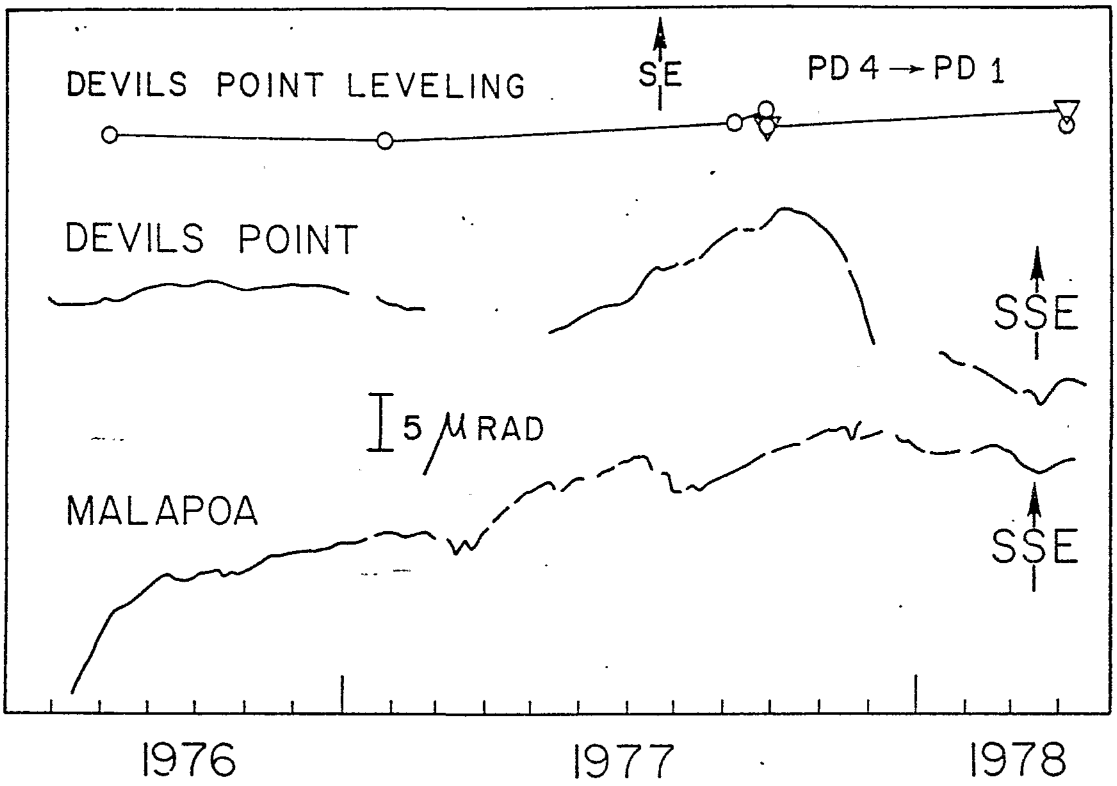

RATARD
5 FEB
Mb = 5.2
distance = 30 KM.
6 DEC
Mb = 4.8
distance = 37 KM.
4 SEPT
Mb = 6.0
distance = 217 KM.
5 μ RAD
ENE
SSE
200
100
00
JUN
AUG
OCT
DEC
FEB
APR
JUN
AUG
OCT
DEC
FEB
APR
1976
1977
1978

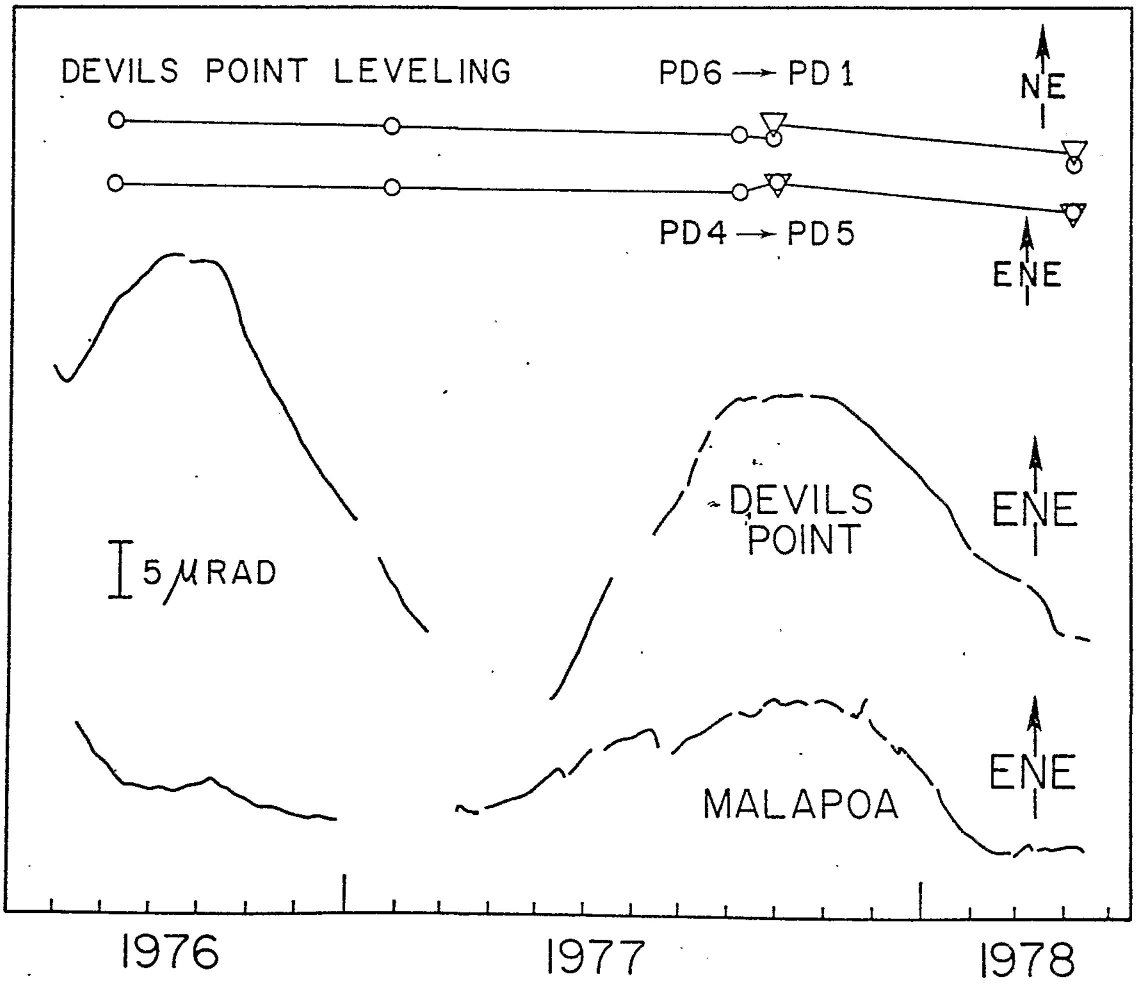

S W BAY
5 μ RAD
SSE
ENE
100
00
JUN
AUG
OCT
DEC
FEB
APR
JUN
AUG
OCT
DEC
FEB
APR
1976
1977
1978

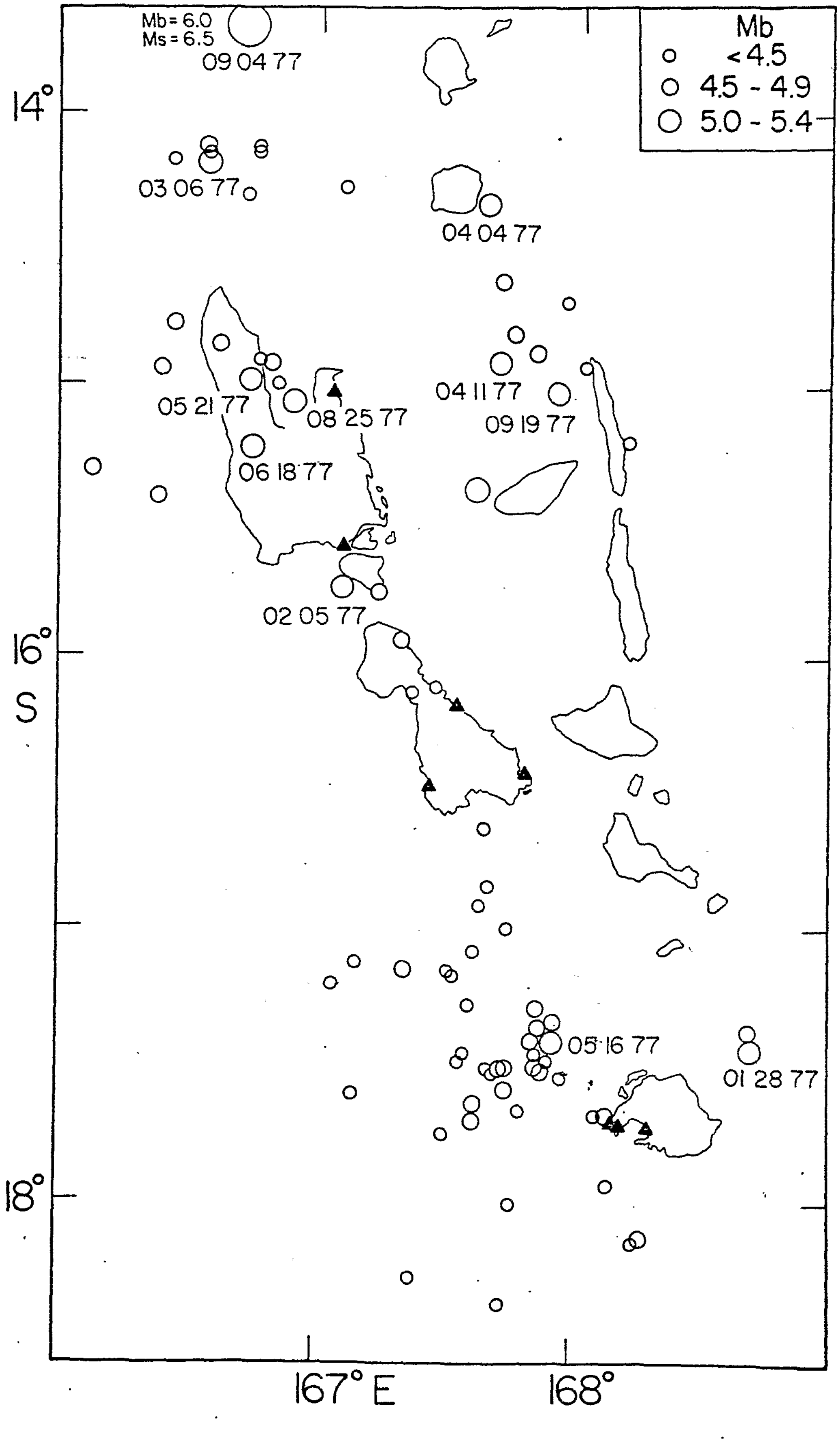

MALAPOA
SSE
ENE
5 μ RAD
9 NOV
Mb = 5.0
distance = 55 KM.
2 AUG
Mb = 6.1 Ms = 7.0
distance = 350 KM.
16 MAY
Mb = 5.1
distance = 61 KM
14 DEC
Mb = 4.9
distance = 70 KM.
10 OCT
Mb = 4.8
distance = 70 KM.
200
100
00
JUN
AUG
OCT
DEC
FEB
APR
JUN
AUG
OCT
DEC
FEB
APR
1976
1977
1978

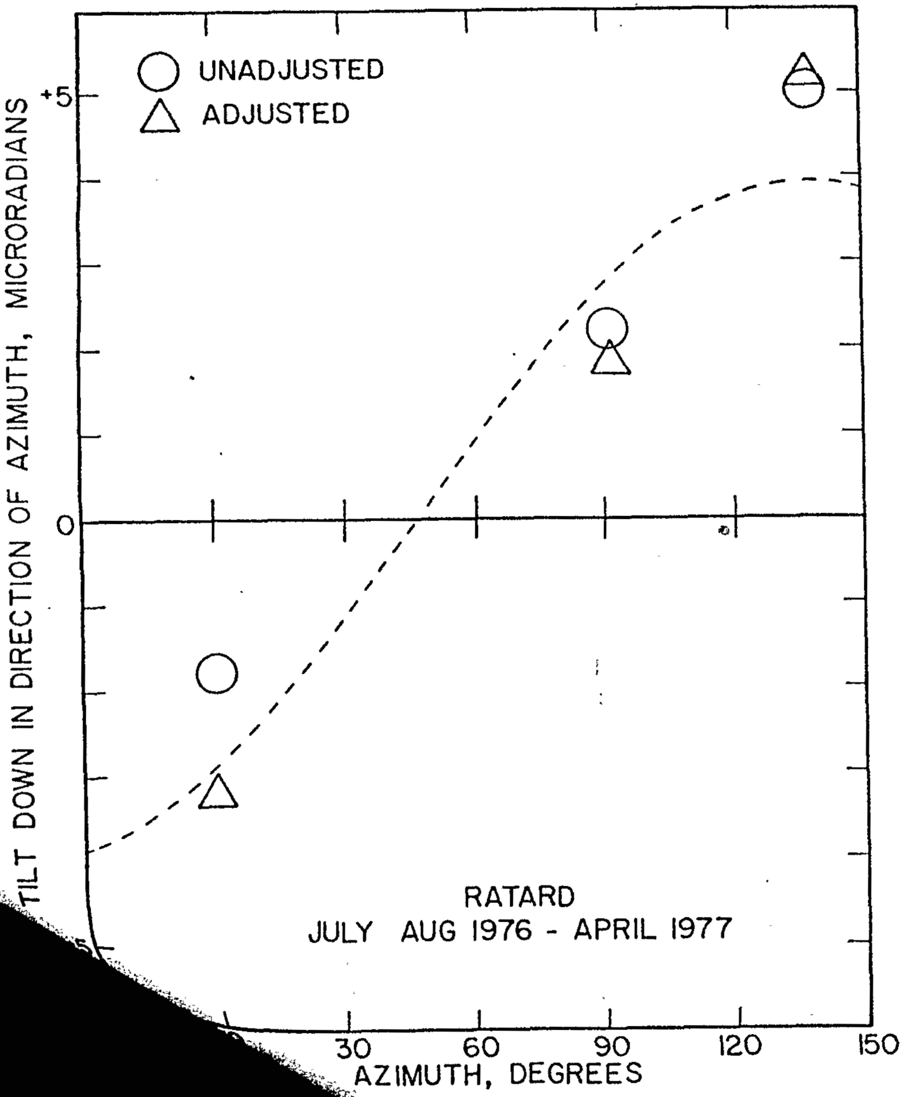

DEVILS POINT
5 μ RAD
9 NOV
Mb = 5.0
distance = 55 KM.
2 AUG
Mb = 6.1 Ms = 7.0
distance = 350 KM.
10 OCT
Mb = 4.8
distance = 63 KM.
14 DEC
Mb = 4.9
distance = 68 KM.
16 MAY
Mb = 5.1
distance = 54 KM.
ENE
SSE
200
100
00
JUN
AUG
OCT
DEC
FEB
APR
JUN
AUG
OCT
DEC
FEB
APR
1976
1977
1978

TUKU TUKU
ENE
SSE
5 μ RAD
100
00
JUN
AUG
OCT
DEC
FEB
APR
JUN
AUG
OCT
DEC
FEB
APR
1976
1977
1978

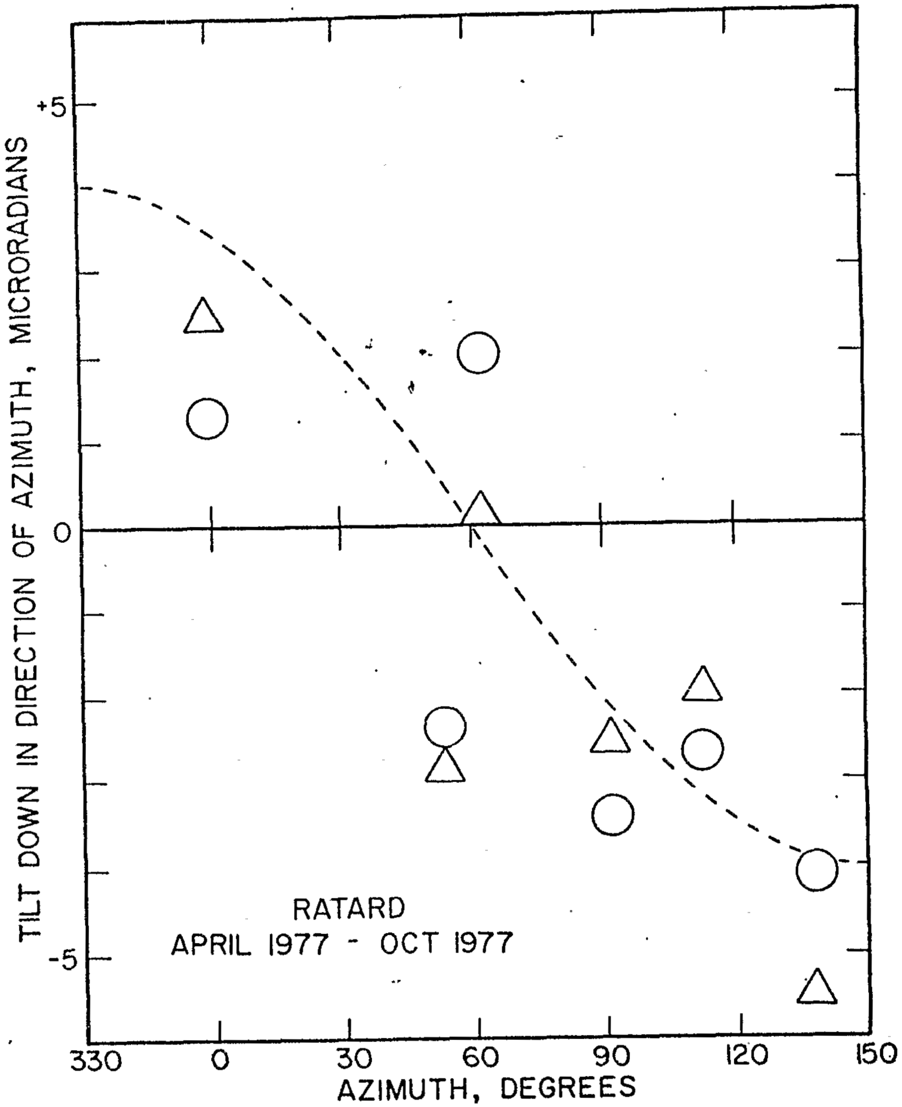

DEVILS POINT LEVELING
SE
PD 4 → PD 1
DEVILS POINT
SSE
5 μRAD
MALAPOA
SSE
1976
1977
1978


DEVILS POINT LEVELING
PD6 → PD 1
NE
PD4 → PD5
ENE
DEVILS POINT
ENE
5 μRAD
MALAPOA
ENE
1976
1977
1978

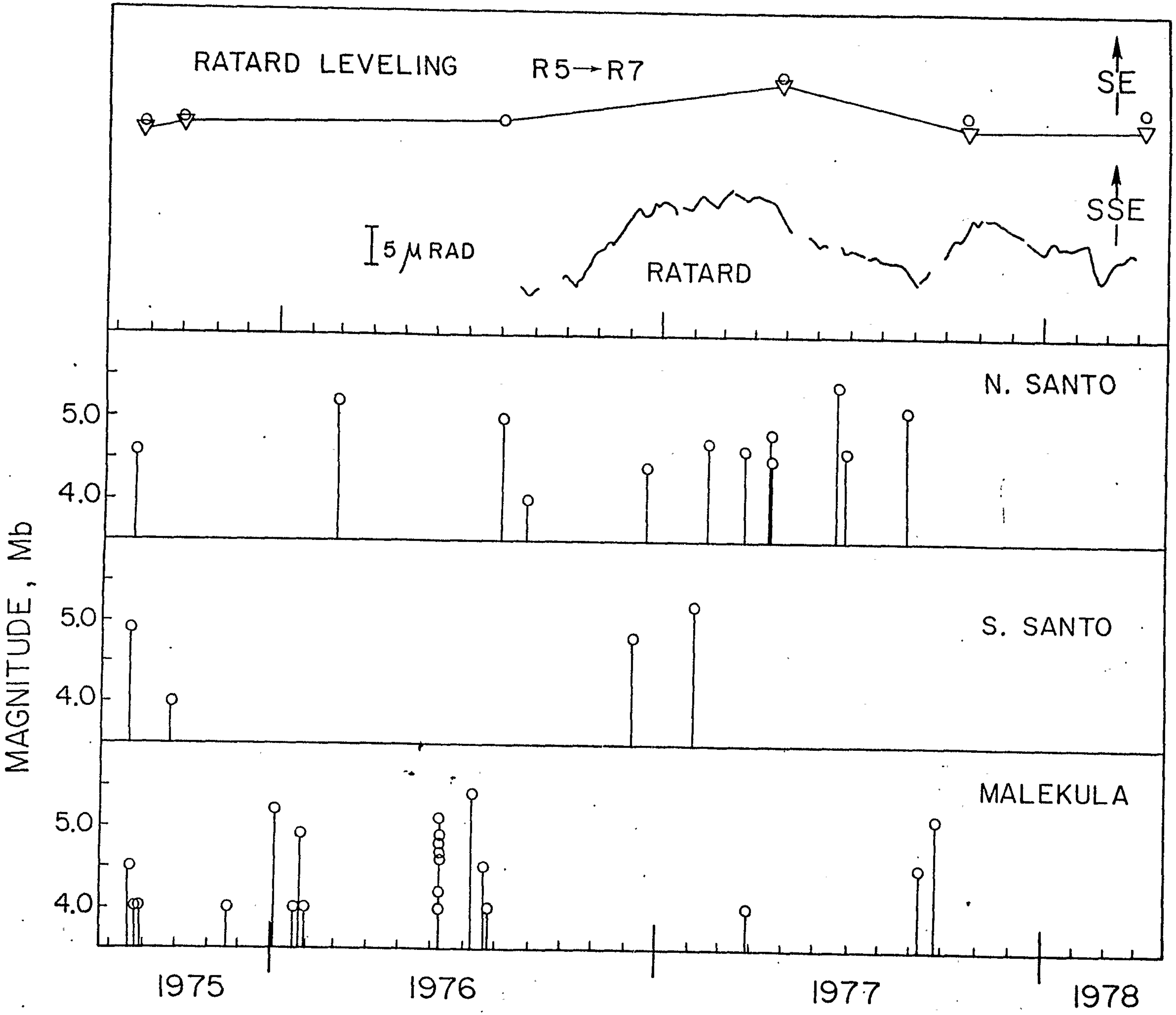

Mb = 6.0
Ms = 6.5
09 04 77
Mb
○ <4.5
○ 4.5 - 4.9
○ 5.0 - 5.4
14°
03 06 77
04 04 77
05 21 77
08 25 77
04 11 77
09 19 77
06 18 77
02 05 77
16°
S
05 16 77
01 28 77
18°
167° E
168°

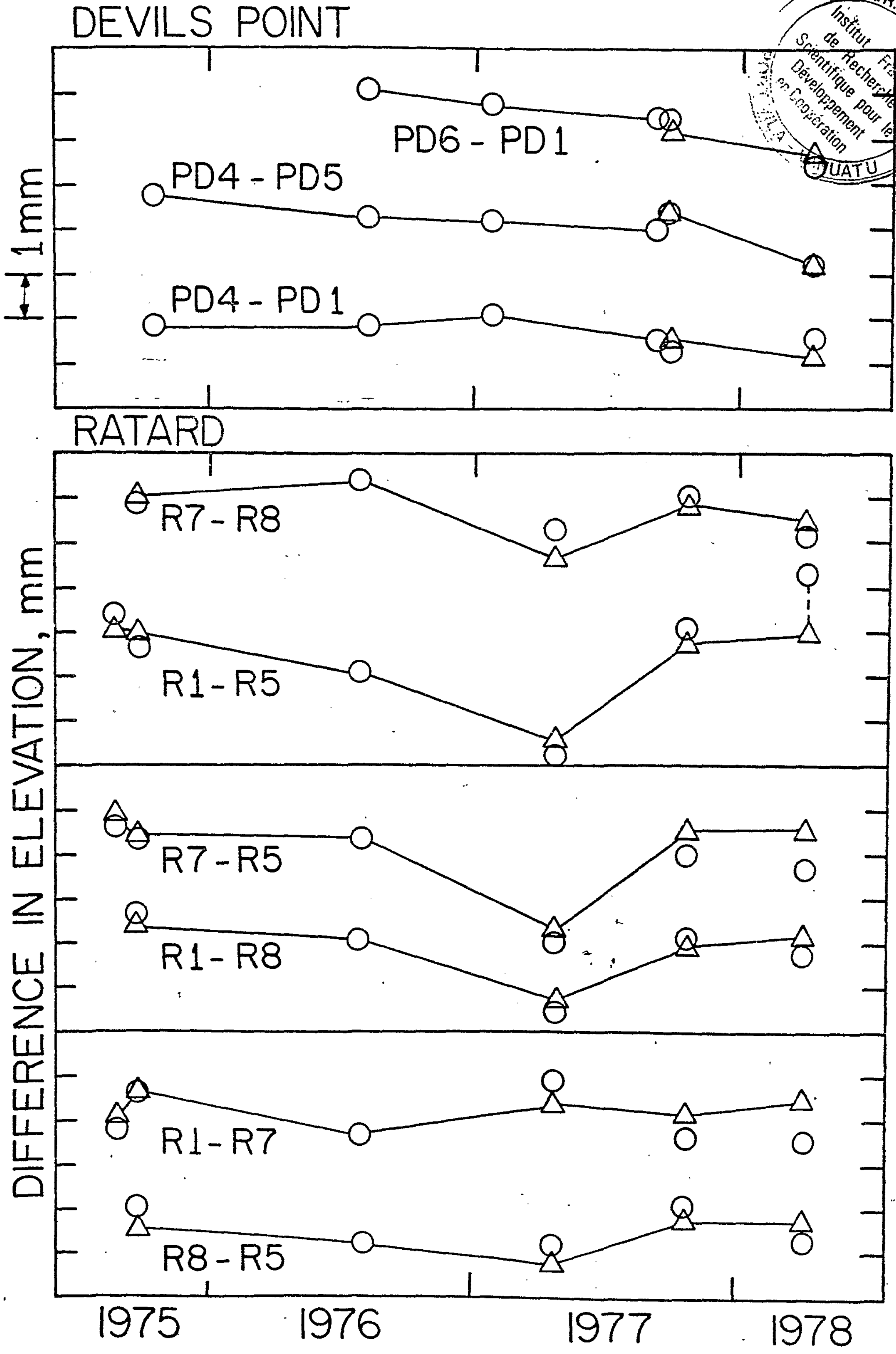


RATARD
JULY AUG 1976 - APRIL 1977



RATARD
APRIL 1977 - OCT 1977


RATARD LEVELING
R5 → R7
SE
SSE
5 μ RAD
RATARD
N. SANTO
S. SANTO
MALEKULA
MAGNITUDE , Mb
5.0
4.0
5.0
4.0
5.0
4.0
1975
1976
1977
1978


DEVILS POINT
PD6 - PD1
PD4 - PD5
PD4 - PD1
1mm
RATARD
R7 - R8
R1 - R5
R7 - R5
R1 - R8
R1 - R7
R8 - R5
DIFFERENCE IN ELEVATION, mm
1975
1976
1977
1978