EVALUATION OF SEISMIC RISK IN THE TONGA-FIJI-VANUATU REGION OF THE SOUTHWEST PACIFIC

A COUNTRY REPORT: REPUBLIC OF VANUATU

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EXECUTIVE SUMMARY

Overall Program

This country report is a summary of our contribution to a long-term program to evaluate earthquake risk to the island countries of Tonga, Fiji, and Vanuatu in the Southwest Pacific. These countries are located within one of the most active belts of seismicity in the world, and seismic hazard in these countries has been largely neglected in national planning and development programs. The fundamental contributions of our investigations include: (1) analysis of regional seismicity and seismotectonic data; (2) maintenance and improvement of seismological facilities in the region; (3) establishment of a regional network of strong-motion accelerographs; (4) initiation of regional cooperation between national and international agencies working in this region; and (5) training of national technical and scientific personnel. Our investigations in Vanuatu have been carried out through coöperative work with ORSTOM.

Earthquake Potential

We have subdivided the New Hebrides Island Arc into four zones of seismic potential, based on the available seismicity data. Zone 1 is the central portion of the arc where no trench is present and is assigned a maximum probable, magnitude of M_s 7 3/4. Zone 2 and Zone 3 include the northern and southern portions of the arc where the trench is present and are assigned a maximum magnitude of M_s 8. Zone 4 is the back-arc region and is assigned a maximum magnitude of M_s 7 1/2. Other zones of potential in the region are Zone 5 which refers to the Hazel-Holmes Fracture Zone which is assigned a maximum magnitude of M_s 7 and the North Fiji Basin which is assigned a maximum magnitude of M_s of 6 1/2.

Tsunami Hazard

The history of earthquake-generated tsunamis in Vanuatu indicates a possible hazard to Vanuatu's population. Tsunamis are of particular concern in low-lying coastal areas with concentrations of population. While tsunamis are not generated by all earthquakes, they must be considered a possible effect of all major earthquakes that occur in submarine areas that lie near the islands. Real-time monitoring of seismic activity, combined with an active tsunami education program, could significantly aid in tsunami risk mitigation.

Conclusions and Recommendations

We recommend that: (1) an earthquake and tsunami education program be adopted and combined with other disaster preparedness programs (e.g., hurricane, floods, and so on); (2) adoption of more stringent building codes for all of Vanuatu is strongly recommended; (3) long-term seismicity and strong motion observations be continued in order to refine estimates of seismic potential; (4) regional cooperation among the island countries of the Southwest Pacific be encouraged in order to assist in Vanuatu's earthquake preparedness program.

INTRODUCTION

The island countries of the Southwest Pacific are subject to natural disasters, including earthquakes, volcanic eruptions, and tsunamis, which threaten human life and property every year. Geological and geophysical observations indicate that these natural disasters are manifestations of continuous geological processes; the inexorable movements of the earth guarantee that they will continue to occur in the future.

The Southwest Pacific region is the source area for a large percentage of the world's seismicity. Approximately seventy percent of the world's intermediate and deep earthquakes occur in this region. A large number of great shallow earthquakes have taken place along the convergent plate boundaries that affect New Zealand, Kermadec Islands, Tonga, Vanuatu, Solomon Islands, and Papua New Guinea.

Normally, public attention focuses on emergency and rescue operations once a disaster has taken place. While little can be done to prevent earthquakes or volcanic eruptions from occurring, significant steps may be taken to minimize the destructive effects of such disasters. Scientists are striving to better understand what causes these phenomena and to learn what measures might be taken to mitigate their destructive nature. This report is a summary of the available scientific data that help constrain the potential for destructive earthquakes that may affect the populated areas of Vanuatu. The report is by no means the final analysis of earthquake hazards in Vanuatu; it is, however, a synthesis of available seismic information that provides a basis for judicious engineering, planning, and civil decisions in the years to come. Definitions of some of the technical terms that will appear in this report are contained in Appendix I.

The ultimate aim of earthquake hazard programs--mitigation of human and economic losses due to earthquakes--involves prediction of the frequency of occurrence and intensity of strong ground motion produced by future earthquakes of specific magnitudes in the vicinity of any given site. These predictions are often summarized in the form of seismic zoning maps and microzonation, which give the spatial distributions of the following parameters: maximum intensity of shaking, engineering design codes, maximum acceleration of ground motion (velocity, displacement) for given return periods of earthquakes of a particular size, or seismic risk (which relates to the expected human and property losses from earthquakes). In this report, we focus on the fundamental seismological observations that will provide the basis for more applied engineering studies of earthquake risk in Vanuatu.

The Republic of Vanuatu is located close to a major seismic zone with an historical and instrumental history of earthquakes with magnitudes as large as 8.0 (Isacks et al., 1981; Marthelot, 1983). In this tectonic environment, we are mainly concerned with the large, shallow, thrust-type earthquakes which accompany major rupture of the plate interface. While this type of faulting is responsible for the world's largest earthquakes (e.g., Aleutian, 1957; Chile, 1960; Alaska, 1964), there appear to be tectonic limitations on the maximum size of the thrust events. These limitations appear to be related to coupling between plates and lateral heterogeneities in the plate interface (Kelleher et al., 1973; Lay and Kanamori, 1981). In the Vanuatu region, the rupture length may be limited by major lateral variations on both the upper and lower plates (Isacks et al., 1981; Chatelain et al., in press).

Although Vanuatu is not heavily populated or industrialized, its proximity to a seismic zone leaves it particularly vulnerable to the risk of earthquake damage. Most of the damaging earthquakes come from the interplate zone beneath and trenchward of the islands, although back-arc and intermediate depth earthquakes are also felt. The capital city of Port Vila is now under increasing development pressures. The construction of multi-storied buildings to accommodate the increasing urban populations and tourism, as well as other essential structures such as dams and power plants, pipelines, schools, and hospitals, adds to the immediacy of the problem of earthquake risk.

Past disaster associated loss of life in the Republic of Vanuatu resulting from earthquake hazard has been relatively limited, but the increasing urban concentration and industrial development raises the potential human and economic losses brought on by a large earthquake occurring in the immediate vicinity. These losses are usually the result of the collapse of man-made structures and can be substantially reduced by adequate engineering precautions. To date, more deaths in Vanuatu have been caused by cyclones than by earthquakes, although material damage has been fairly severe from shaking, landslides, or tsunamis produced by earthquakes.

TECTONICS AND GEOLOGY

Plate Tectonic Setting

The Republic of Vanuatu lies along a portion of what is commonly called the "Pacific Ring of Fire." The concentration of earthquakes (Figure 1A) and volcanoes (Figure 1B) along this trend were used to

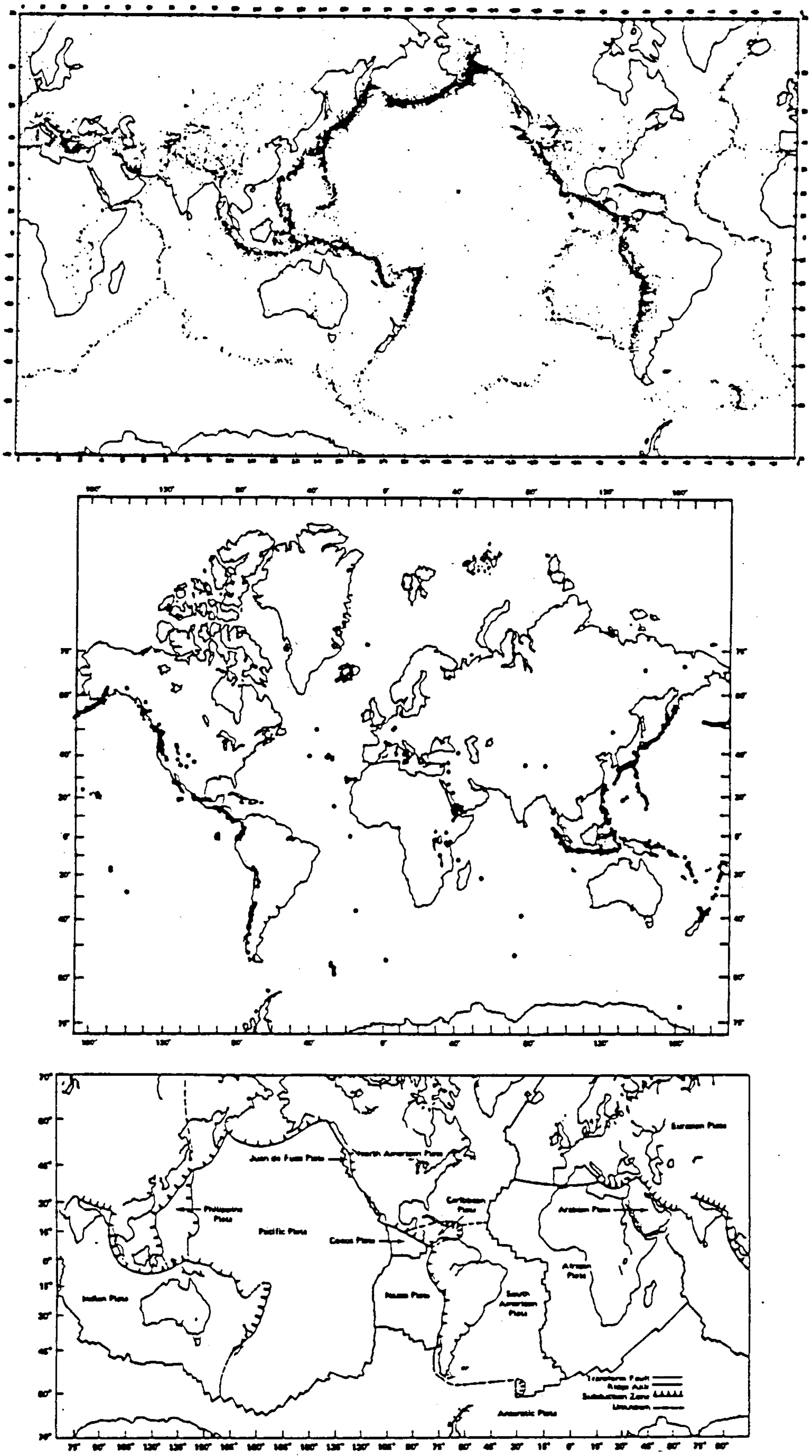


Figure 1. World distribution of (A) earthquakes and (B) volcanoes. (C) Configuration of the major tectonic plates on the earth's surface (Turcotte and Schubert, 1982).

establish the boundaries of the lithospheric plates in the modern view of plate tectonic theory (Figure 1C). These plates, which are relatively rigid, cover the surface of the earth like a mosaic of rigid caps, and move against each other by sliding (1) past at a transform fault, (2) over at a convergent margin (such as subduction at a deep sea trench), or (3) apart from one another at a divergent margin (such as spreading at a mid-ocean rift). Figure 2 shows schematically the spatial relationship of these different types of boundaries. Convergent plate boundaries are responsible for the majority of the world's large earthquakes and most of the world's tsunamis. Many volcanic arcs form parallel to these deep-sea trenches, above the point where the subducted plate reaches about 100 km depth (Isacks and Barazangi, 1977). The relative motion of two convergent lithospheric plates may be accumulated over a time period of tens to hundreds of years and then released in large earthquakes or aseismic creep (motion without earthquakes) may occur instead of earthquakes. The area over which the descending and over-riding plates interact, the age of the sea floor, the topography of the sea floor and many other factors appear to influence the recurrence interval, and the size of earthquakes along the interplate zone.

The New Hebrides island arc trends linearly south-southeastward from 11°S to approximately 20°S (Figure 3). The northern end of the trench bends sharply westward to merge with the east-west trending Solomon Trench. The southern end of the trench curves around eastward to merge with the east-northeast trending Hunter Fracture Zone. The arc is a component of the Melanesian Borderlands that form the boundary between the Indo-Australian and Pacific lithospheric plates (Figure 4). This

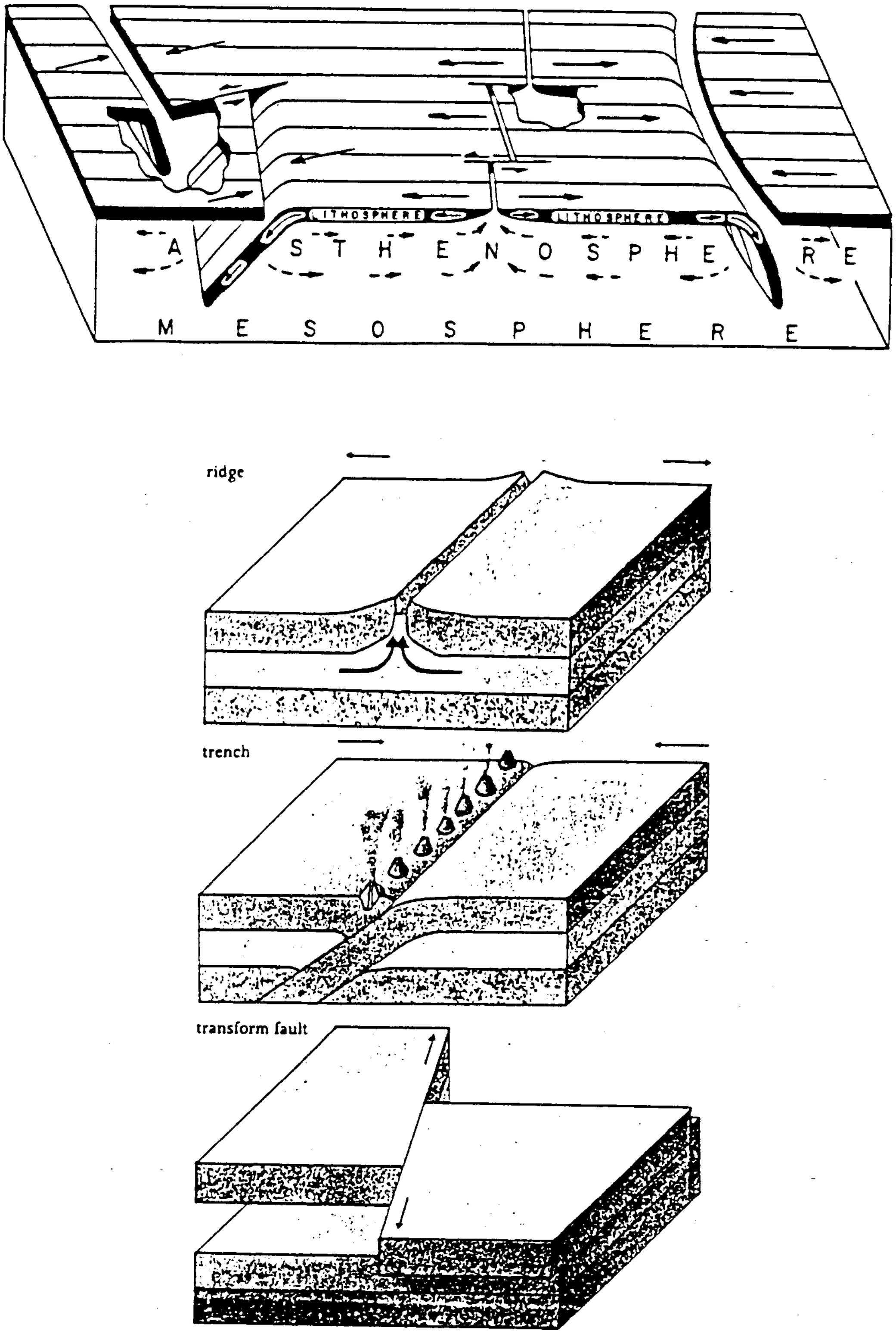


Figure 2. (A) Sketch of the different types of plate tectonic boundaries and their relationships (Isacks et al., 1968). (B) Diagrams of the three types of boundaries in three dimensional view (Calder, 1972).

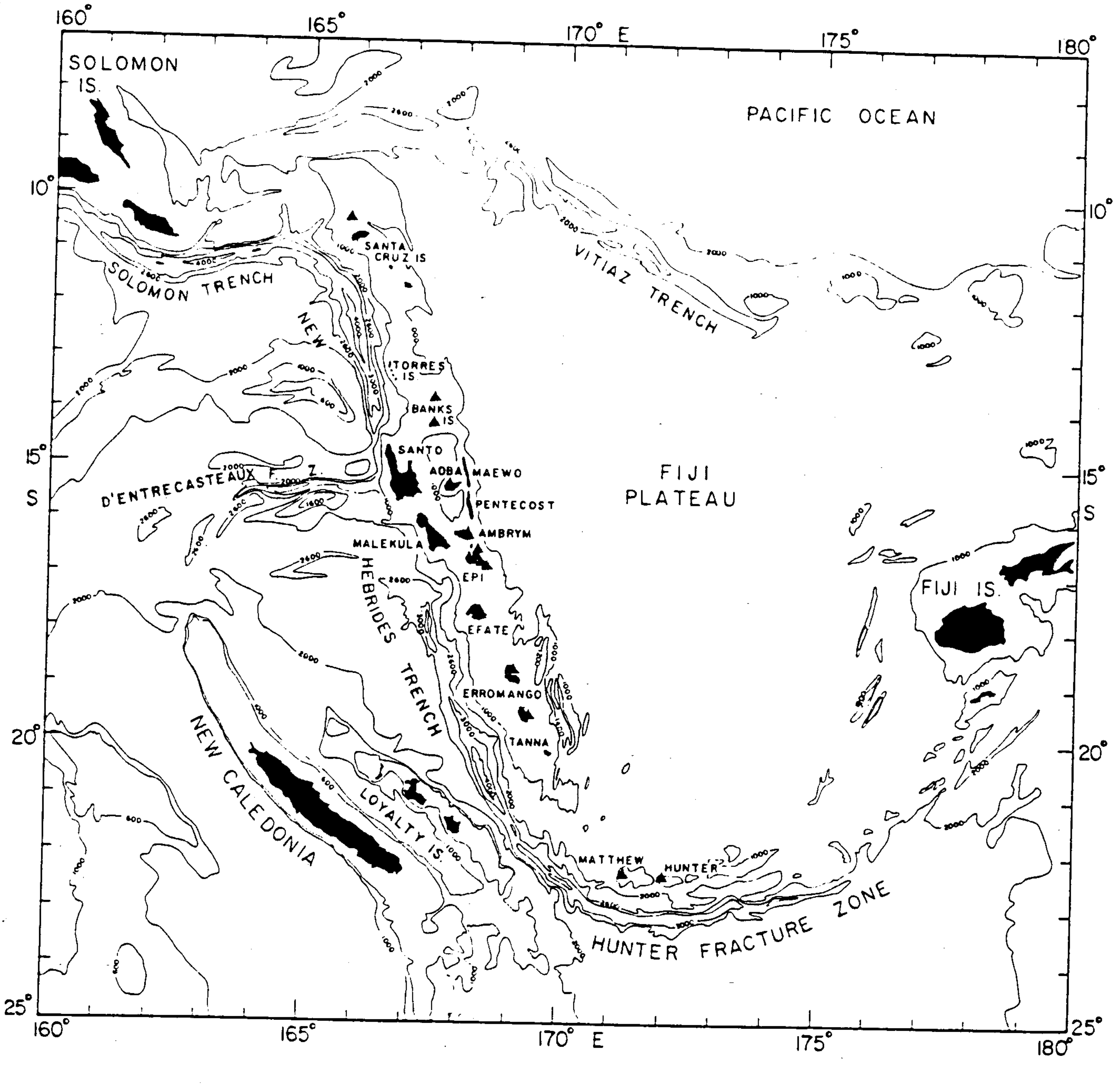


Figure 3. Bathymetric map of the New Hebrides Island arc and the surrounding region, taken from Mammerickx et al., 1971. The filled triangles denote Quaternary volcanoes. Contours are in fathoms.

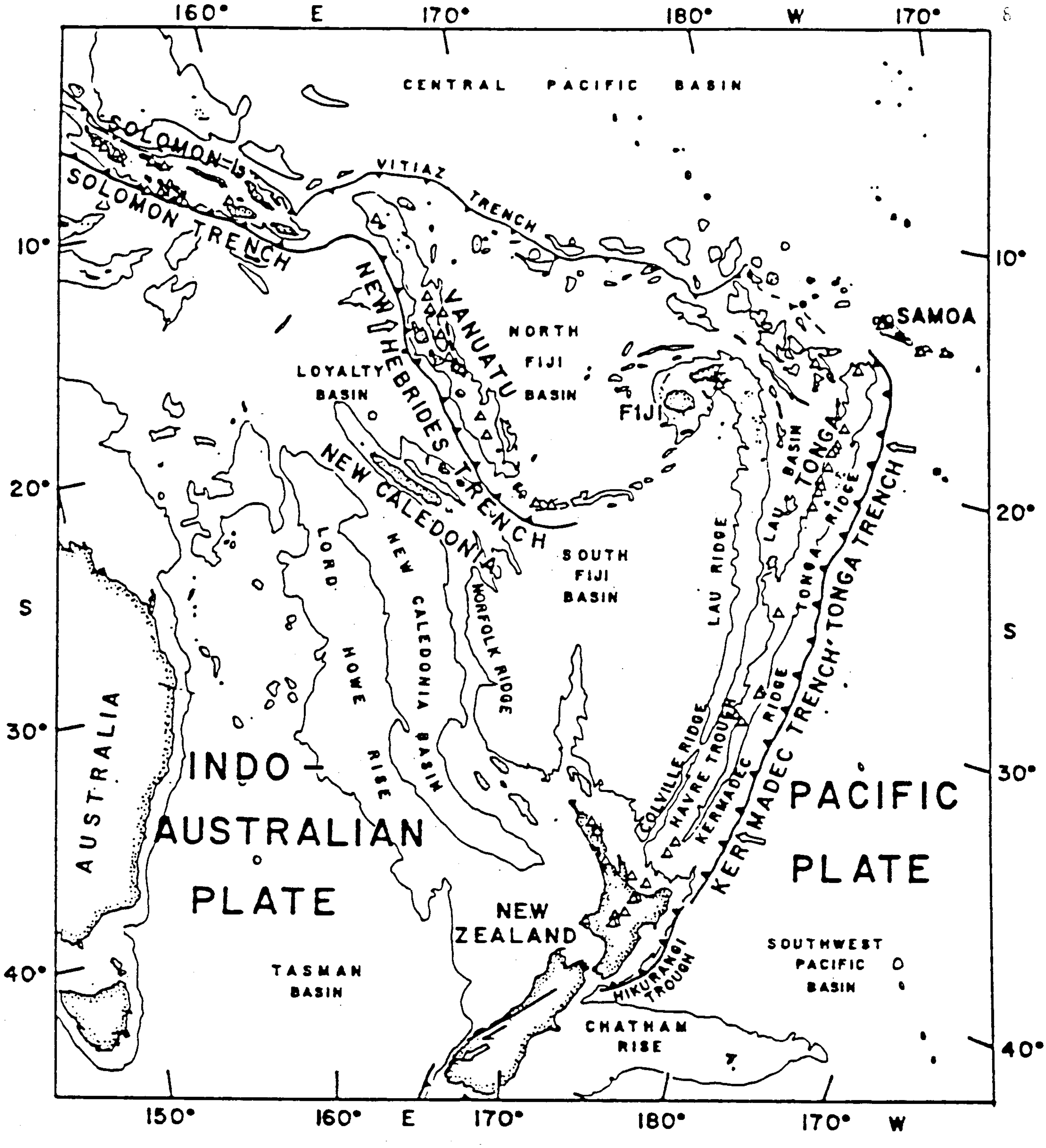


Figure 4. Regional setting of the Southwest Pacific. Tectonic and morphologic features of the Pacific/Indo-Australian plate boundary. Open arrows indicate direction of relative plate convergence. Contour line shows 2-km isobath. Holocene volcanoes are indicated by open triangles. Data on bathymetry, seismicity, volcanoes, and plate motions are taken from the Circum-Pacific Council for Energy and Mineral Resources (1981) map.

intra-oceanic arc is unusual in that the subducting slab dips toward the Pacific Basin. The Indo-Australian plate is being subducted at a rate of approximately eleven centimeters per year (Dubois et al., 1977; Pascal et al., 1978; Isacks et al., 1981) in a direction perpendicular to the trench (Isacks et al., 1969; Johnson and Molnar, 1972; Pascal et al., 1978). Relative to other convergent plate boundaries (e.g., Chile and Alaska), the width of the zone of interaction between these two plates is limited to approximately 50 km in extent because the subducting (Indo-Australian) plate is steeply downbent (70°) at intermediate depths. This geometry produces a narrow ribbon of potentially damaging seismicity rather than a large region of seismicity. The northern and southern portions of the arc are typical of arc-trench systems, but the central portion exhibits several unusual features: (1) The bathymetric expression of the trench is obscured between 13°S and 17°S where a submarine ridge known as the d'Entrecasteaux Fracture Zone intersects it at approximately 16°S. (2) The upper plate protrudes westward in this central portion of the arc such that the western coast of Malekula Island is located where the inner slope of the trench is normally positioned (Karig and Mammerickx, 1972; Isacks et al., 1981; see Figure 3).

Shallow Vanuatu earthquakes (Figure 5) are located in the interplate zone between the two plates. They are associated with slippage of the Indo-Australian Plate as it descends beneath the Pacific Plate. Intraplate earthquakes also occur within the descending and overlying plates in the trench region and behind the island arc in what is known as the back-arc region. An actual and a schematic, vertical cross section near Tanna, perpendicular to the trend of the arc, is representative of the

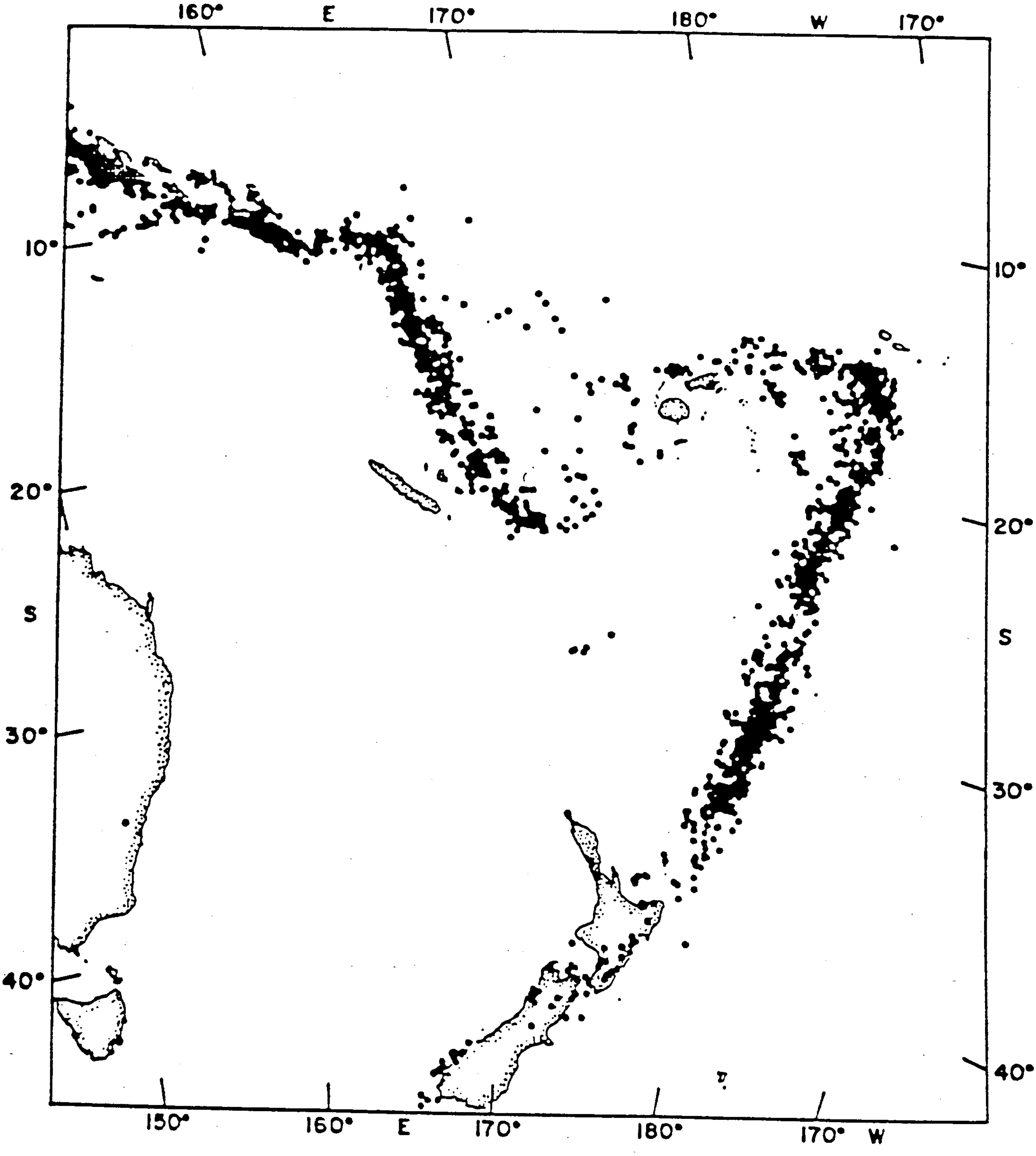


Figure 5. Regional setting of the Southwest Pacific. Shallow seismicity associated with the plate boundaries in this region.

relationship of the seismicity to the trench, islands, and back-arc region (Figure 6). In Vanuatu, earthquakes occur from near the surface to approximately 300 km depth. The earthquakes systematically deepen eastward, from the New Hebrides Trench, forming a narrow dipping plane (Benioff zone). Thus shallow, potentially destructive earthquakes occur under islands located in the central portion of the arc, and intermediate depth earthquakes occur progressively farther eastward. Large ($M_s \geq 7$) earthquakes, but few great ($M_s \geq 7\ 3/4$) earthquakes, have occurred along the island arc as a result of the subduction of the Indo-Australian plate.

In spite of the anomalous protrusion of the upper plate in the central part of the arc, the Benioff zone and convergent plate boundary appear to be relatively uniform in configuration and continuous along the entire length of the arc (Pascal et al., 1978; Isacks et al., 1981). The linear distribution of the islands of Vanuatu and their location so close to the main interplate thrust zone of the convergent plate margin result in a geometry that is uniquely suited for subduction zone studies in comparison to most other subduction zones on earth. This also results in a unique earthquake hazard in central Vanuatu. Behind and eastward of the New Hebrides island arc lies the North Fiji Basin (Figure 4) where the presence of shallow seismicity (Figure 5), fresh basalts, little sedimentation (Karig and Mammerickx, 1972; Luyendyk et al., 1974), and high values of heat flow (Sclater and Menard, 1967) indicate active tectonism. The Vitiaz Trench forms the northern boundary of the North Fiji Basin and represents the site of an old subduction zone that existed before the modern New Hebrides arc formed. Subduction (of the Pacific Plate) ceased at the Vitiaz Trench sometime in mid-Miocene (Falvey, 1978) or earlier (Chase,

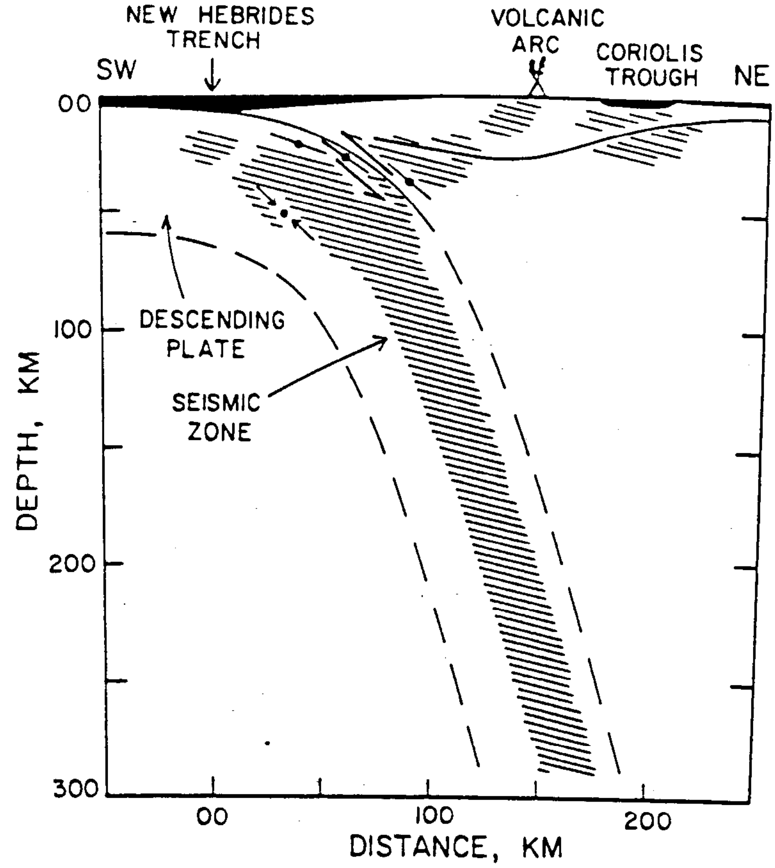


Figure 6. A schematic cross secion showing the region where shallow and intermediate-depth earthquakes were recorded (inclined lines) and the inferred geometry of the descending plate beneath the southern New Hebrides arc. The inferred geometry of the interplate thrust zone is partly based on the slip vectors (short, solid lines) of the shallow thrust-type focal mechanisms. The Moho discontinuity of the overriding plate estimated from refraction and gravity studies is also shown (Condert et a., 1981).

1971; Mitchell and Warden, 1971; Karig and Mammerickx, 1972) and resumed at the modern New Hebrides Trench with the opposite polarity (Indo-Australian Plate underthrusting beneath the Pacific Plate). Deep earthquakes are still recorded near Vanuatu that result from this episode of subduction. The New Hebrides arc has migrated away from the trend of the older Vitiaz Trench to its present position (Hamburger, 1986).

Geological Setting

The islands of Vanuatu are volcanic in origin with older islands fringed or capped with reefal limestones. In the central region of the arc, the single chain of islands gives way to a more complex structure (Figure 7): (1) the eastern Miocene-Pliocene chain, with tholeiitic and calc-alkaline volcanoclastics, includes the islands of Maewo, Pentecost, Efate, and parts of Epi; (2) the slightly older western Oligocene-Miocene chain includes the islands of Santo, Malekula, and the Torres and (3) the central late Pliocene-Recent portion contains active aerial and subaerial alkaline volcanics (Mitchell and Warden, 1971). The volcanic rocks of the western chain are similar to slightly more acidic composition than the eastern chain. Local outcrops of ultramafic rocks are found in several places in the eastern chain.

REGIONAL BACKGROUND INFORMATION

Historical Earthquakes in the Vanuatu Region

An accurate evaluation of the earthquake hazard for a particular region includes a survey of historical seismicity in the region in question. Historical earthquakes are important because they help to better determine the potential size, frequency of occurrence, and possible effects of future earthquakes.

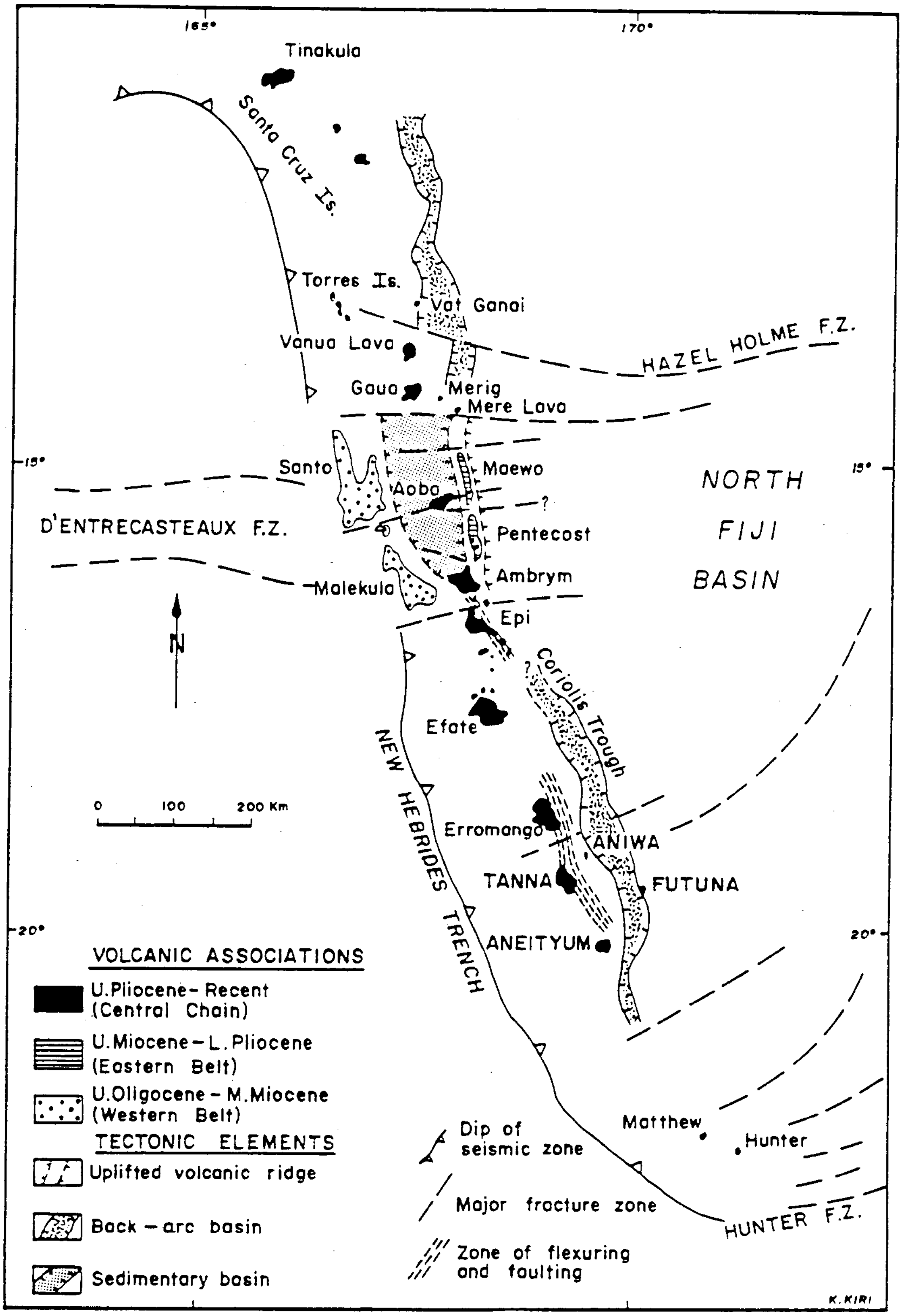


Figure 7. Geology of New Hebrides Arc (Carney and Macfarlane, 1979).

The earliest reports of earthquakes in the Vanuatu region is a series of earthquakes which began on 28 March 1875 and were felt on Anatom (Mercalli intensity VIII-IX for the largest event) and Erromango and in the Loyalty Islands of Lifou, Mare, and Ouvea (Iida et al., 1967). On 10 January 1878, a tsunamigenic earthquake associated with the eruption of Yasowa Volcano, Tanna was felt in Port Resolution, Tanna. Another strong tsunamigenic earthquake occurred on 11 February 1878 associated with another eruption of Yasowa Volcano.

Since 1900, 5 great earthquakes ($M_s > 7\ 3/4$) and 52 major earthquakes ($7 \leq M_s < 7\ 3/4$) have occurred along the arc (McCann, 1980). However, the great earthquakes that occurred near the turn of the century are not well-constrained in size or place and their magnitudes were probably overestimated (due to the way in which the magnitudes were calculated). Moderate-sized earthquakes are distributed throughout the arc (Figure 8C), but the largest events are more clustered, especially in the northern portion of the arc (Figure 8B; Marthelot, 1983 and Figures 9A and 9B; McCann, 1980). There is a distinct gap in the seismicity at the point where the d'Entrecasteau Ridge intersects the line of the trench.

Because the occurrence of shallow earthquakes near population centers are of greatest concern for earthquake hazard, in this report we have focussed on shallow earthquakes near the main islands of Santo, Malekula, and Efate in the central portion of the arc. Maps of shallow seismicity (depth $\leq$ 70 km) of the region, based on the U.S. Geological Survey's Preliminary Determination of Epicenters (PDE) catalog for the period 1961-1981 are shown in Figure 8B and 8C (from Marthelot, 1983). This

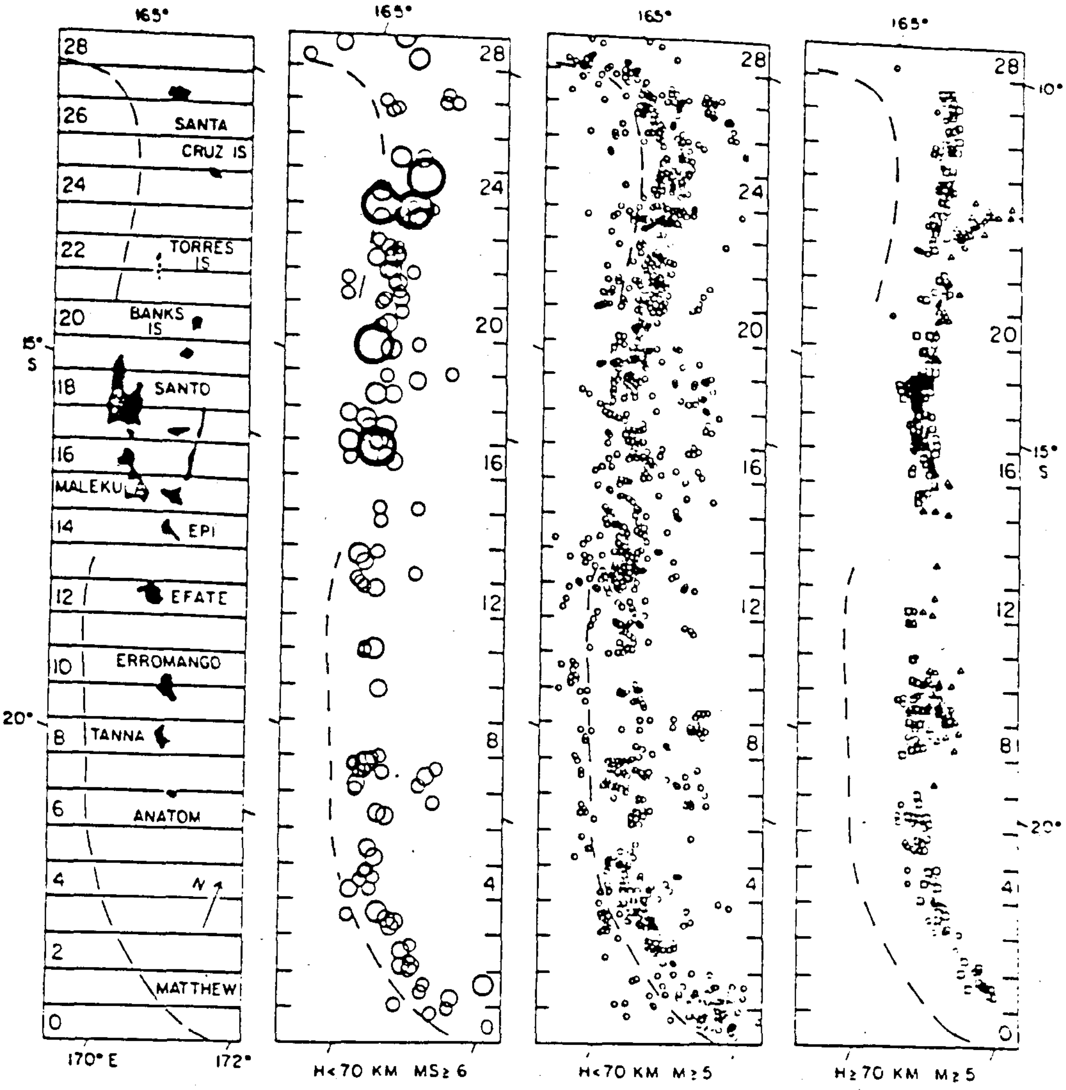


Figure 8. Map of the Vanuatu island arc (far left) showing how the arc has been divided in contiguous segments identified by a number from 0 to 28 to study the distribution of the events located in the arc. The dashed lines represents the axis of the trench. The trench disappears in the central part of the arc. The remaining maps show the distribution of the seismicity in the period from 1961 through 1981. From left to right, they respresent 1) shallow earthquakes (h < 70 km) having magnitude $M_s > 6$ (the size of the circle increases for each 0.5 unit of magnitude and the largest size shown represents $M_s = 7.5 - 7.0$); 2) shallow earthquakes (h < 70 km) having magnitude larger than 5; and 3) intermediate-depth earthquakes (h> 70 km) having magnitude larger than 5 (circles represent earthquakes with depths between 70 and 100 km; squares, between 100 and 200 km; triangles, between 200 and 340 km). Note: (1) the concentration of large shallow events in the northern half of the arc that contrasts with the juxtapostion of active and quiet regions in the southern half; (2) the presence of nests and gaps of intermediate-depth activity.

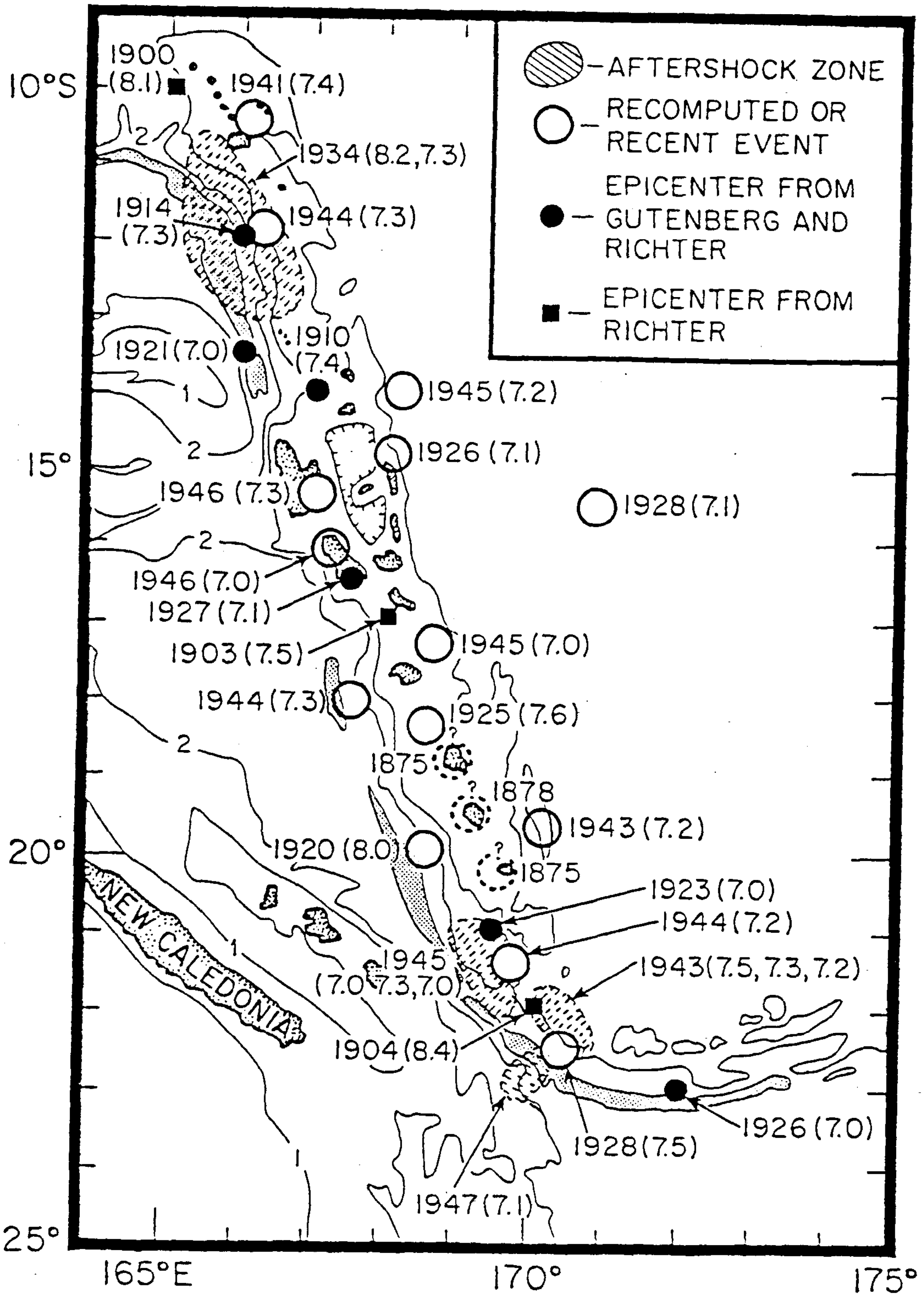


Figure 9A. Map showing locations of large ($M_s > 7$) and great ($M_s \geq 7$ 3/4) historical earthquakes along the New Hebrides Trench for the time period 1900 to 1950 (McCann, 1980).

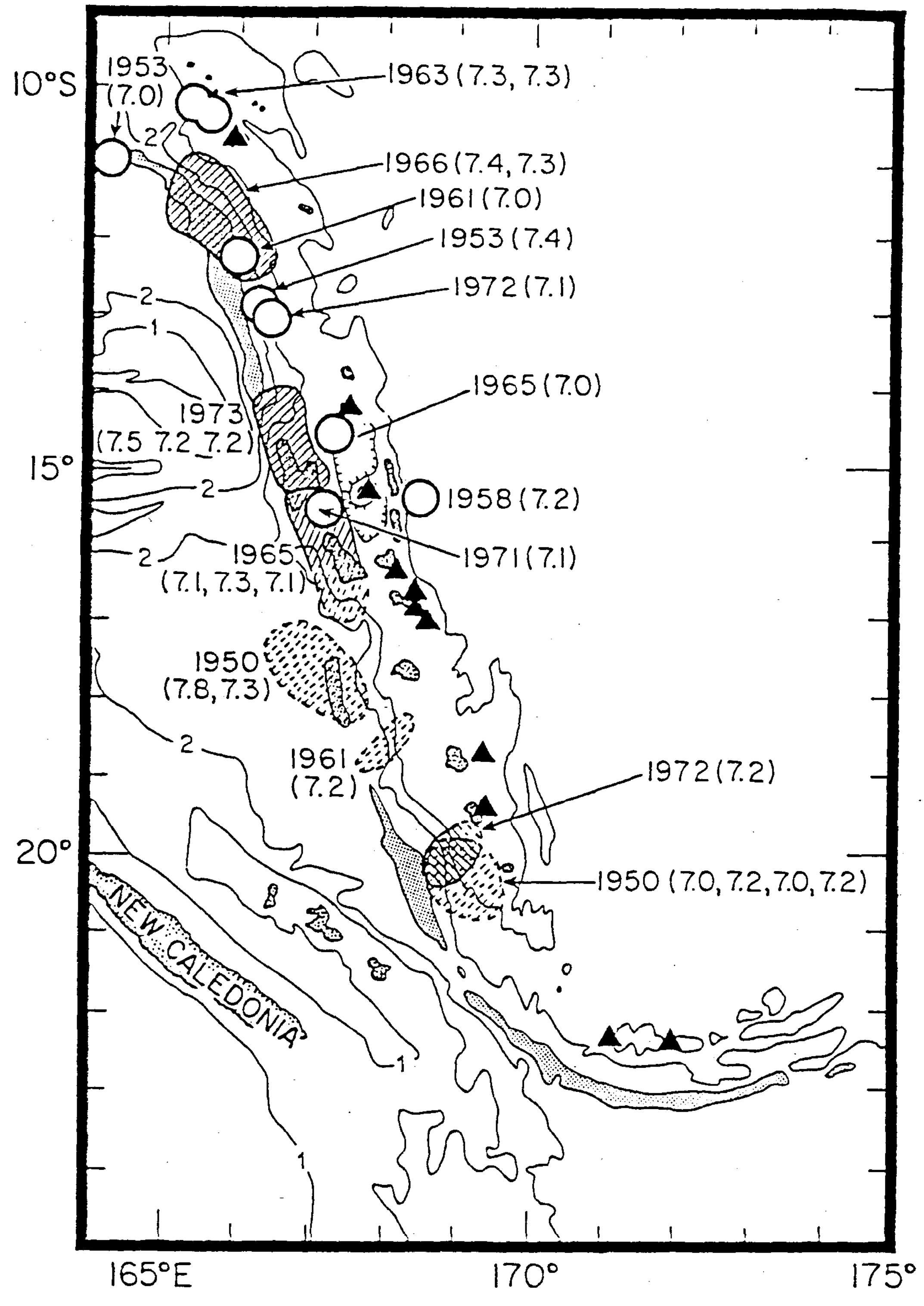


Figure 9B. Map showing locations of large ($M_s > 7$) and great ($M_s \geq 7\ 3/4$) historical earthquakes along the New Hebrides Trench for the time period 1950 to 1979 (McCann, 1980).

figure illustrates the dense concentration of interplate events close to and landward of the New Hebrides Trench.

Very little information exits concerning the effects of strong earthquakes prior to 1961, apart from a few sketchy damage reports. The location accuracy of earthquakes was improved in 1961. Before this time locations were located to the nearest tenth of a degree and magnitudes were considerably over-estimated. The last major seismic episode of interplate slippage in central Vanuatu occurred in a sequence of earthquakes in August 1965 (Figure 10) which accumulated a total seismic moment equivalent to a single magnitude $M_S = 7.7$ event (Isacks et al., 1981). The 1965 Santo earthquakes caused significant damage to buildings, wharves, and bridges in Luganville on Santo Island and major damage to buildings and water tanks in Norsup and Sarmet on Malekula Island (Prévot and Chatelain, 1983). Coseismic tectonic uplifts on Malekula Island were also measured in association with the 1965 earthquakes (Figure 10). Over 1 meter of uplift was detected for the 1965 earthquake sequence (Taylor et al., 1980).

Only one sequence of earthquakes has been relatively damaging since the Cornell-ORSTOM network began operating in 1978. The Mere Lava earthquake (M_S 6.1) occurred on 12 May 1980 at 14.80°S and 167.82°E and a depth of 23 km. The worst damage from this event was caused by landslides.

SUMMARY OF FACILITIES AND PROGRAMS

Critical Facilities

Port Vila, with a population of 15,088 in 1979, is the administrative and commercial center of the country. There are a number of multistory buildings in the capital, and most of Vanuatu's tourist industry is located

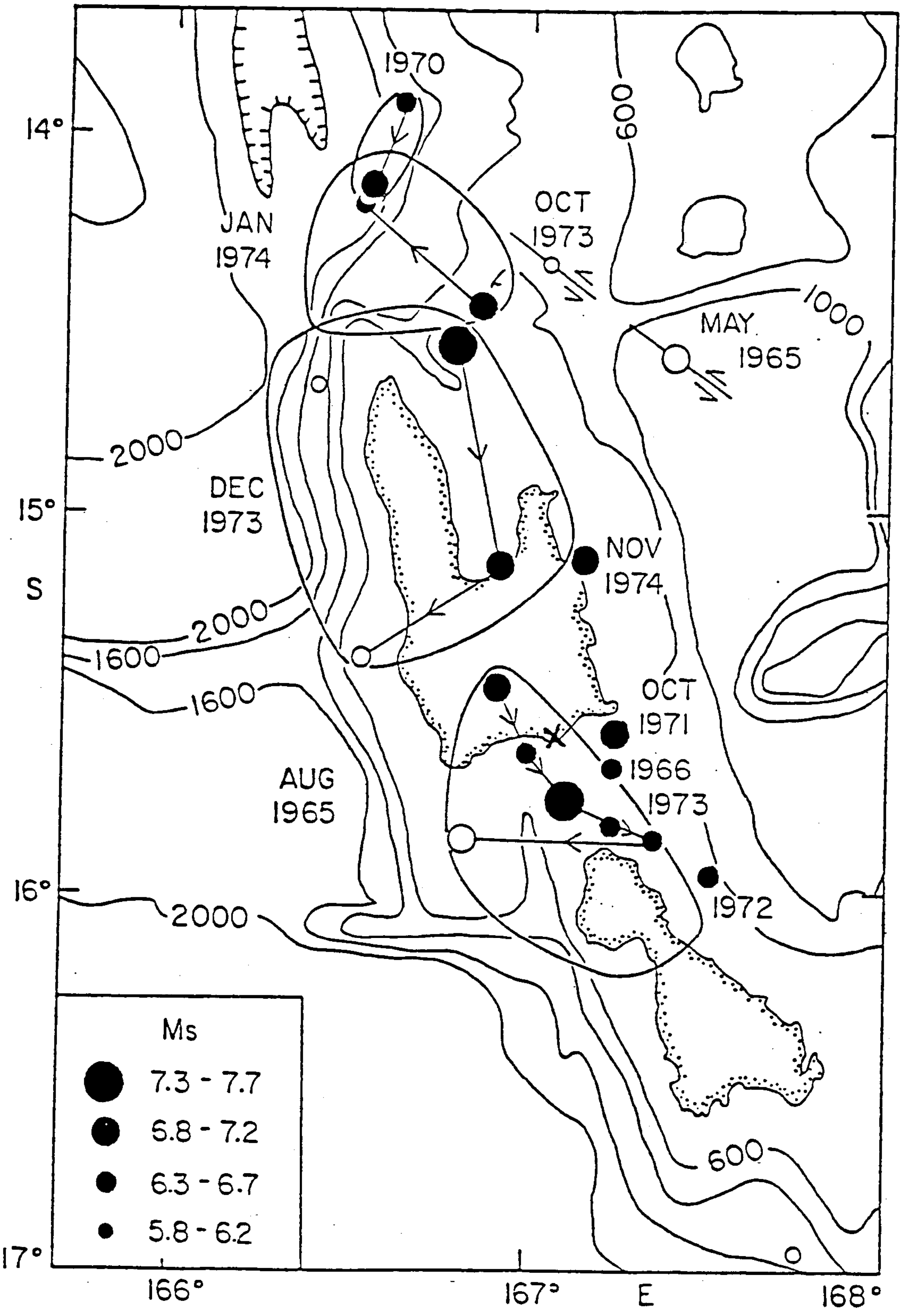


Figure 10. August 1965 earthquake sequence (from Isacks et al., 1981).

in and near Port Vila. A large shipping wharf is located near the center of the city, on Vila Bay.

Apart from Port Vila, the only significant development in Vanuatu is at Luganville, on Santo Island (pop. 5116 in 1979). It remains an important economic center for the country, with agricultural processing and shipping facilities located there. There are several three- and four-story buildings in the center of Luganville.

Earthquake Preparedness Programs

As of late 1983, the Government had requested the assistance of a consultant from New Zealand to help provide uniform building codes for the country. The Public Works Department enforces New Zealand seismic zone "B" codes to construction of public buildings. Large buildings for the most part are designed by overseas engineering firms, and generally comply with the earthquake design standards. Smaller buildings are generally designed close to the New Zealand loading specifications, but there continues to be great difficulty in supervising construction projects.

There is no large-scale earthquake education program in Vanuatu. Materials have been prepared by ORSTOM seismologists for distribution to teachers, public officials and planners involved in earthquake hazards (e.g., Prévot and Chatelain, 1983).

Seismological Facilities

Seismological observations are necessary to the accurate location, study, and ultimate prediction of earthquakes. Seismic stations were first established in Vanuatu in the mid-1960's by the French Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM). Station PVC in Port Vila has operated continuously from 1964 to the present, while LUG in

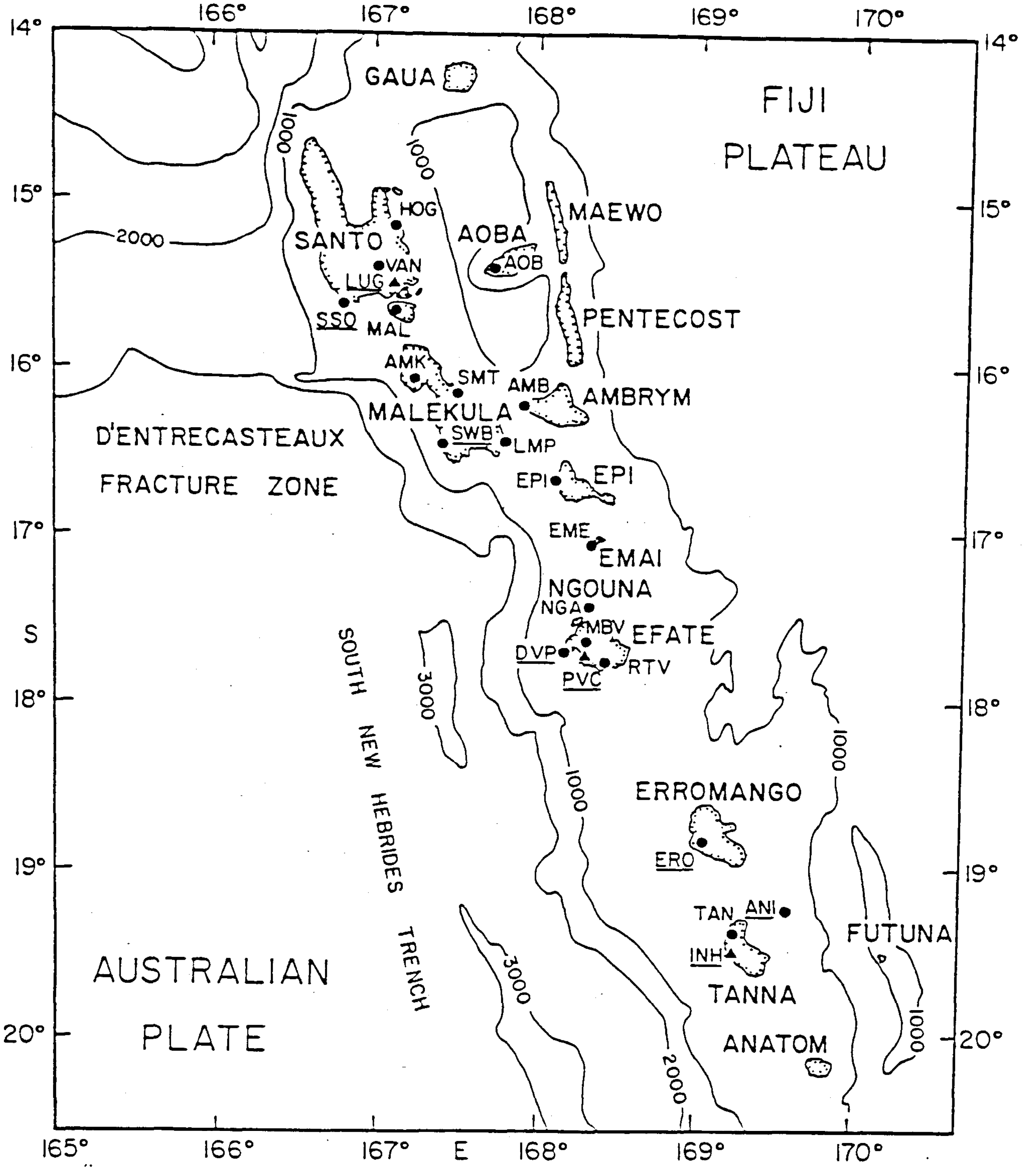


Figure 11. Map showing the seismograph stations in Vanuatu. Circles are stations telemetered to the base station PVC on Efate island, and underlined stations have two components--one horizontal and one vertical. The triangles are older ORSTOM stations. INH and LUG are no longer operational. Strong motion instruments are located at SWB and LMP on Malekula island, DVP and PVC on Efate island, and LUG on Santo island.

Luganville, Santo operated through 1980. A third station on Tanna Island (INH) operated through 1978. Cornell University began cooperative field programs with ORSTOM in 1975 with a microearthquake experiment on Santo Island. An ocean-bottom seismograph experiment was carried out in southern Vanuatu in 1977 and in central Vanuatu in 1978. The Cornell-ORSTOM telemetered seismic network was established in 1978, and has operated continuously since that time. The seismic network now includes 19 telemetered stations (Figure 11); to date, over 20,000 earthquakes have been recorded by the network. A permanent ORSTOM mission is now based in Port Vila and takes primary responsibility for day-to-day maintenance of the network. The availability of continuous earthquake monitoring in Vanuatu is an important component of any earthquake or earthquake hazard study for the country. Figure 12 shows the seismicity level (magnitudes > 4) recorded by the Worldwide Seismograph Station Network (WWSSN). Compare these results with the increased sensitivity (magnitude > 2.5) and location accuracy of the regional Cornell-ORSTOM network which is shown by better definition of seismic zones in Figure 13. These network data clearly define the heterogeneous distribution of seismic activity in the central portion of the arc.

These seismological facilities are complemented by studies of ground deformation using seven bubble-level tiltmeters, a two-component long-baseline water tube tiltmeters, and two levelling arrays.

Strong-Motion Accelerographs.

As part of the present program of seismic hazard evaluation in Vanuatu, Cornell and ORSTOM have installed five strong-motion accelerographs on the islands of Efate, Malekula, and Santo (Figure 11).

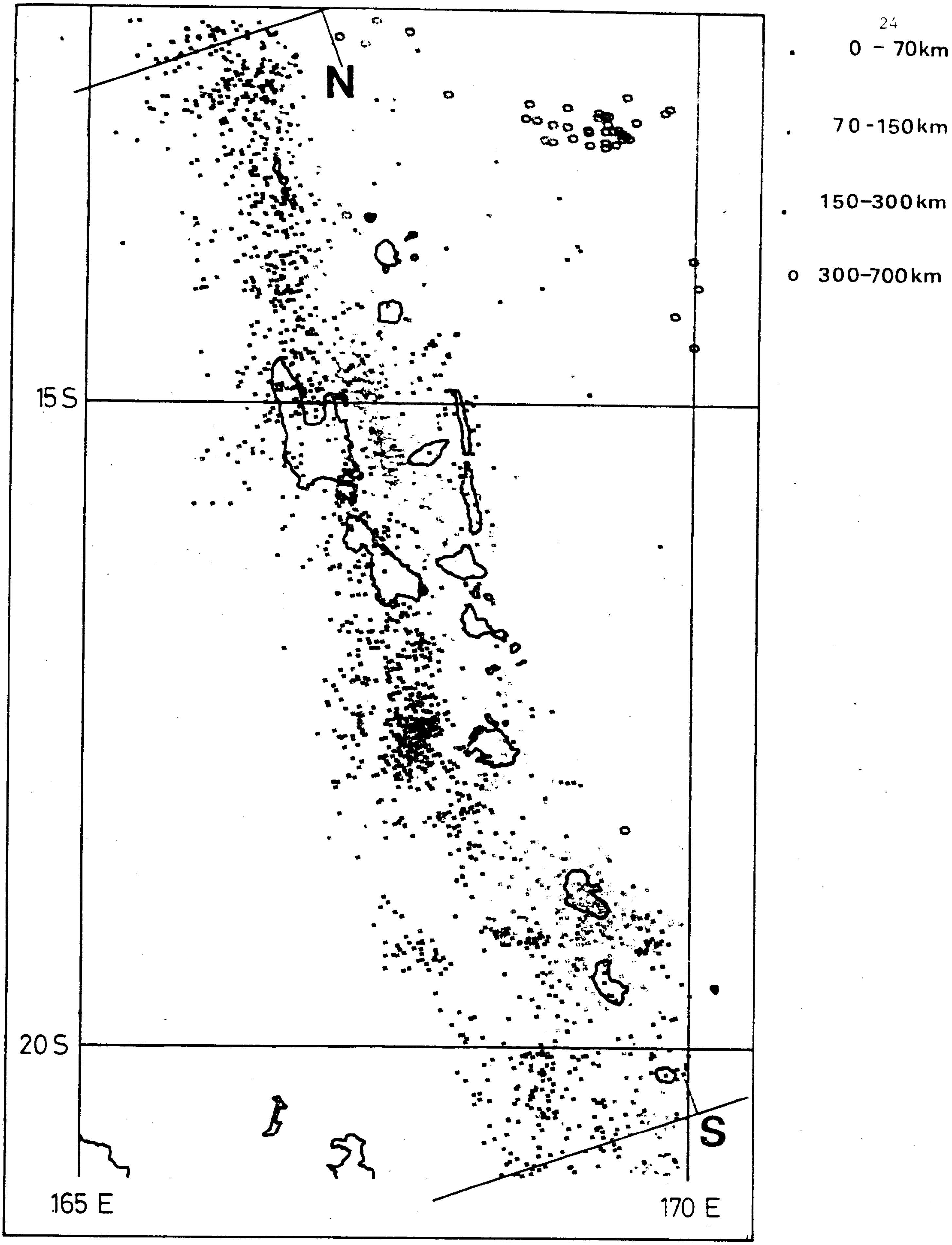


Figure 12. Epicentres des séismes localisés par le réseau mondial de stations (1967-1982). PDE locations of events (1967-1982). (Prévot and Chatelain, 1983).

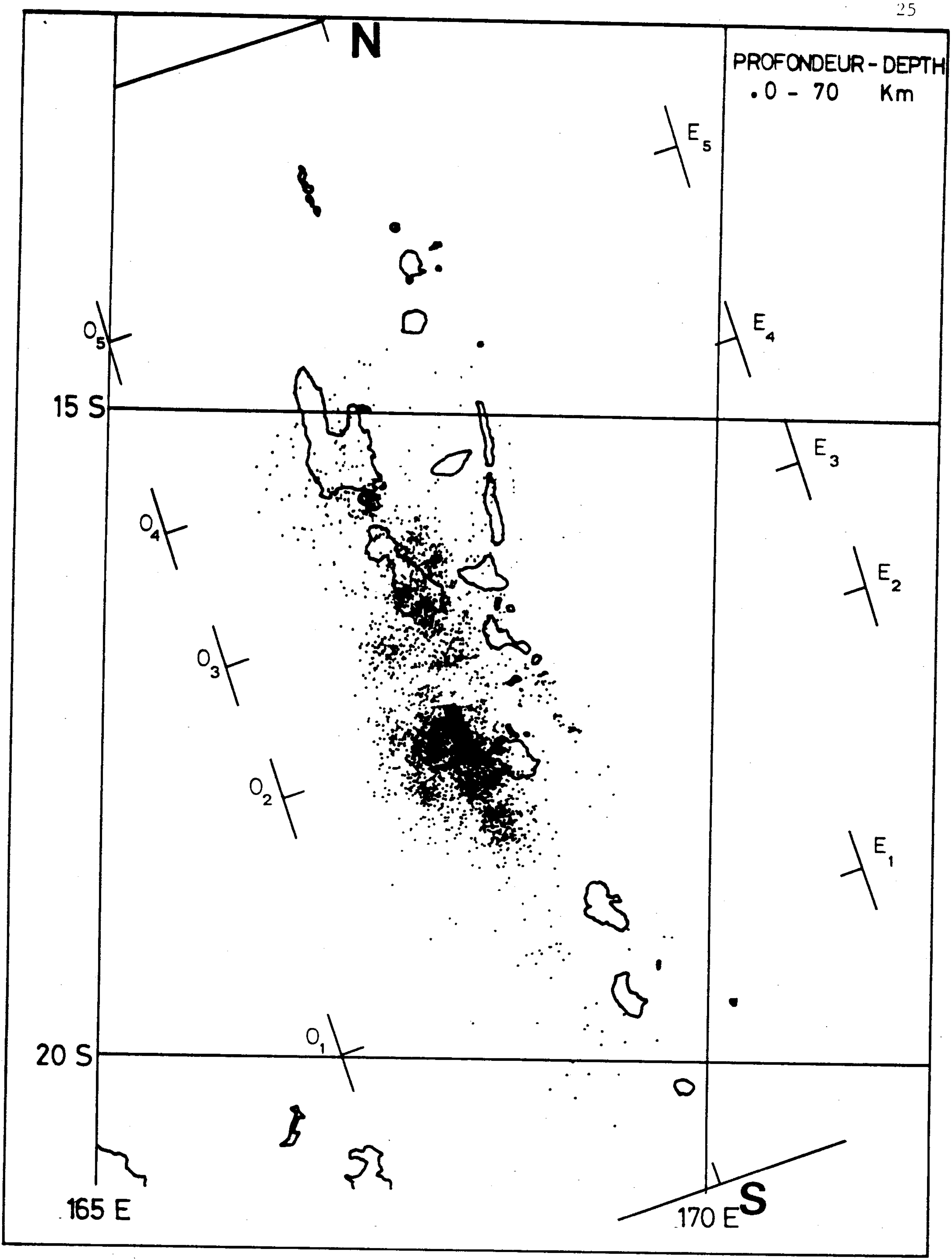
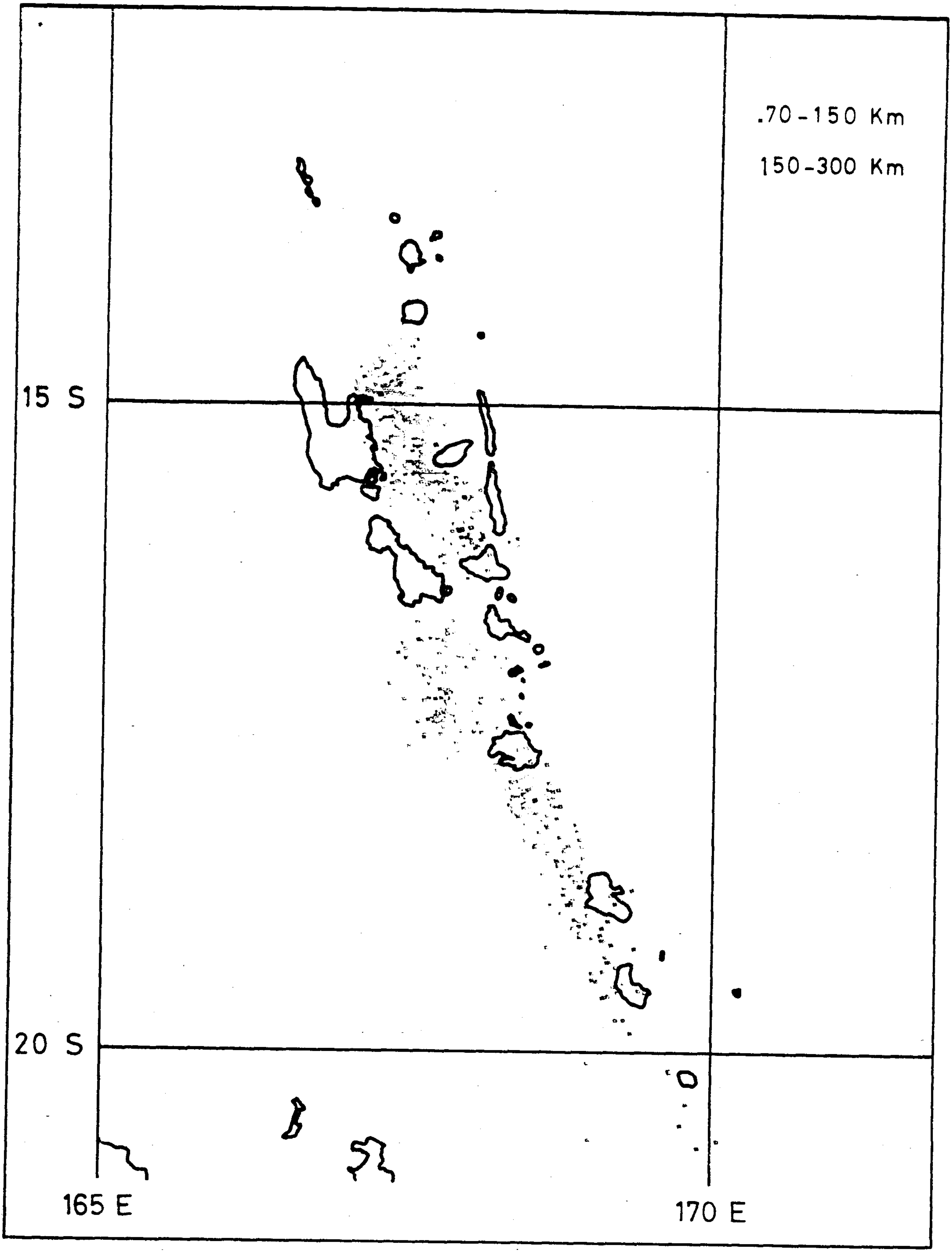


Figure 13. Epicentres des séismes localisés par le réseau ORSTOM-CORNELL (1978-1982). Epicenters of events located by ORSTOM-CORNELL network (1978-1982). (Prévot and Chatelain, 1983).


.70-150 Km
150-300 Km
15 S
20 S
165 E
170 E

These accelerographs complement the other instruments being used to study the seismicity in the region. The accelerographs record the ground accelerations at a particular site from an earthquake strong enough to trigger the instrument. To date, these instruments have already been triggered by five moderate-sized shallow events, and will be used to provide a basis for prediction of local ground motion induced by large interplate earthquakes in Vanuatu. The high level of seismicity along this plate boundary suggests that a valuable baseline of strong-motion data can be collected in a relatively short period of time.

Related Research Programs.

The seismology program is carried out in cooperation with the Vanuatu Department of Mines, Geology, and Rural Water Supplies. They are responsible for regional geology studies, resource assessment, detailed mapping, and hydrological activities. In addition, ORSTOM's geology and geophysics department, based in New Caledonia, carries out an extensive program of investigations, covering submarine morphology, marine geology and geophysics, island geology, and crustal structure. The U.S. Geological Survey has undertaken a series of detailed marine studies in the central and northern portions of the island arc using the research vessel S.P. Lee (1982 and 1984). A detailed hydrographic survey was carried out in coastal waters by Australian researchers. A tide gauge is maintained by the ORSTOM mission in Port Vila (Prévot and Chatelain, 1983).

PREVIOUS STUDIES

Seismicity Studies Along the New Hebrides Arc

Seismicity studies of the New Hebrides Arc by Isacks et al. (1981) found that major bathymetric and structural complexities divide the central part of the arc into segments approximately 100 km long. The segment near Santo and northern Malekula islands ruptured during two complex sequences of events occurring in August 1965 and in late December 1973 through early January 1974 (Table 1). In contrast, the segments near the southern part of Malekula and Efate islands may not have ruptured during the past 75 years. Moreover, between southern Malekula and Efate islands, the orientation of the horizontal compressive stress within the upper plate changes from a direction perpendicular to the arc to a more complex and variable pattern found in the southern portion of the arc.

Since the Cornell-ORSTOM network was established in 1978, 10 moderate ($5.8 < M_S < 7$) earthquakes have occurred within the network (Table 2). A description of the seismicity recorded by the network follows:

(A) Fore- and Aftershock Sequences of the August 1979 and July 1981 Main shocks

(1) 17 August 1979 Sequence. Figures 14A and 14B show earthquakes in the foreshock sequence of the 17 August 1979 earthquake. The spatial and temporal development of this activity was described by Isacks et al. [1981]. This section provides a more detailed analysis of a longer period of time. A small zone near the epicenter of the 17 August earthquake was intermittently active during late June - early July 1979 (Figure 14A). The more immediate foreshock sequence (Figure 14B) started eight days before the main shock and consisted of five groups of events. Each group of foreshocks began with an earthquake having a magnitude between 4.2 and 4.9, and each was followed by a number of small aftershocks. The first foreshock cluster was located just landward of the trench. Each successive cluster migrated in time northeast toward the

Table 1: Events of northern Santo ('73/'74)

	Event	Date GMT	Depth, km	M_s	
A	12-28-83	13:41:46	18 ± 4		7.4
B	12-29-73	00:19:30.8	43	6.4	7.2
C	12-30-73	16:39:30.9	10		6.6
D	01-10-74	08:51:13.8	36	7.6	7.1
E	01-11-74	05:36:34.3	37	7.6	6.4

Table 2: Parameters of Mainshocks ($M_w \geq 5.8$)

Date	Origin time HR:MN	Lat[1] °S	Long[1] °E	Magnitudes		
				M_s[2]	M_w[4]	M_0[3] x 10^{25} dyne-cm
01 Sep 1978	04:16	17.38	167.88	5.9	6.0	1.1
27 Jan 1979	18:15	18:52	168.15	6.3	6.2	2.1
17 Aug 1979	12:59	17.73	167.87	6.1	6.3	3.1
26 Aug 1979	11:47	17.63	167.71	6.0	6.2	2.5
15 Jul 1981	07:59	17.26	167.60	7.1	7.1	58.
18 Jan 1982	04:23	17.33	167.80	5.6	5.8	0.63
12 Mar 1983	08:49	18.15	168.16	5.8	6.1	1.7
03 Aug 1983	18:17	17.47	167.81	5.6	5.8	0.68
05 Aug 1983	05:25	17.36	167.81	5.7	5.9	0.96
03 Jul 1985	15:55	17.24	167.83	6.4	6.4	5.9

[1] Relocations with all available teleseismic and local data for 1978-1981 events, except 27 Jan 1979 [Bulletin of the International Seismological Centre (ISC) location]; remaining locations based on local data only.

[2] M_s, surface-wave magnitude taken from Monthly Bulletins of the Preliminary Determination of Epicenters (PDE).

[3] M_0, seismic moments reported by Chinn and Isacks [1982] or in Monthly Bulletins of the PDE (1981-1985 events).

[4] M_w is calculated from M_0 by $M_w = (1/1.5) \times (\log(M_0)-16.1)$.

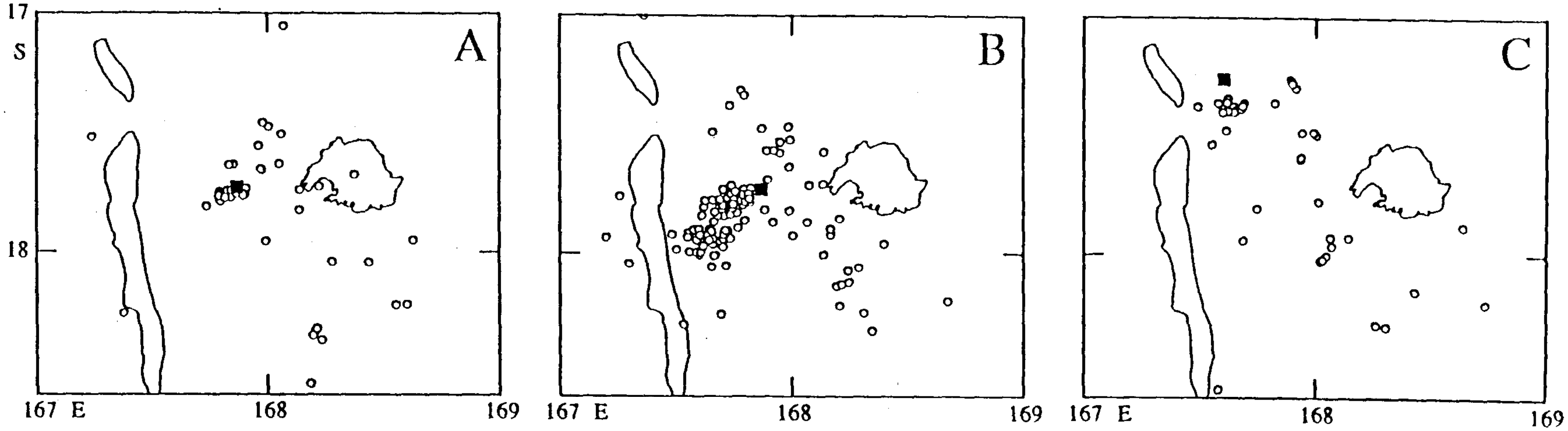


Figure 14. (A) Early foreshocks of the 17 August 1979 main shock (shown as a filled square) that occurred at the end of June to the beginning of July 1979. Island contours and 6 km bathymetry are shown. (B) Late foreshock activity preceding the 17 August 1979 earthquake. Foreshocks migrated from the trench toward the location of the main shock. (C) Foreshocks preceding the 15 July 1981 earthquake.

epicenter of the main shock. The foreshock sequence ended with a very intense concentration of seismicity near the 17 August 1979 main shock epicenter. The final foreshock cluster began eight hours before the main shock and continued until the region became seismically quiet three hours before the main shock. The main shock occurred at the northeastern end of these clusters.

The development of the aftershock activity in Figure 15 is shown for two time intervals during the nine days following the main shock. During the first day the aftershocks were initially located close to the epicenter of the mainshock and rapidly expanded towards the west. At the end of this day, aftershocks occurred as far north as the site of the 26 August main shock and as far south as about 18.1°S (Figure 15A). Most of the increase in the aftershock area occurred during the first day, as can be seen by comparing Figures 15A and 15B. To the north, the expansion of the aftershock zone stopped near the epicenter of the next main shock of the sequence that occurred nine days later on 26 August. In the south, aftershocks were located in the same zone defined by the early foreshocks (also see Figures 18C and 18D).

(B) 26 August 1979 sequence. The development of the 26 August aftershock zone (Figure 16) shows very similar patterns to the development of the 17 August aftershock zone. The activity developed very rapidly during the first two days following the main shock (26 -- 27 August). Then, as in the case of the 17 August aftershock sequence, the cumulative sequence occupied an area larger by a factor of 2 or 3 than the one expected for an earthquake of such magnitude [Isacks et al., 1981]. The main shock was located on the southern edge of the aftershock zone -- the aftershock activity developed to the north, east and west only, while the aftershock zone of the 17 August event was nearly inactive (Figures 16A, 16B). By 27 August aftershocks were located as far north as the epicenter of the future 15 July 1981 earthquake and as far west as the New Hebrides

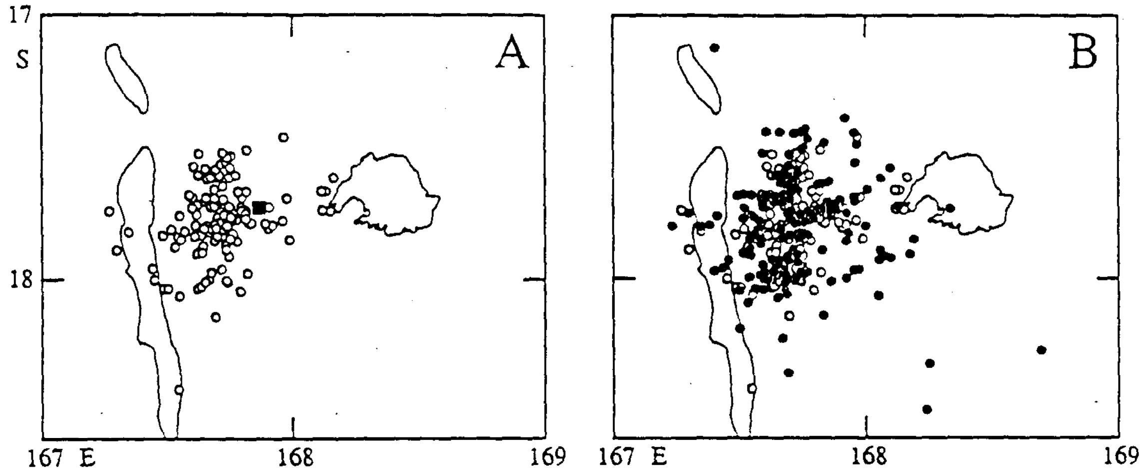


Figure 15. Maps of epicenters showing the development of the 17 August 1979 aftershock sequence. Format as in Figure 14. (A) 12H:59M, 17 August 1979 to 12H:59M, 18 August; (B) 13H:00M, 18 August to 11H:46M, 26 August (to just before the 26 August main shock).

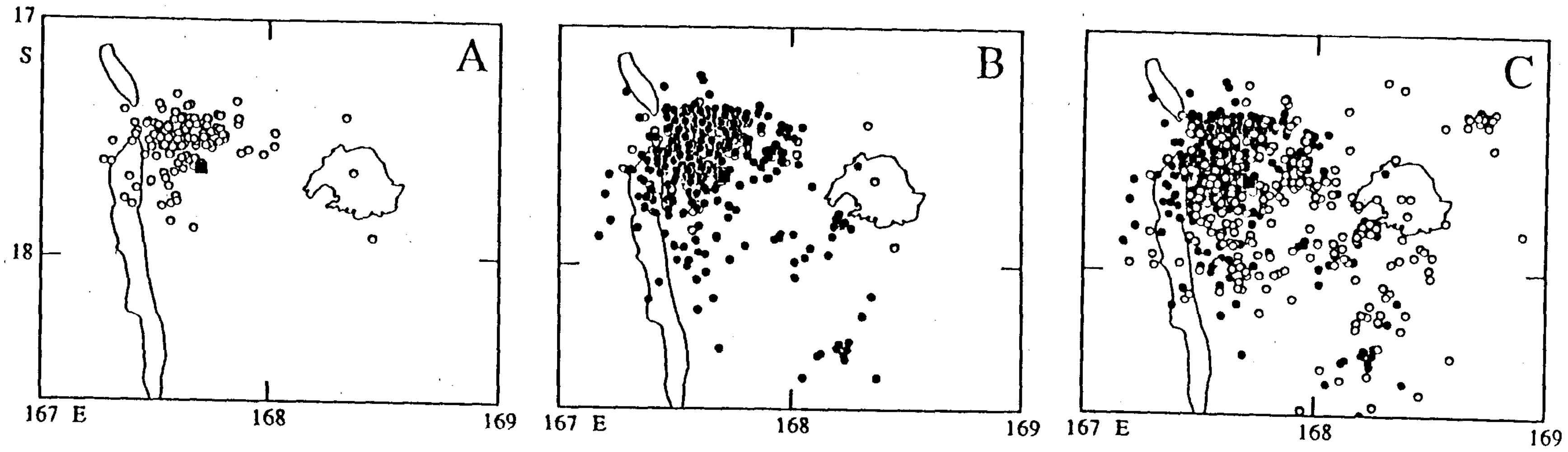


Figure 16. Maps of epicenters showing the development of the 26 August 1979 aftershock sequence. Format as in Figure 14. (A) 11H:47M, 26 August 1979 to 11H:47M, 27 August; (B) 11H:48M, 27 August to 11H:47M, 4 September; (C) 11H:47M, 4 September to 11H:47M, 26 October, 1979.

trench. The aftershock zone ends very abruptly to the north along a sharply defined east - west trending line which passes close to the epicenter of the 1 September 1978 earthquake (Figure 18A). After the first two days the level of aftershock activity decreased rapidly. During the entire period from the main shock to 14 September the aftershock zone of the 17 August earthquake remained relatively quiet (Figures 16A, 16B). From 15 September to about mid - October both the 17 August and the 26 August aftershock zones were reactivated (Figure 16C) although the level of activity was much lower than that during the days immediately following each of the main shocks. During this later period some activity occurred in the back-arc region. Northeast of Efate Island, a small intense cluster occurred in 1979, followed by shallow events spread around Efate Island (Figure 16C). The level of activity then decreased and by the end of October was back to a more normal background level of seismicity in the entire region.

The two aftershock zones of the 17 and 26 August 1979 earthquakes are contiguous with some overlap in the area between the two epicenters (Isacks et al., 1981; Chatelain et al., 1986). Chatelain et al. (1986) show that this area plays a key role in the development of the seismicity in the Efate region.

(3) The 15 July 1981 earthquake. In contrast to the 17 August 1979 earthquake, no outstanding foreshock activity occurred prior to the 15 July event. Small clusters occurred on 5-6 and 12 July (see Figure 14C). Both clusters included few events, although each started with a magnitude (m_b) 5.0 earthquake. The larger of the two occurred on 12 July near the pending main shock epicenter. In contrast to the 17 August 1979 case, no unusual

concentration of activity was noticed in the epicentral region during the months immediately preceding the main shock. Possible long-term precursory activity may be the clusters observed in March and June 1980 and are discussed in the next section.

Figure 17 illustrates several outstanding features of the aftershock sequence of the 15 July earthquake. First, an intense zone of activity develops during the first day and continues throughout the sequence (Figure 17A). This zone is coincident with the aftershock zone of the preceding 26 August 1979 event (compare Figures 17A and 16). The southern boundary of this activity is quite sharp and coincides with the region between the two August 1979 epicenters; this again emphasizes the importance of the area of the two 1979 epicenters. The epicenter of the main shock is located on the northern boundary of the region of intense activity.

Second, the aftershock activity expands in size during the succeeding nine days, primarily northwards [see also Chatelain et al., 1983]. To the northwest, significant activity develops within the oceanic plate beneath the trench axis (Figure 17B). This activity is concentrated beneath the ORSTOM seamount [see USGS map by Chase et al., 1983] near 17.3°S and 167.2°E. During the second through the ninth days, activity continues to develop in the area west of Epi Island and south of Malekula Island (Figure 17B), while in the succeeding 50 days, the area of southern Malekula is activated with a remarkable cluster occurring beneath the southern coast (Figure 17C). The region of southern Malekula and Epi has been notably quiet for much of the period prior to the July 1981 earthquake. Back-arc activity is also notable, with a cluster occurring on 29 July east of

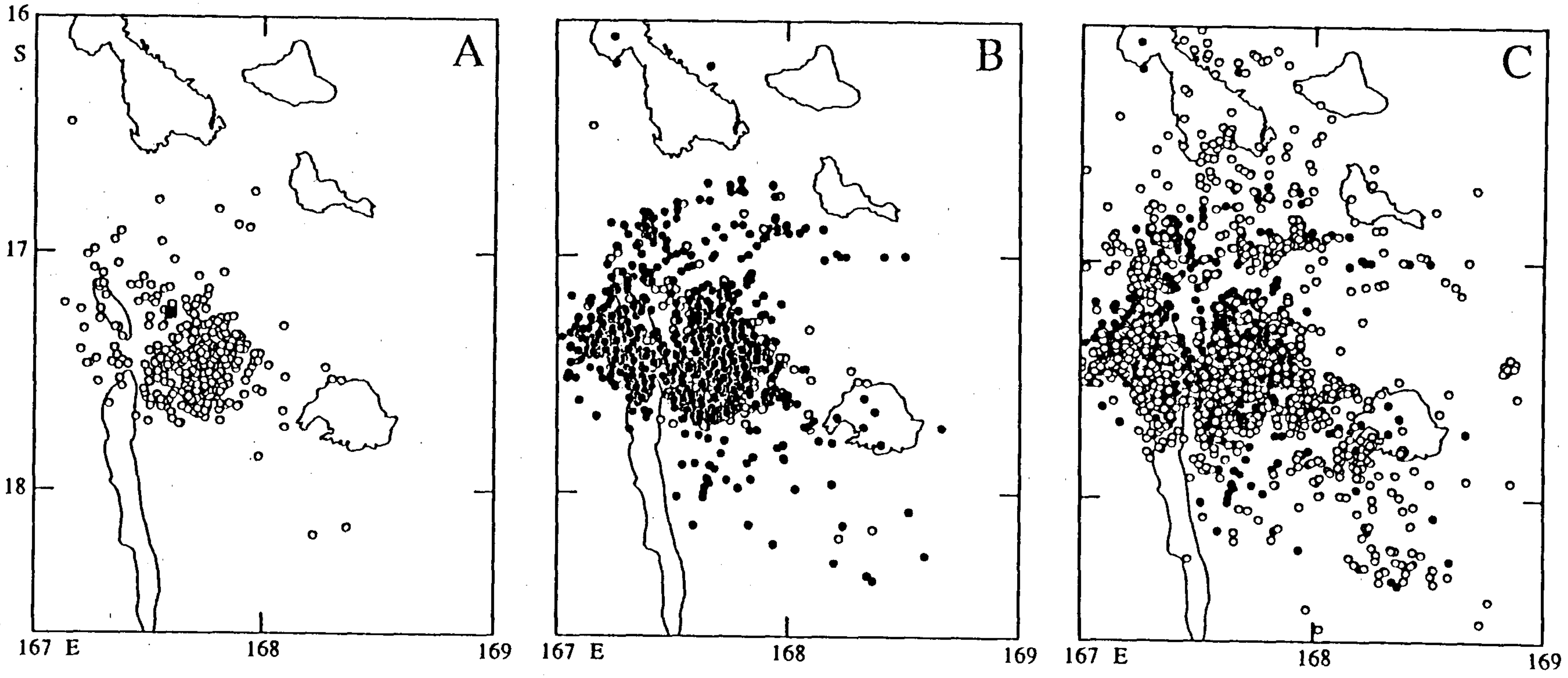


Figure 17. Maps of epicenters showing the development of the 15 July 1981 aftershock sequence. Format as in Figure 14. (A) 07H:59M,15 July 1981 to 07H:59M, 16 July; (B) 08H:00M, 16 July to 07H:59M, 24 July; (C) 08H:00M, 24 July to 07H:59M, 15 September 1981.

Efate, and increased activity in the region of Ambrym and Epi islands (Figure 17C).

The aftershocks of the 15 July 1981 event thus affected four distinct regions: (1) the former 26 August 1979 aftershock zone, presumably on the interplate boundary; (2) a region of the suboceanic plate near the ORSTOM seamount; (3) the region between South Malekula and 17.2°S, presumably also part of the interplate boundary; and (4) upper plate crust east of Efate Island. The total area affected by this earthquake was about 10 times larger than the area expected for the rupture zone of an earthquake with magnitude of the July 1981 event [Chatelain et al., 1983].

(B) Prominent Clusters

Aside from aftershocks of the August 1979 and July 1981 events, the Efate - Malekula region also experienced several remarkable earthquake clusters. Some of these have the characteristics of an aftershock sequence, with the initiating event having the largest magnitude (and sometimes preceded by a few foreshocks). Others have characteristics intermediate between an aftershock sequence and a swarm [Mogi, 1963], where there may be several dominant shocks within the sequence and a more symmetric shape to temporal variation of the number of events per unit time. The clusters are shown together with the larger aftershock sequences in the summary of seismicity presented in Figure 18. For clarity, the aftershocks of the August 1979 and July 1981 events are represented by the first nine days of activity.

(A) Clusters in the forearc region. The first cluster recorded by the local network occurred in late September and early October 1978 near the 1

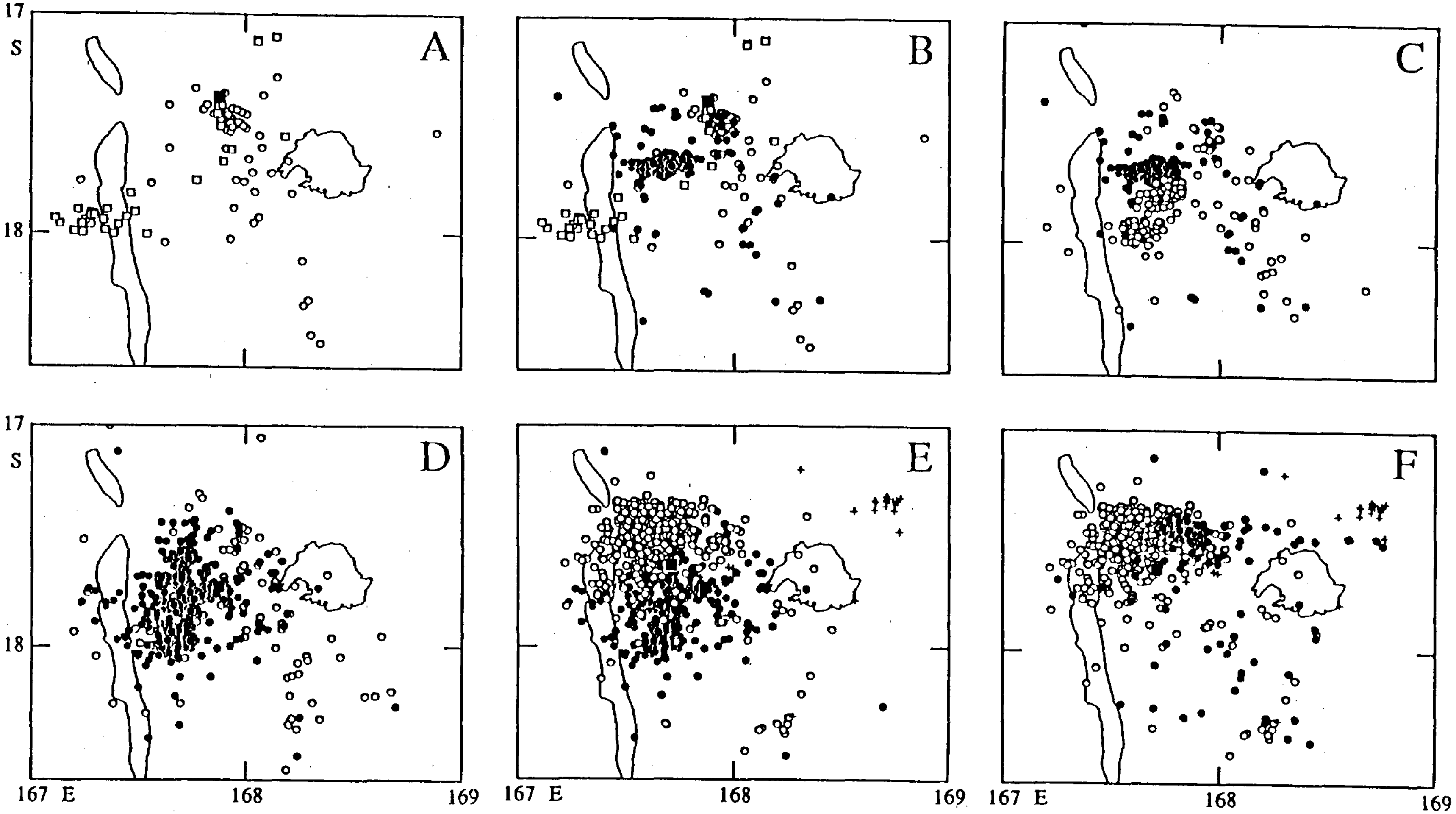
September mainshock (Figure 18A), and can be considered as a late part of the aftershock sequence of the 1 September event. The location of this cluster, however, is activated again in later clusters (December 1979, August 1983 and April 1984). Figure 18A shows the next significant activity in the region, a cluster of earthquakes in December 1978 located west of the August 1979 aftershock zone beneath the New Hebrides trench. The region was then fairly quiet until March 1979, when an intense cluster of earthquakes occurred over a period of five days (Figure 18B). Activity in the same area resumed again in April 1979 for a period of two days. The most active parts of both clusters are located at the same place, which defines an east - west trending zone located near the epicenter of the 26 August 1979 event and at the junction of the 17 August and 26 August aftershock zones.

After the August 1979 shocks, three clusters occurred in December 1979, March 1980 and June 1980 (Figure 18G and 18H) near the epicenter of the 1 September 1978 main shock (and also near the mid September 1978 cluster noted above). This location is on the eastern edge of the future 1981 aftershock zone. The three clusters also tended to migrate toward the July 1981 main shock epicenter (Figure 18G). A smaller cluster occurred in August 1980 beneath Malekula Island (not shown on Figures). Actually, the entire region was rather quiet during 1980. The three 1980 clusters were relatively small.

In February 1981 a cluster of earthqukes occurred just west of the location of the March - April 1979 clusters, between those clusters and the location of the December 1979 cluster (Figure 18H and 18I). This location

Figure 18. Maps of epicenters in aftershock zones and clusters located by the Cornell-ORSTOM network, shown sequentially in time. Epicenters of main shocks are shown by filled squares. In each successive frame, the next cluster overlays the preceding one for comparison. Only successive clusters are shown in each frame. All the activity recorded for the periods chosen is plotted. Ten days of aftershock activity are shown for the August 1979 and July 1981 earthquakes:

(A) 1 September 1978 main shock with September-October 1978 cluster (open circles) and December 1978 cluster (open squares).
(B) 27 January 1979 mainshock (no aftershock activity) with clusters of March-April 1979 (filled circles).
(C) Foreshock sequence for 17 August 1979 (open circles).
(D) 17 August 1979 mainshock and aftershock sequence (filled circles).
(E) 26 August 1979 mainshock and aftershock sequence (open circles); back-arc activity in September 1979 (crosses).
(F) Cluster in December 1979 (filled circles).
(G) Clusters in March 1980 (open circles), June 1980 (open squares), and February 1980 on Efate island (plus signs).
(H) Cluster in February 1981 (filled circles).
(I) 15 July 1981 foreshocks (open circles) and June 1981 back-arc cluster (plus signs).
(J) 15 July 1981 aftershock sequence (filled circles) and back-arc activity during July 1981 (plus signs).
(K) Clusters in September-October 1981 (open circles) and activity on Efate island in December 1981 (plus signs).
(L) 12 March 1983 earthquake and aftershock sequence (filled circles).
(M) Cluster in June 1983 (open circles).
(N) 3 August and 5 August 1983 events and aftershock sequence (filled circles).
(O) Clusters in April 1984 (open circles) and in the back-arc near Epi Island in March 1984 (plus signs).
(P) Cluster in October 1984 (filled circles).
(Q) Clusters in February 1984 (open circles) and April 1984 (open squares).
(R) 3 July 1985 aftershock sequence (filled circles).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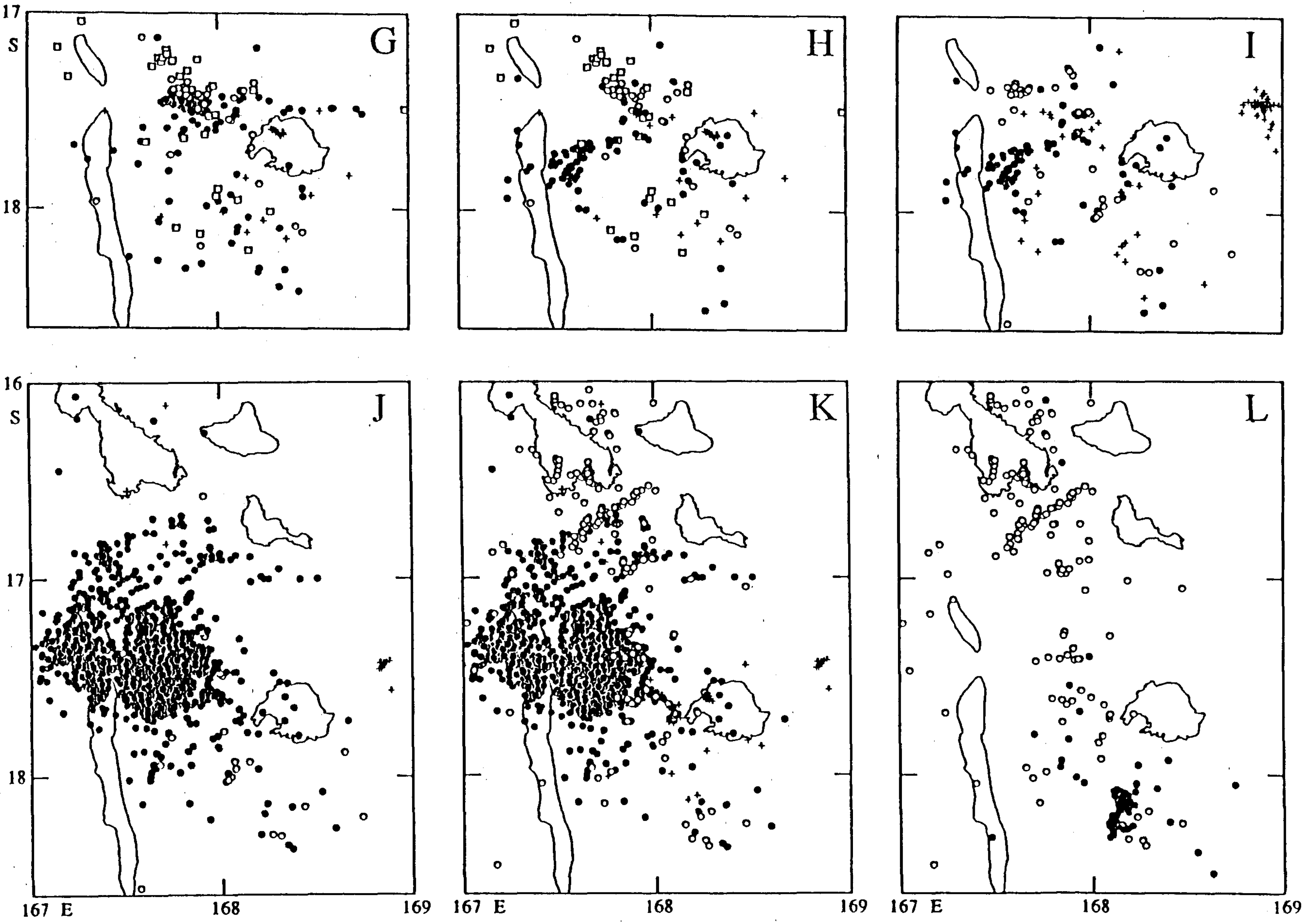
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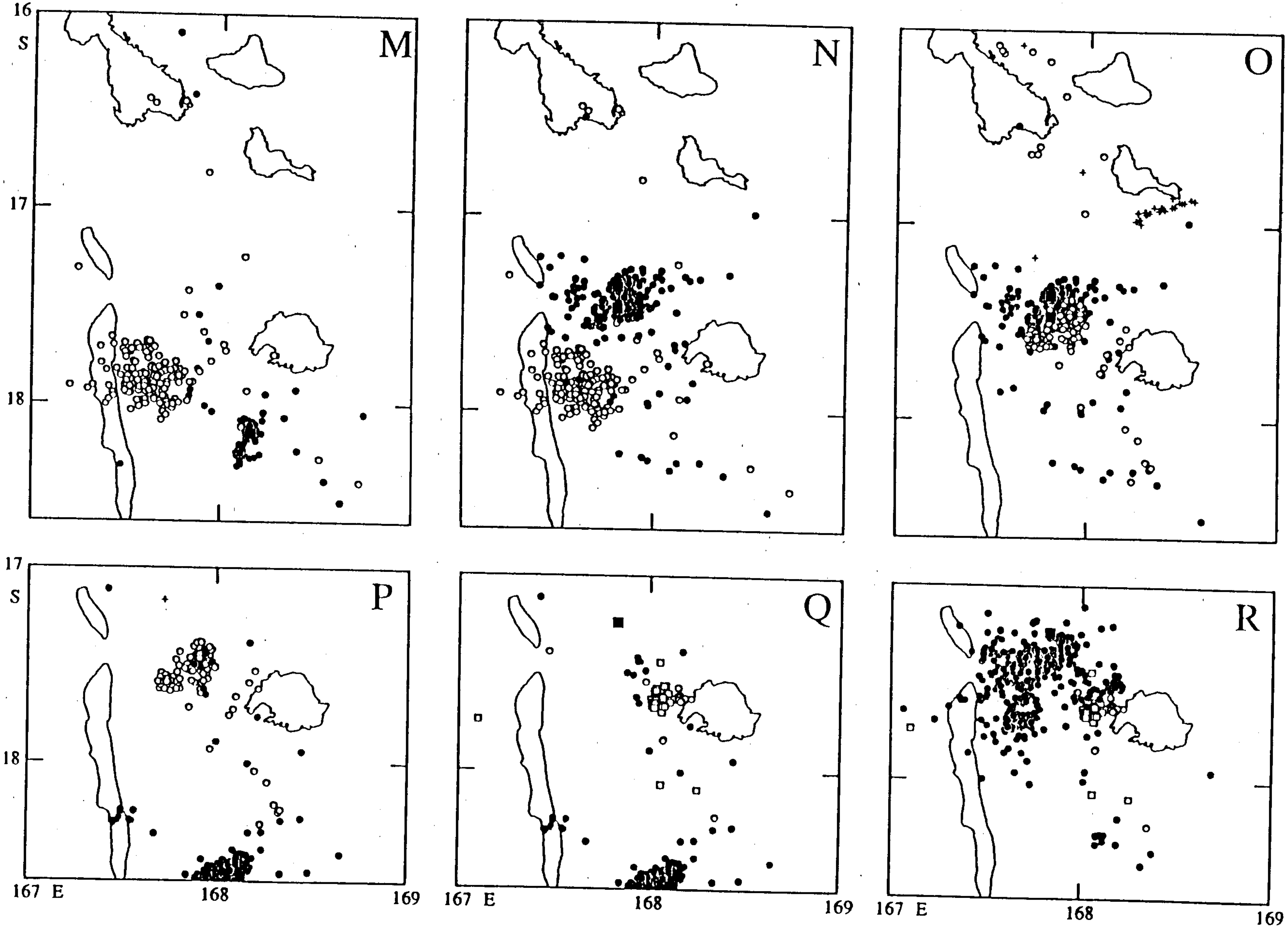
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is part of the overlapping aftershock zones of the August 1979 events, and is also at the southern limit of the 15 July 1981 aftershock zone.

The clusters thus have a very close spatial relationship to the aftershock zones of the main shocks. They occurred near the boundaries of the aftershock zones and appear to be related to features delimiting or defining the spatial development of the aftershock zones (see also Chatelain et al., 1986).

From February 1981 until August 1982, except for the aftershock sequence of the July 1981 earthquake, not a single fore arc cluster was detected in the Efate - Malekula region. Starting in September 1982, clusters began to occur around the former July 1981 immediate aftershock zone. In September and October 1982, four clusters occurred south of and beneath Malekula Island (Figure 18K). Besides the aftershocks of the 15 July 1981 earthquake, the September - October 1982 clusters were the most prominent activity in the Malekula region during the entire 1978-1984 period. These clusters did not occur at random places. The first one was located beneath Malekula Island at the site of the previous cluster in 1980. The second cluster is located southwest of Epi Island in an area which experienced significant activity during the aftershock sequence of the 15 July 1981 earthquake (compare Figure 17C and 18L). The third cluster shows a very linear pattern trending southwest - northeast, right along the extension of the northern edge of the 15 July aftershock zone. The fourth cluster then occurred beneath southern Malekula Island.

In March and June 1983 two clusters occurred in the southern part of the Efate zone. The March 1983 cluster (Figure 18L and 18M) occurred near the January 1979 epicenter, and comprised a relatively small aftershock sequence of a magnitude (M_s) 5.8 earthquake. The June 1983 cluster occurred just south of the July 1981 aftershock zone (Figure 18M and 18N). This cluster affected the same zone which had already been affected by both foreshocks and aftershocks of the 17 August 1979 mainshock. Most of the cluster occurred after a magnitude (m_b) 5.4 shock which was the largest event in the cluster. The cluster thus has the charactistics of an aftershock sequence, but one with an abnormally large area for the main shock magnitude. The main shock was also preceded by a small foreshock sequence that started a day before and stopped six hours before the "main shock".

In August 1983 a dense cluster, following a $M_s = 5.6$ and a $M_s = 5.7$ event, occurred northwest of Efate Island (Figure 18N and 18O). The latest cluster recorded in the region occurred in April 1984, again activating the same zone (Figure 18O).

(2) Clusters in the back-arc region. Although the back-arc region is usually relatively aseismic, there were clusters of earthquakes located east of Efate Island and beneath Efate Island itself. The clusters were shallow and located in the island arc crust. The areas affected were much smaller than those in the forearc clusters. Three of the clusters occurred just before or after the August 1979 and July 1981 main shocks (Figures 18E, 18F, 18I, and 18J). The August 1979 event was followed in September 1979 by a cluster east of Efate and in February 1980 beneath Efate. The July 1981 main shock was preceded in June - July 1981 by a swarm occurring just south of the cluster following the August 1979 events. Another cluster occurred shortly after the July 1981 event at the same place. The July 1981 main shock was also followed by a swarm on Efate Island at about

the same place as the one following the August 1979 earthquakes. No clusters have been located in the Efate back-arc region from December 1981, when the last swarm occurred on Efate Island, up to the most recent data available, October 1984, thus giving support to the close temporal relationship between these clusters and the 1978 - 1983 sequence (see also Chatelain et al., 1986). In December 1980 a larger cluster occurred farther east, near the Coriolis trough (not shown on figures). The only other back-arc activity occurred in March 1984 farther north, just south of Epi Island (Figure 18O).

(3) Summary of Results from the Cornell-ORSTOM Network. Investigation of the patterns of seismicity associated with the earthquakes which have occurred within the Cornell-ORSTOM network has shown that: (1) not all medium to large size events are associated with foreshock activity; (2) long term precursory activity sometimes occurs, but not with enough consistency to use in forecasting an impending event; and (3) some zones are activated before and after the main shocks, without defining any clear cycle (Chatelain et al., in press). These earthquakes and their associated seismicity suggest that specific features along the interplate zone, produced by the interaction of structures in the overriding and subducted plates, appear to control the seismicity in the Efate region (Chatelain, et al., in press; Isacks et al., 1981).

Seismic Potential Studies Along the New Hebrides Arc

The earthquake hazard from the interplate zone is generally high because of the rate of relative motion of the two plates (approximately 11 cm/yr) and the stick-slip nature of the boundary. However, in addition to large to great earthquakes along the plate interface, moderate to large magnitude events can occur within either plate and cause considerable damage locally.

One approach to determining the seismic potential of a region is to identify a seismic gap or portion of an arc that has not produced a large earthquake for some period of time. The identification of a seismic gap does not mean that a large earthquake will necessarily occur in a given region because not all gaps will produce large earthquakes. The gap may indicate that (1) the section of the plate boundary is locked, stress is accumulating along the interface, and will be the site of a future earthquake or (2) the relative plate motion is being accommodated by continuous slippage (aseismic creep and/or by slip during small and moderate events) such that sufficient stress to generate large earthquakes along that section of the plate boundary does not accummulate. Historical information regarding the occurrence of earthquakes in a particular region and regional tectonic constraints are necessary to clarify which of these two possibilities is valid for the region in question. In many cases, however, the historical record may be incomplete or too short to accurately determine which option is correct.

Evaluation of the recurrence history of a particular region can be investigated using: (1) Teleseismically recorded earthquakes, (2) recurrence relations of smaller earthquakes recorded by seismograph networks; (3) pre-instrumental historical records of large earthquakes; and (4) evidence of prehistoric and historic large earthquakes observable in the geological record. Recurrence relations may help determine return periods for certain sizes of earthquakes. Recurrence intervals are dependent upon the observations of seismograph networks, and are incomplete since the period of record keeping is short compared to the time necessary to develop these relationships. Indirect evidence of large earthquakes can sometimes be found in the geologic record in the form of uplift rates and used to address the problem of recurrence intervals. However, information obtained from the geologic record is necessarily limited in accurracy.

McCann (1980) has divided the New Hebrides arc into different zones and assigned values of seismic potential to these zones (Figure 19) based on his study of historical and instrumental seismicity. He has assigned 6 different divisions based on his study of the historical record: (1) site of a great ($M_s \geq 7\ 3/4$) earthquake more than 100 years ago; (2) site of a great earthquake within the past 100 years, but more than 30 years (before 1978); (3) incomplete historical record, but indication that the region may have the potential for a large earthquake; (4) plate motion is subparallel to the arc; (5) no historical record of a great earthquake and the region may not have the potential for one; and (6) site of a large earthquake within the past 30 years and presumably the lowest seismic potential.

Marthelot (1983) used PDE data to determine some general segmentations in the seismicity of the New Hebrides arc and the patterns of seismic activity that characterize these segments (Figure 20). Marthelot (1983) found that coupled, interplate, large ($M_s \leq 7.9$) thrust earthquakes which are preceded by intense activity dominate the northern end of the New Hebrides arc near the Santa Cruz islands (between 11°S and 13°S). Moderate ($M_s \leq 7.2$) thrust events concentrate between 13°S and 14°S. Coupled, moderate ($M_s \leq 7.5$) interplate thrust earthquakes occur near Santo and northern Malekula islands (14°S to 16.5°S). The southern end of Malekula and slightly south (16.5°S to 17.5°S) exhibit coupled interplate thrust

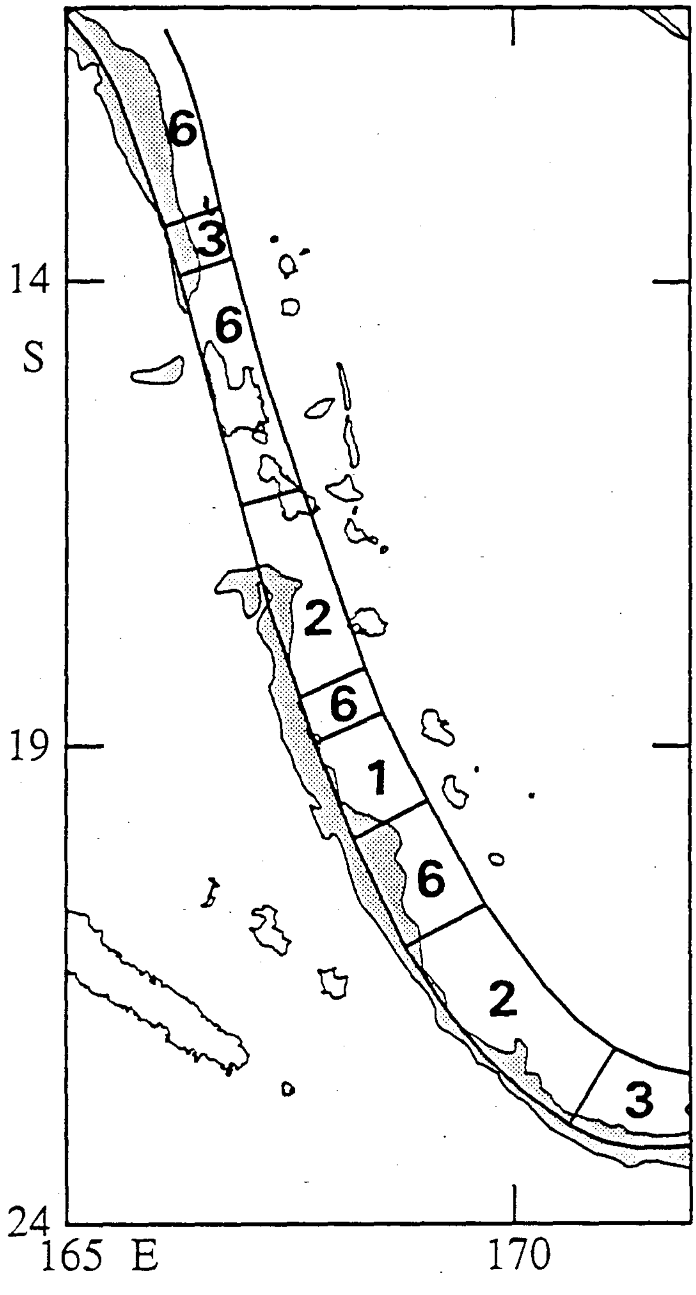


Figure 19. McCann's seismic potential for New Hebrides island arc (McCann, 1980. See text for discussion of numbers.

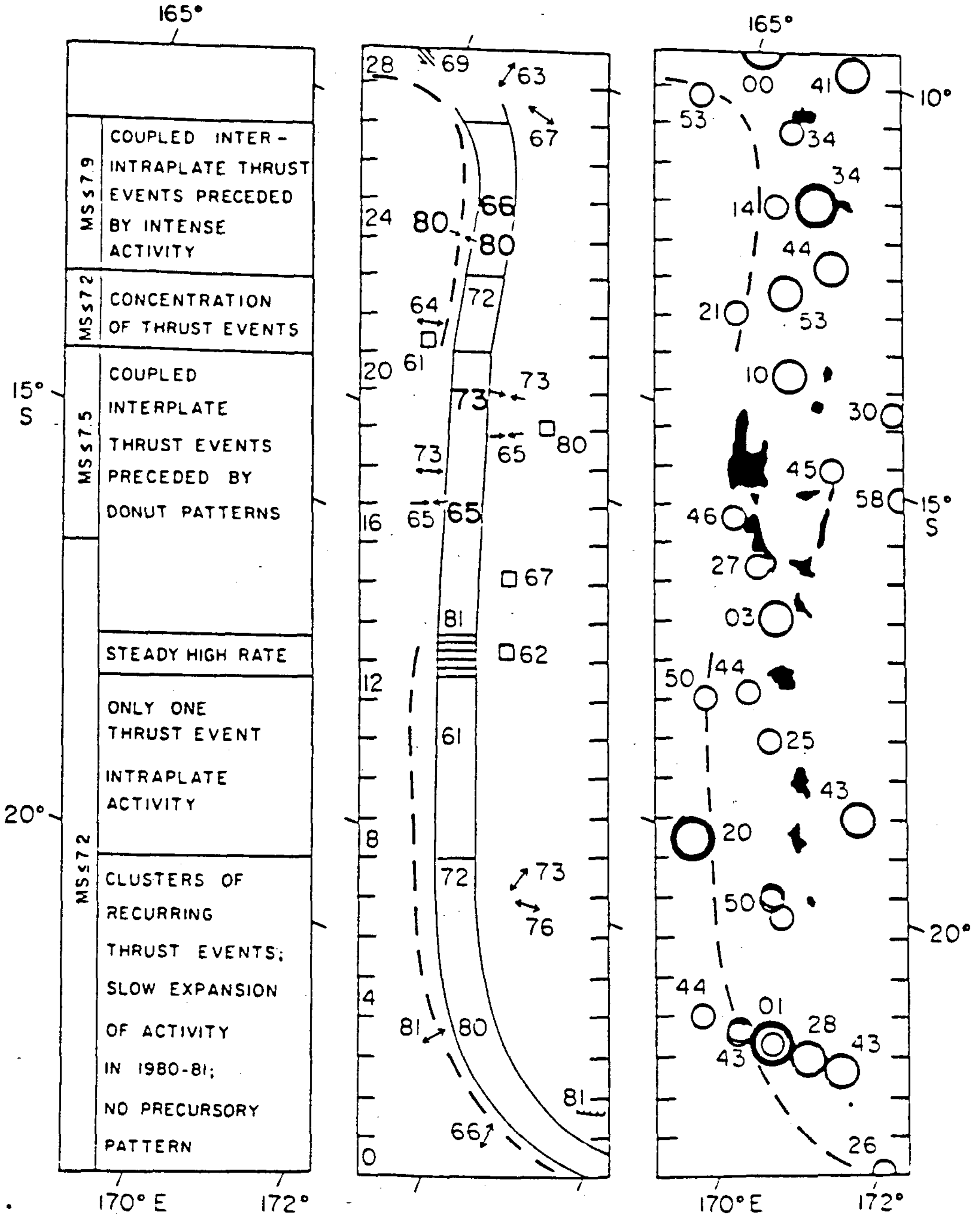


Figure 20. Summary of the characteristics of the distribution of shallow earthquakes along the New Hebrides island arc. The dashed line represents the axis of the trench. The trench disappears in the central part of the arc. Horizontal lines separate regions characterized by distinct seismicity patterns. Middle figure shows years of occurrence of large ($M_S > 7.0$) and moderate-sized events (ms > 6.0) 1961-1981. Right figure shows the large earthquakes that occurred from 1900 through 1960 (Marthelot and Isacks, 1984).

earthquakes that are not quite as large ($M_S \leq 7.2$). The zone west of Efate (17.5°S to 18°S) exhibits a steady high rate of seismicity with magnitudes (M_S) less than or equal to 7.2. Between 18°S and 20°S, intraplate activity ($M_S \leq 7.2$) dominates. South of Anatom (e.g. south of 20°S), the seismicity is characterized by clusters of recurring thrust events that do not exhibit any precursory activity.

In another study utilizing the PDE data set, Wyss et al. (1983) and Habermann (1984) have used the shallow New Hebrides seismicity in order to (1) identify areas of higher and lower strength within the plate interface which might control the rupture length of future earthquakes and (2) test for changes in the rate of seismicity prior to large earthquakes using a statistical procedure. The trend toward low stress drops in the central portion of the arc, near the intersection of the d'Entrecasteaux Fracture Zone with the New Hebride Trench, is consistent with other studies which indicate that this region is anomalous. However, a region of high or low strength does not indicate anything about the nature of the region and these regions do not help pinpoint when a large, destructive earthquake will occur within or near them.

ASSESSMENT OF EARTHQUAKE HAZARD

Seismotectonic Provinces

We propose the following seismotectonic provinces and the maximum probable (but not absolute) sizes of earthquakes be considered for the subregions within Vanuatu when considering a design earthquake for these regions (Figure 21). These provinces are based on the instrumental history of earthquakes near Vanuatu. The northern end of the New Hebrides Trench is a complex zone of deformation where the interplate motion is changing

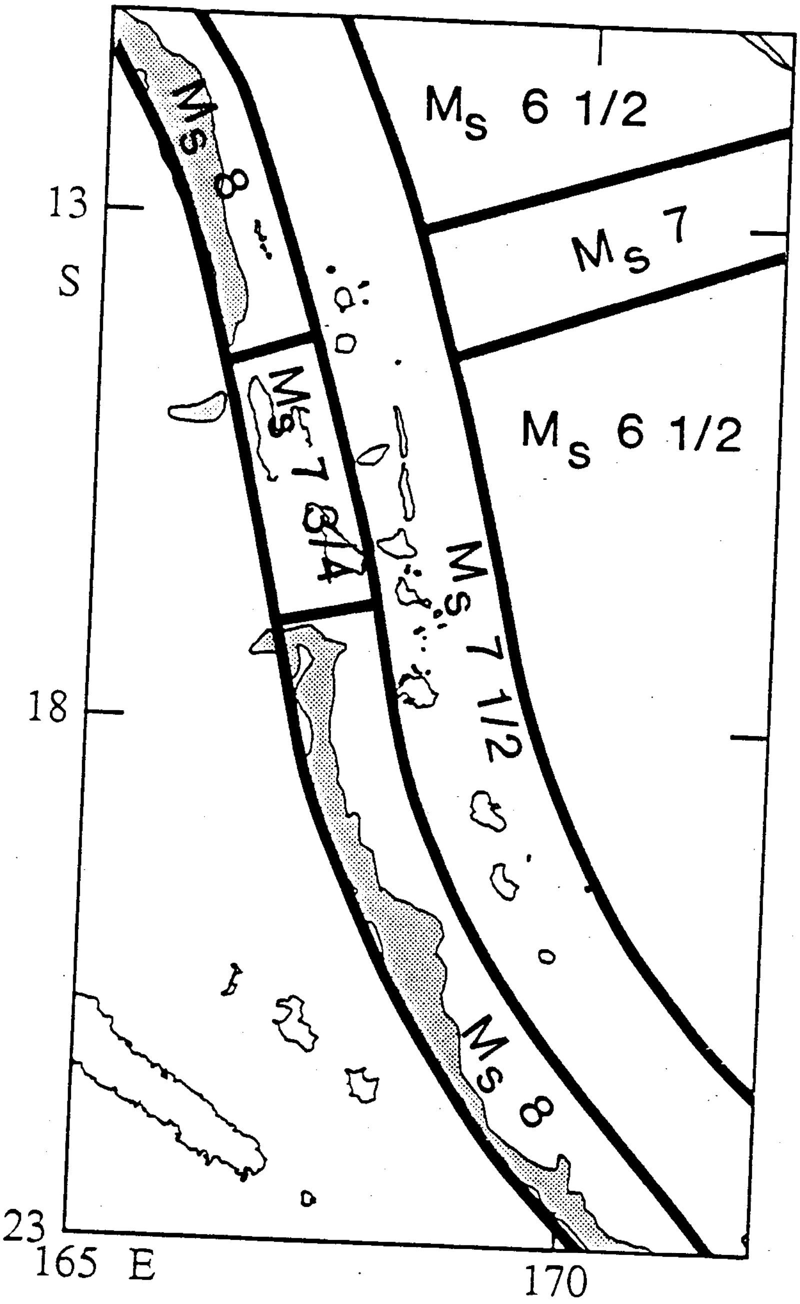


Figure 21. Earthquake potential for Vanuatu.

from thrusting in the southern portion to mostly strike-slip motion in the northern portion and has the potential for great (M_s 8) earthquakes. The central portion of the New Hebrides Trench, here called the Santo -- Malekula segment exhibits characteristics different from the rest of the arc as the result of the d'Entrecasteaux ridge interaction and has the potential for M_s 7 3/4 earthquakes. The southern end of the New Hebrides Trench, here called the Efate -- Tanna segment may have the potential for M_s 8 earthquakes. The extreme southern end of the New Hebrides Trench is another complex zone where the interplate motion is changing from thrusting in the north to strike-slip motion in the south and may be limited to infrequent, moderate (M_s 7 1/2) earthquakes. Other sources of seismicity include back-arc spreading east of the New Hebrides Trench (M_s 7 1/2) and diffuse shallow activity along the Hazel-Holme Ridge (M_s 7) in the North Fiji Basin (M_s 6 1/2).

One method for estimating the maximum possible magnitude earthquake in a region is to look at the amount of deformation that has accumulated from past earthquakes. The deformation is assumed to be proportional to the square root of the energy released by a powerful earthquake. The energy (E, in joules) of each earthquake can be calculated from its magnitude (M_s) using a formula developed for the region. Prévot and Chatelain (1983) have used the formula:

$$\text{Log } E = 4.8 + (1.5 \times M_s)$$

to calculate the amount of energy which has been released since 1965 in the central portion of the arc (Figure 22). The calculated values tend to fall within a range of values which can be bounded by two parallel lines, since deformation occurs more or less uniformly in time. The maximum possible

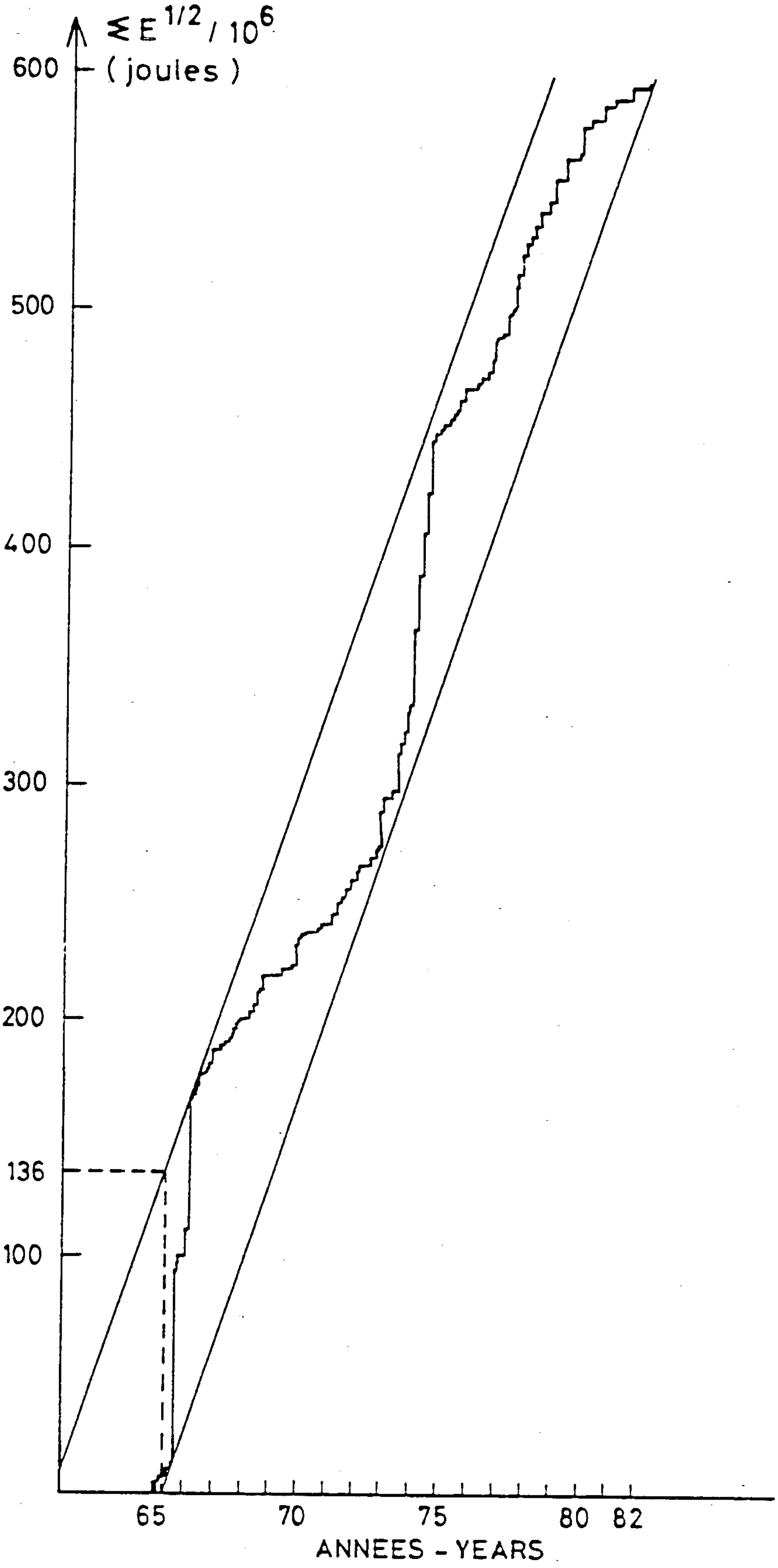


Figure 22. Seismic energy release along the New Hebrides Arc since 1965 (Chatelain and Prévot, 1983).

magnitude earthquake calculated by this method is $M_s = 7.6$. Prévot and Chatelain (1984) computed a similar result using all of the earthquakes which have occurred since 1900.

Ground Motion

Once the location and magnitude of potential earthquakes have been determined for a region, the next step is to determine the characteristics of the ground shaking at a particular site. This accomplished by the condsideration of such quantities as: earthquake source mechanism, epicentral distance, and geometry and physical properties of the geologic structures located between the source and the site.

Strong-motion records provide one measure of site response. To date, a relatively large number of strong-motion records have been generated in the far-field of large earthquakes, especially in California and Japan. In contrast, relatively few near-field records of moderate and large shocks have been recorded in island arcs. These few have shown large scatter with unpredictable results. The 3 March 1985 Chilean and 19 September 1985 Mexican earthquakes constitute the most important exceptions and are invaluable additions to the library of strong motion data for subduction zones. Nonetheless, these two events do not constitute a databank of information, especially for intraoceanic tectonic settings such as Vanuatu. A major difficulty arises in trying to translate past earthquake "size" (intensity values), which are based on cultural effects or magnitudes derived from widely varying instrumental parameters, into values of ground motion. The development of earthquake resistant design is usually based on intensity of ground motion at a particular site. The most widely applied standard of comparison for strong motion data is the peak ground accelereation (PGA). Figure 23 shows a general relationship between peak acceleration and distance from hypocenter which has been derived from worldwide earthquake data. Some earthquakes generate relatively high single peaks of ground accleration which represent little ground energy. Therefore, on an absolute basis the use of PGA can be misleading for smaller events.

Peak ground accelerations are easily obtained from accelerogram records; however, most historical information consists of earthquake intensities. Numerous relationships between ground acceleration and Modified Mercalli intensities have been developed (Table 3). Two of these proposed relationships are shown in Figure 24. For worldwide data, Murphy and O'Brien (1977) have computed statistical correlations between Modified Mercalli intensity values and ground accelerations (horizontal and vertical). The resultant relationships and the geometrical standard deviation (s) are:

$$\log A_v = 0.28\ I_{mm} - 0.40 \qquad s = 2.53$$

$$\log A_h = 0.24\ I_{mm} - 0.26 \qquad s = 2.19$$

where A_v = peak vertical ground acceleration

A_h = peak horizontal ground acceleration

I_{mm} = Modified Mercalli intensity.

Using the relationship of earthquake intensity to distance and size of Fiji earthquakes, Everingham (1984) has produced a plot for the Fiji region (Figure 25). Although these results are for a nearby region, they give a general indication of what might be expected for Vanuatu. Figure 26 (Prévot and Chatelain, 1983) shows the recurrence of Modified Mercalli intensities per number of earthquakes.

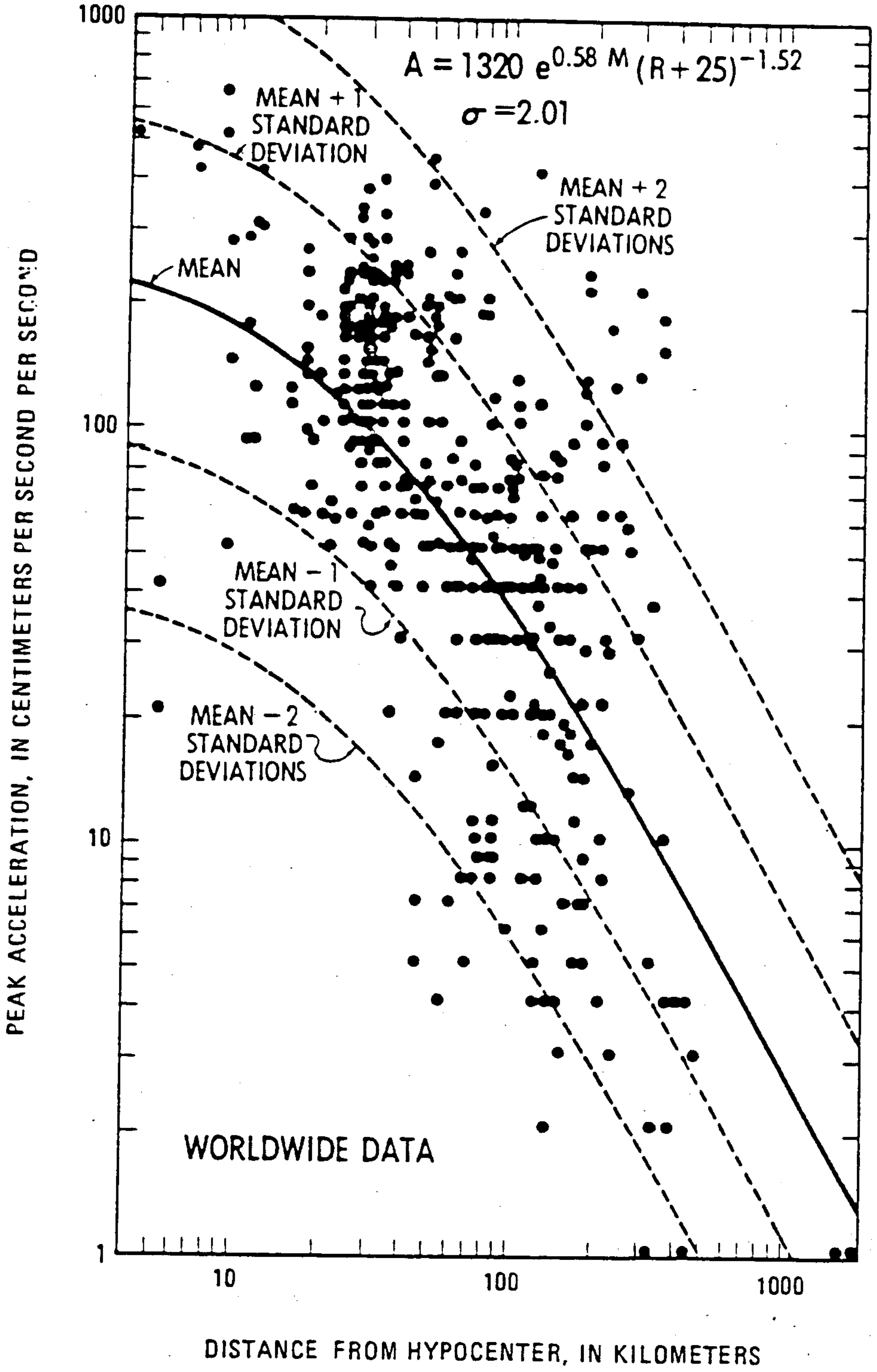


Figure 23. Acceleration-attenuation relations derived from worldwide earthquakes (Hays, 1980).

Table 3. Characteristics of the data samples used in selected studies of the correlation of Modified Mercalli intensity and peak ground acceleration (modified fom O'Brien et al., 1977)

Study	Number and location of earthquakes	Number of recordings	Range of Modified Mercalli intensity	Distance range (km)	Acceleration range (cm/s^2)
Gutenberg and Richter, 1942 1956	61, Western United States	167	III-VIII	3-450	1-300
Neumann, 1954	10, do.	10	V-VIII	Averages of 25 and 160 (distance dependent)	40-300
Hershberger, 1956	60, do.	108	II-VIII	-----	1-300
Coulter, Waldron and Devine 1973	----, do. (Not based entirely on observed data)	-----	IV-X	Short distance	6-3000 (Dependent on site geology and local amplification)
Trifunac and Brady, 1975c	57, do.	187	IV-X	3-250	7-1150

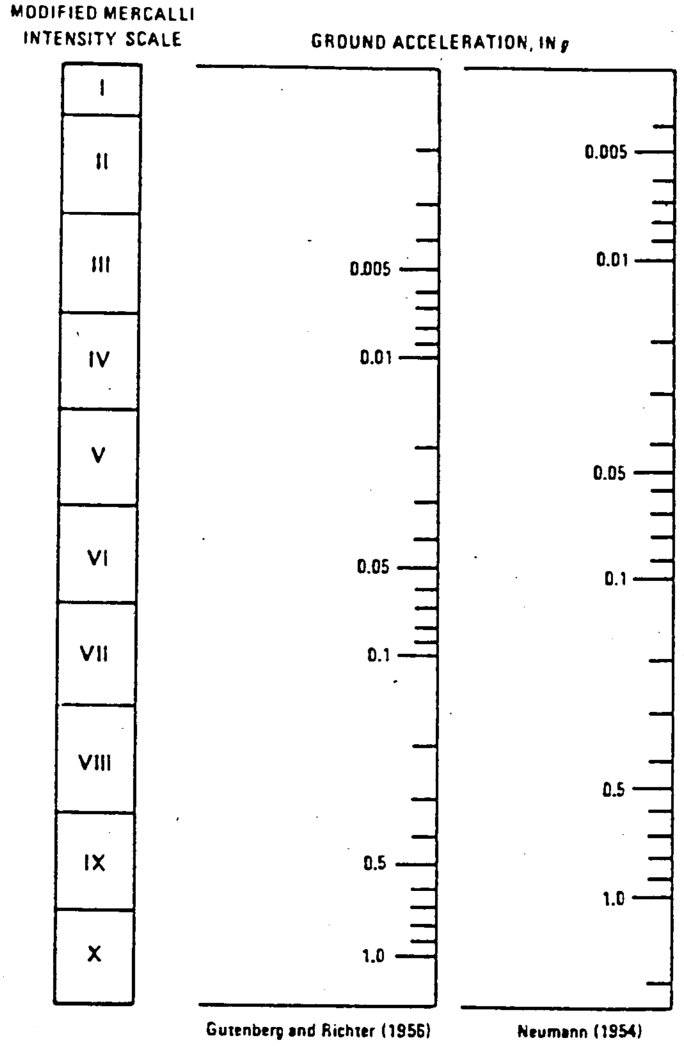


Figure 24. Proposed relationships between earth quake intensities and peack accelerations.

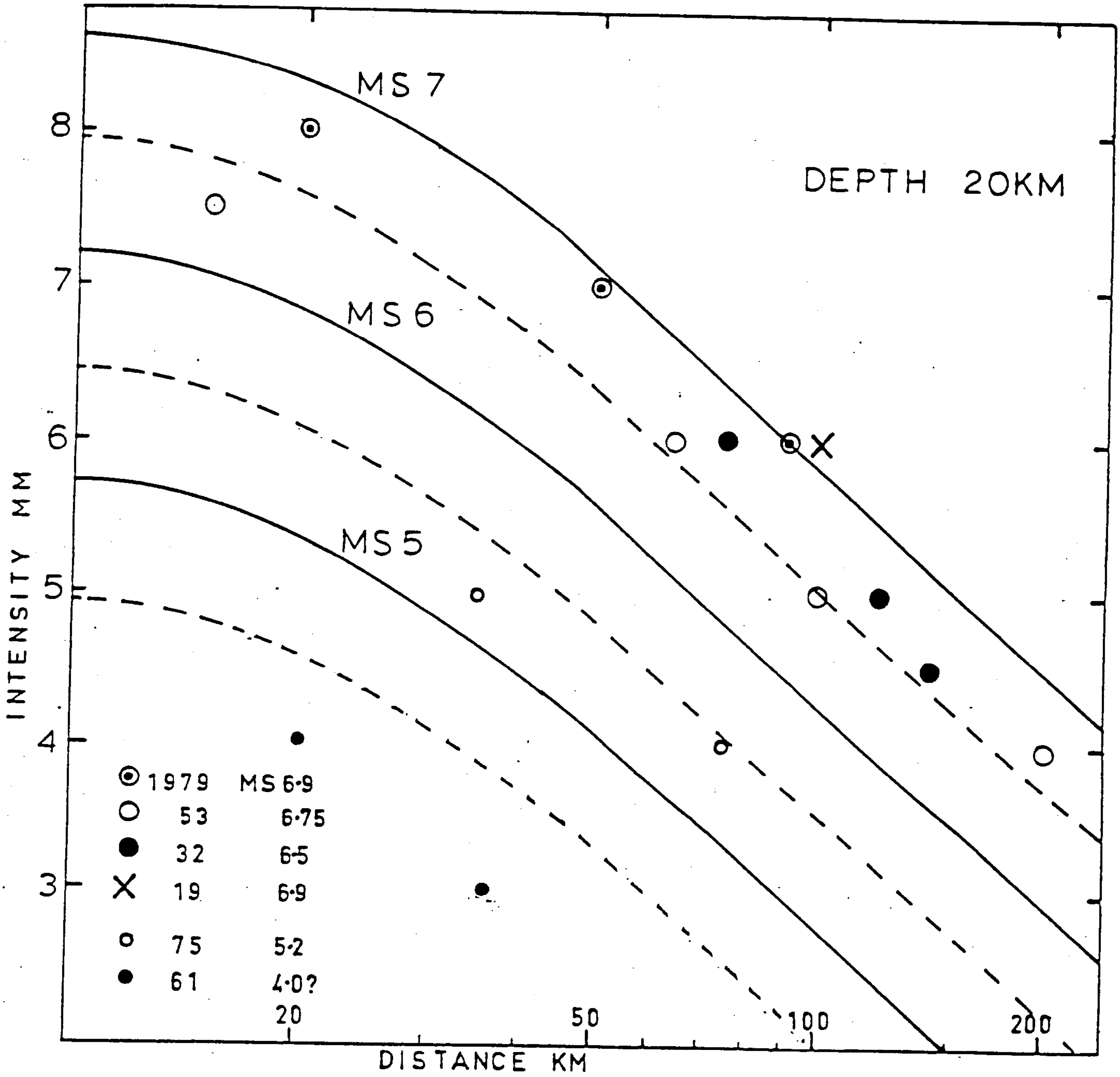


Figure 25. Modified Mercalli earthquake intensities observed in Fiji as a function of magnitude and epicentral distance (Everingham, 1984).

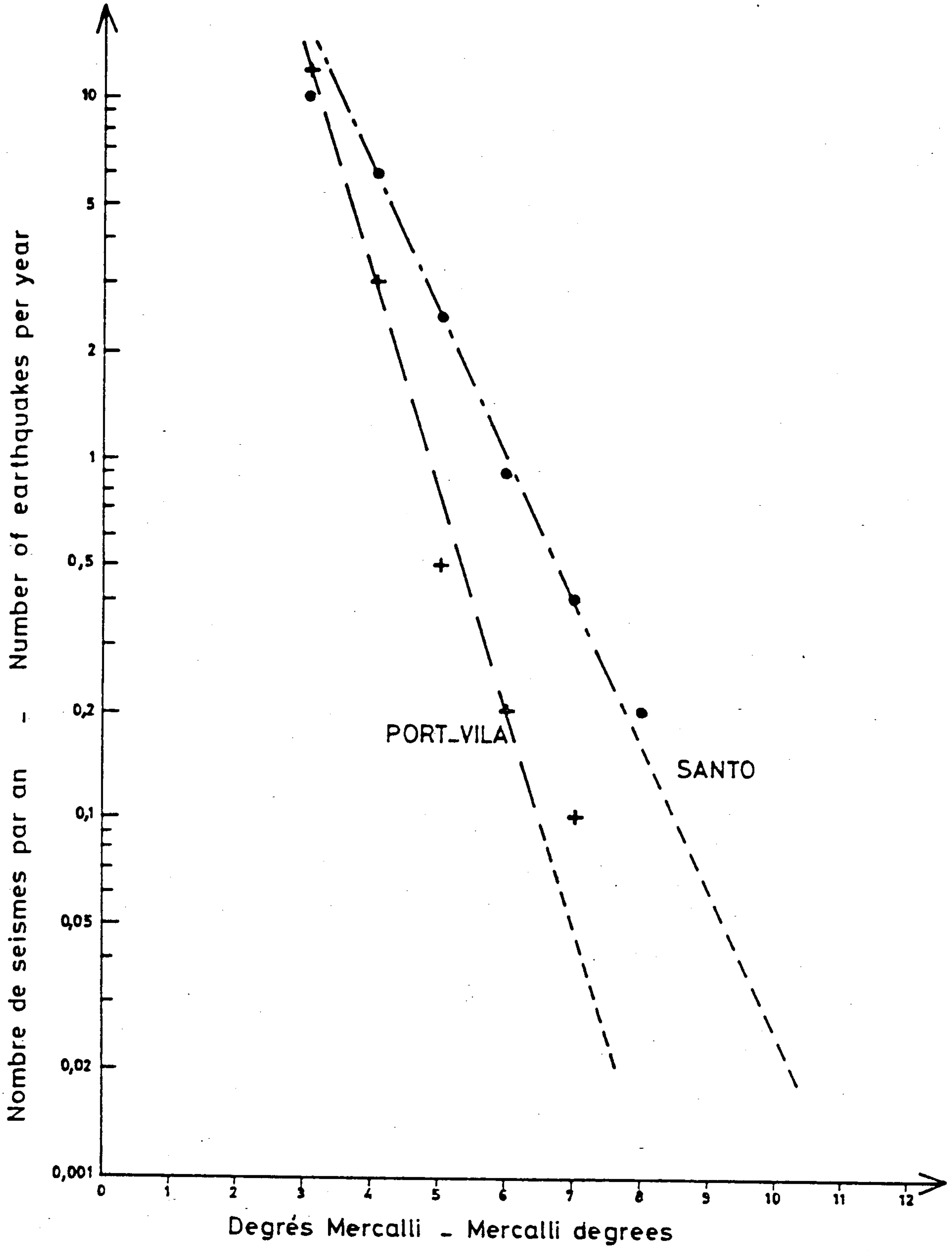


Figure 26. Frequency of Modified Mercalli earthquake intensities felt in Port Vila and Santo (Chatelain and Prévot, 1983).

Tectonic Uplift

Studies of longer term island uplift on Santo and Malekula, as evidenced by the uplift of coral reefs, have related segmentation of these islands to features of the subducting topography of the d'Entrecasteaux fracture zone (Taylor et al., 1980). The proximity of these two islands to the main interplate thrust zone and the growth of the coral reef terraces around the islands has resulted in preservation of long-term deformation. Taylor et al. (1980) have studied late Quaternary coral reefs that have been uplifted on Santo and Malekula islands. They identified four main blocks based on long-term tilt differences (Figure 27). The rupture zones of the 1965 and 1973-1974 earthquake sequences correlate to the tectonic discontinuities in the Santo -- Malekula region. Taylor et al. (1980) studied the uplift of coral terraces on Malekula over a period of three years (9/76, 11/77, and 7/79) and found that just over 1 meter of uplift had occurred in the northern part of the island as a result of the 1965 earthquake (Figure 28, Table 4).

Tsunamis in Vanuatu

Tsunamis (seismic sea waves) are caused by displacements in submarine topography that are induced by earthquakes and/or volcanic activity occurring below or near the floor of the ocean. Low-lying areas near the shore are particularly vulnerable to damage by these waves. The shallow seismic zones of the Southwest Pacific have a history of earthquake-generated tsunamis (Figure 29). A few tsunamis have originated in the Vanuatu region. A tsunami was produced by the first earthquake of the March 1875 sequence (Iida et al., 1967). The earliest known significant one was the 10 January 1878 earthquake which produced a large tsunami

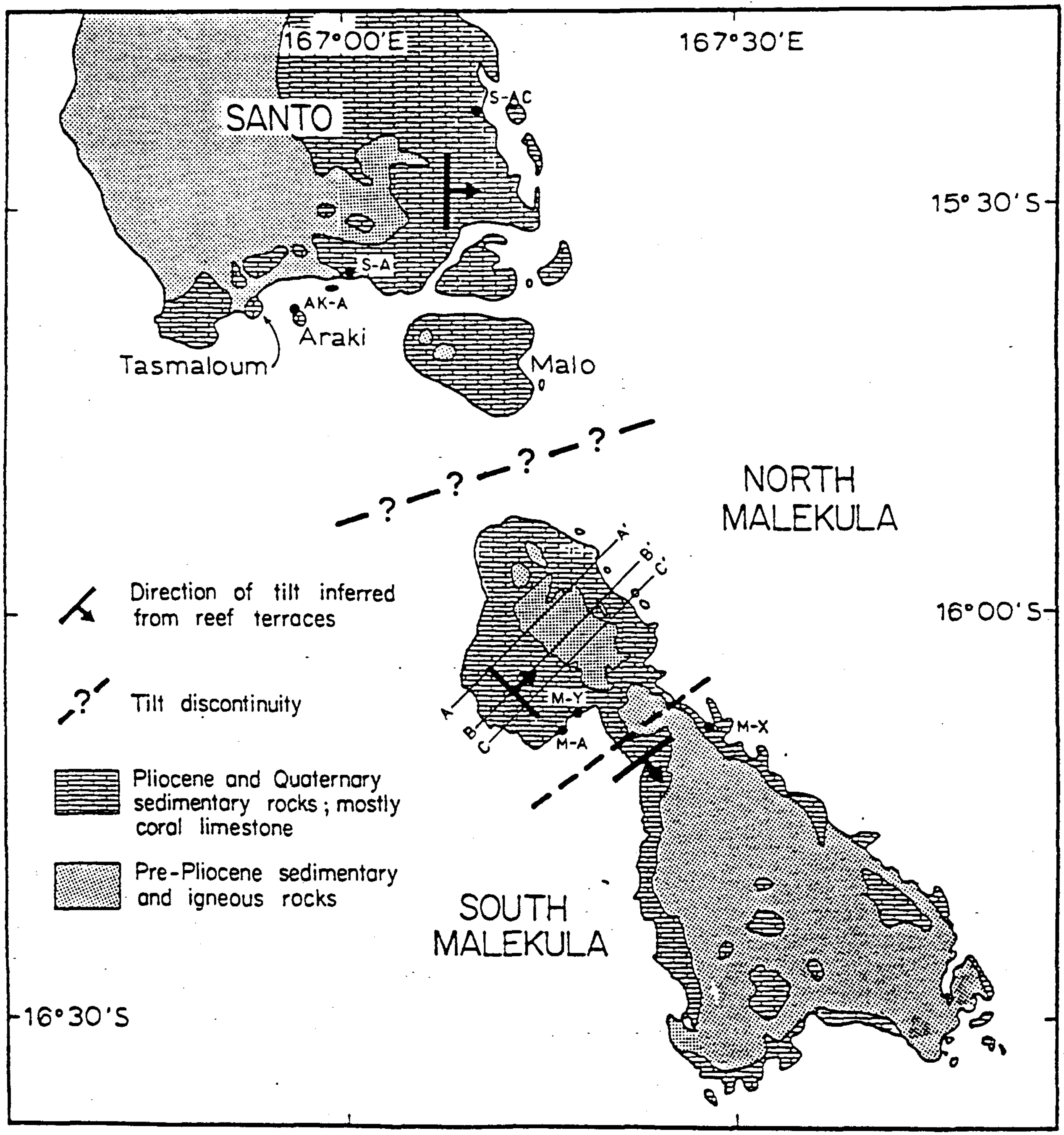


Figure 27. Tectonic uplift associated with the 1965 Santo earthquakes (Taylor et al., 1980).

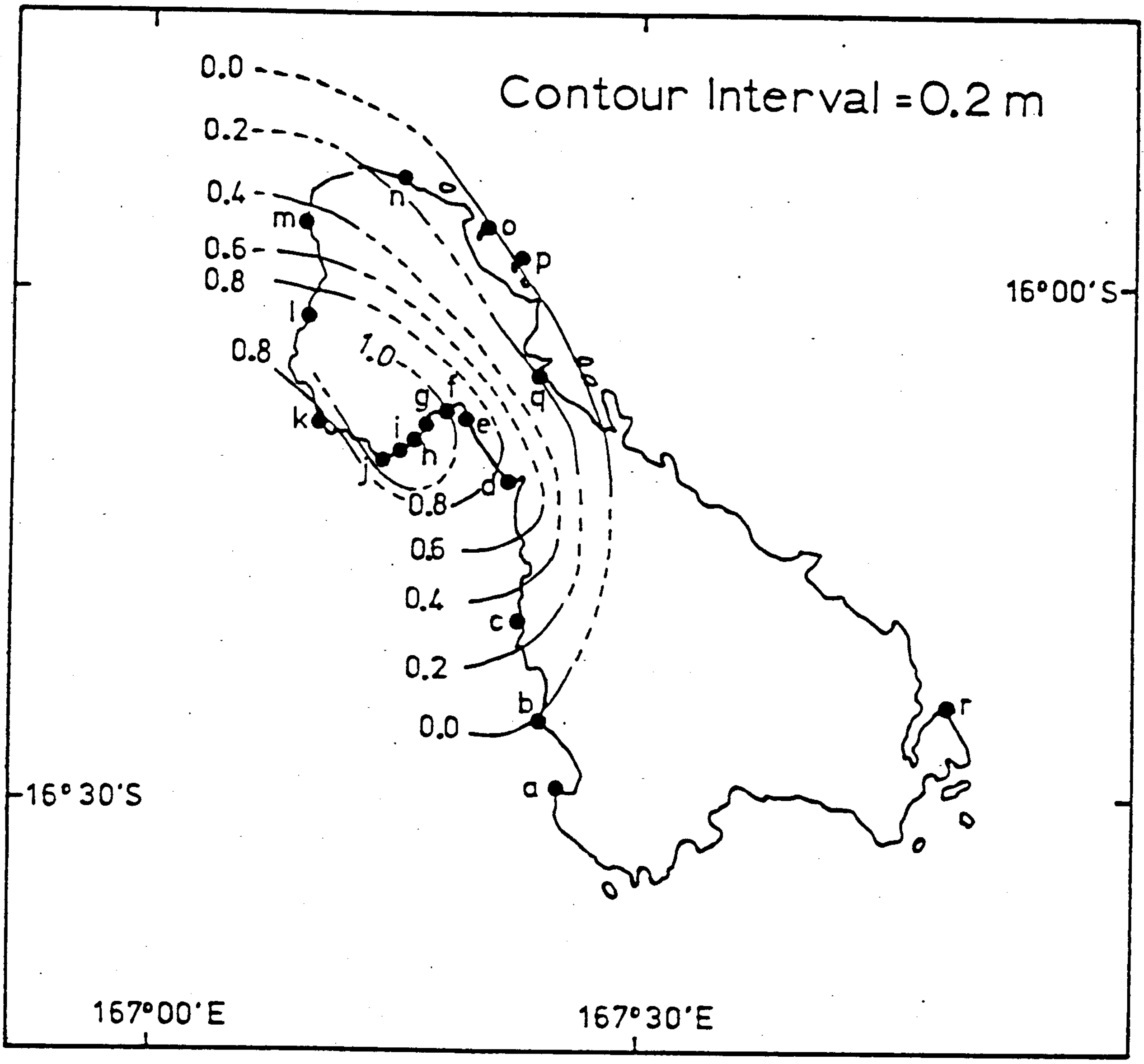
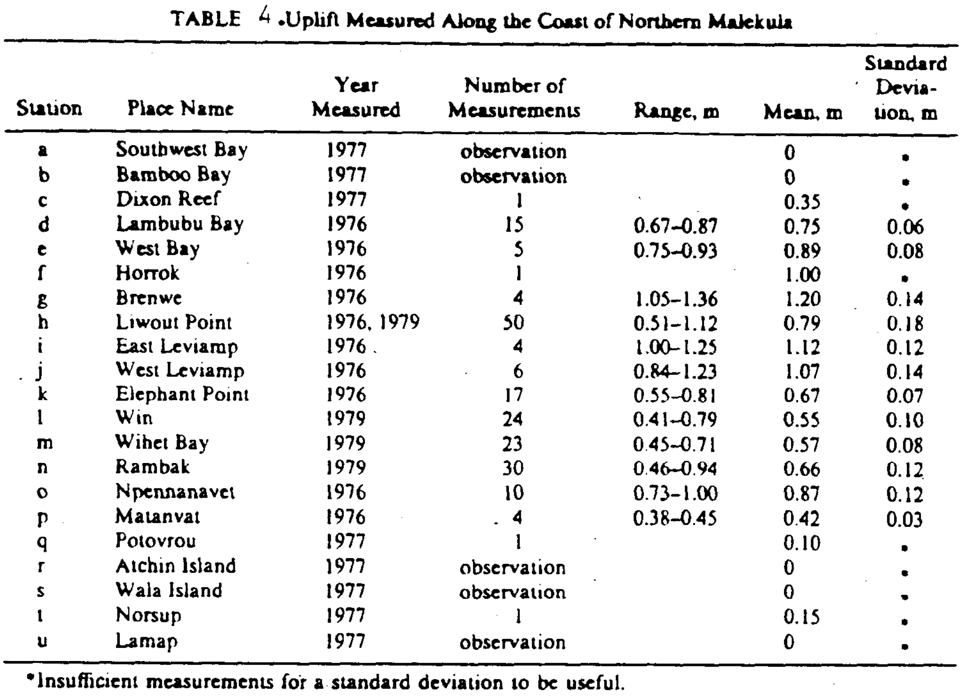


Figure 28. Measurements (meters) of 1965 uplift made in September 1976, November 1977, and July 1979. The letters on the figure represent the places and amounts of uplift given in Table 2. The contours of uplift (contour interval = 0.2 ,) represent one of the simplest interpretations of the uplift pattern consistent with the measurements (Taylor et al., 1980).

TABLE 4 .Uplift Measured Along the Coast of Northern Malekula



Station	Place Name	Year Measured	Number of Measurements	Range, m	Mean, m	Standard Deviation, m
a	Southwest Bay	1977	observation		0	•
b	Bamboo Bay	1977	observation		0	•
c	Dixon Reef	1977	1		0.35	•
d	Lambubu Bay	1976	15	0.67–0.87	0.75	0.06
e	West Bay	1976	5	0.75–0.93	0.89	0.08
f	Horrok	1976	1		1.00	•
g	Brenwe	1976	4	1.05–1.36	1.20	0.14
h	Liwout Point	1976, 1979	50	0.51–1.12	0.79	0.18
i	East Leviamp	1976	4	1.00–1.25	1.12	0.12
j	West Leviamp	1976	6	0.84–1.23	1.07	0.14
k	Elephant Point	1976	17	0.55–0.81	0.67	0.07
l	Win	1979	24	0.41–0.79	0.55	0.10
m	Wihet Bay	1979	23	0.45–0.71	0.57	0.08
n	Rambak	1979	30	0.46–0.94	0.66	0.12
o	Npennanavet	1976	10	0.73–1.00	0.87	0.12
p	Matanvat	1976	4	0.38–0.45	0.42	0.03
q	Potovrou	1977	1		0.10	•
r	Atchin Island	1977	observation		0	•
s	Wala Island	1977	observation		0	•
t	Norsup	1977	1		0.15	•
u	Lamap	1977	observation		0	•

•Insufficient measurements for a standard deviation to be useful.

(Taylor et al., 1980).

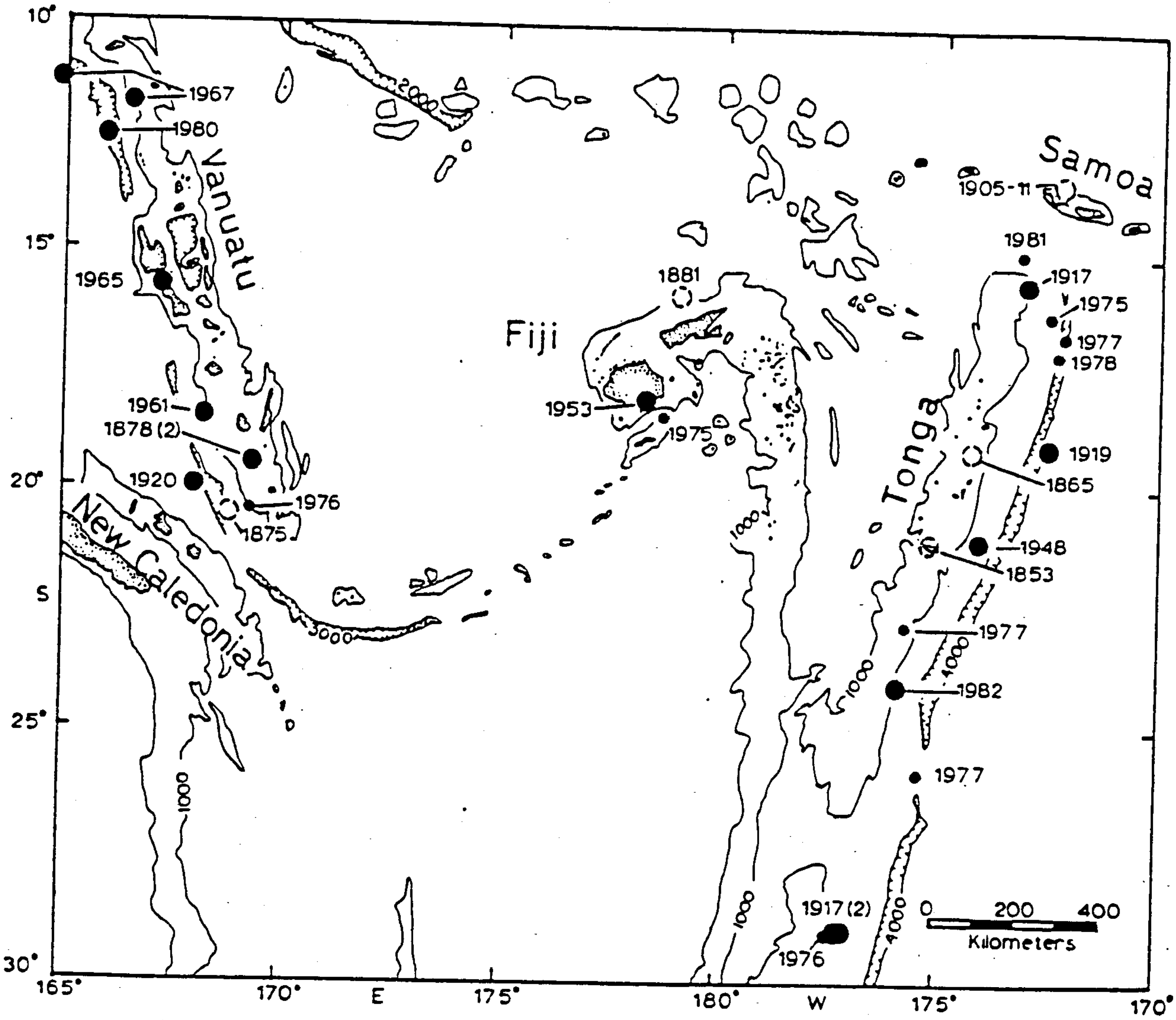


Figure 29. Tsunami history of the Southwest Pacific. Filled circles indicate locations of tsunamigenic events; dashed circles indicate inferred locations of tsunamigenic events.

(12-17 m; Iida et al., 1967) and 6 meters of uplift of the harbor at Port Resolution (Warden and Mitchell, 1974). Other earthquake generated tsunamis have occurred in 1961, 1965 and 2 in 1967 (Iida et al., 1967). While major Pacific-wide tsunamis such as those generated along the South American or Alaskan plate margins apparently do not affect Vanuatu, significant local tsunamis may be generated by large shallow earthquakes occurring within the region.

Volcanic Eruptions in Vanuatu

Volcanic activity is concentrated in the central belt of the Vanuatu island arc. Much of the present activity is confined to solfataric eruptions, however, explosive eruptions are known (e.g. the 1878 Yasowa eruptions).

In general, the potential effects of a volcanic eruption on the inhabitants of the islands of Vanuatu are small, except for those people who are living in the immediate vicinity of an active volcano. However, evacuation of inhabited volcanic islands may be necessary in larger eruptions. Even distant volcanic eruptions such as those at Home Reef in the Kingdom of Tonga during March 1984 produced large quantities of pumice, some of which rafted across large portions of the Southwest Pacific. The floating pumice interfered with shipping throughout the Southwest Pacific region (SEAN Bull., 1984).

IMPLICATIONS FOR MITIGATION OF EARTHQUAKE RISK

Several significant steps may be taken that will significantly mitigate the loss of life and property from future earthquakes in Vanuatu. The following five steps provide suggestions for mitigation of the earthquake risk.

Earthquake Education

First, an earthquake education program, such as that adopted in Fiji or Papua New Guinea, is strongly recommended. At minimal cost to the Government, such a program may be mounted through the schools, Red Cross programs, and through the news media. In other countries, earthquake education programs have taught simple methods of strengthening house construction, and minimizing hazardous conditions within the home; they have warned of tsunami hazards to coastal dwellers; they have instructed on proper behavior during an earthquake; they have helped to encourage storage of emergency food, water, and equipment in many households; and importantly, they have helped avoid panic during an earthquake and stimulated cooperation with government officials following such a disaster. Earthquake education programs are effectively combined with other disaster preparedness programs (e.g., cyclones, floods, and so on). An example of educational materials prepared by the Fiji Mineral Resources Department is included in Appendix IV.

A few, simple measures can be taken to reduce the likelihood of damage to personal property. A system of baffles in water reservoirs can reduce the chances of seiches being set up in the tanks and the ultimate collapse of the tower if the motion is large enough. Large, heavy objects should not be put in high places where they can be easily dislodged, unless they are anchored in place. This would apply to things like stereo speakers and other objects that might be on shelves. Products on shelves in stores and books in offices can be restrained with wire retainers along fronts of shelves. Heavy objects that could tip over (such as hot water heaters and gas tanks) can be fastened with anchoring bands. This is especially a concern with gas tanks which could fall over, rupture lines, and result in fire.

Building Codes

Second, adoption of building codes for Vanuatu is imperative. There is a real danger of a large earthquake occurring very close to Port Vila or Luganville. In general, the adequacy of construction is a major factor controlling the damage and loss of life brought on by such an earthquake. Building codes designed for areas of similar earthquake hazard, such as New Zealand Code A, California Building Codes, or Papua New Guinea Codes 1 or 2, would be appropriate for Vanuatu. Observation of such codes is most crucial for public multistory buildings in the major towns of Port Vila, Efate and Luganville, Santo. As important as the design of such buildings are the construction methods and quality of construction material used to implement building design. Careful monitoring of construction by competent engineers is important for critical facilities. The traditional houses have kept down past losses of life and property, but increasing population and rapid urbanization can result in higher potential damage, if earthquake-resistant designs are not implemented. One of the primary reasons for property damage resulting from the Mere Lava earthquakes was related to the siting of newer homes. Houses located on steep slopes suffered damage when they were not situated on competent substrate (Figure 30). The shaking of the fill and loose soils by the earthquakes caused unconsolidated materials to shift under the foundations.

Emergency Civil Defense Procedures

Third, development of specific Civil Defense plans for emergency procedures following an earthquake or tsunami should be initiated. Of

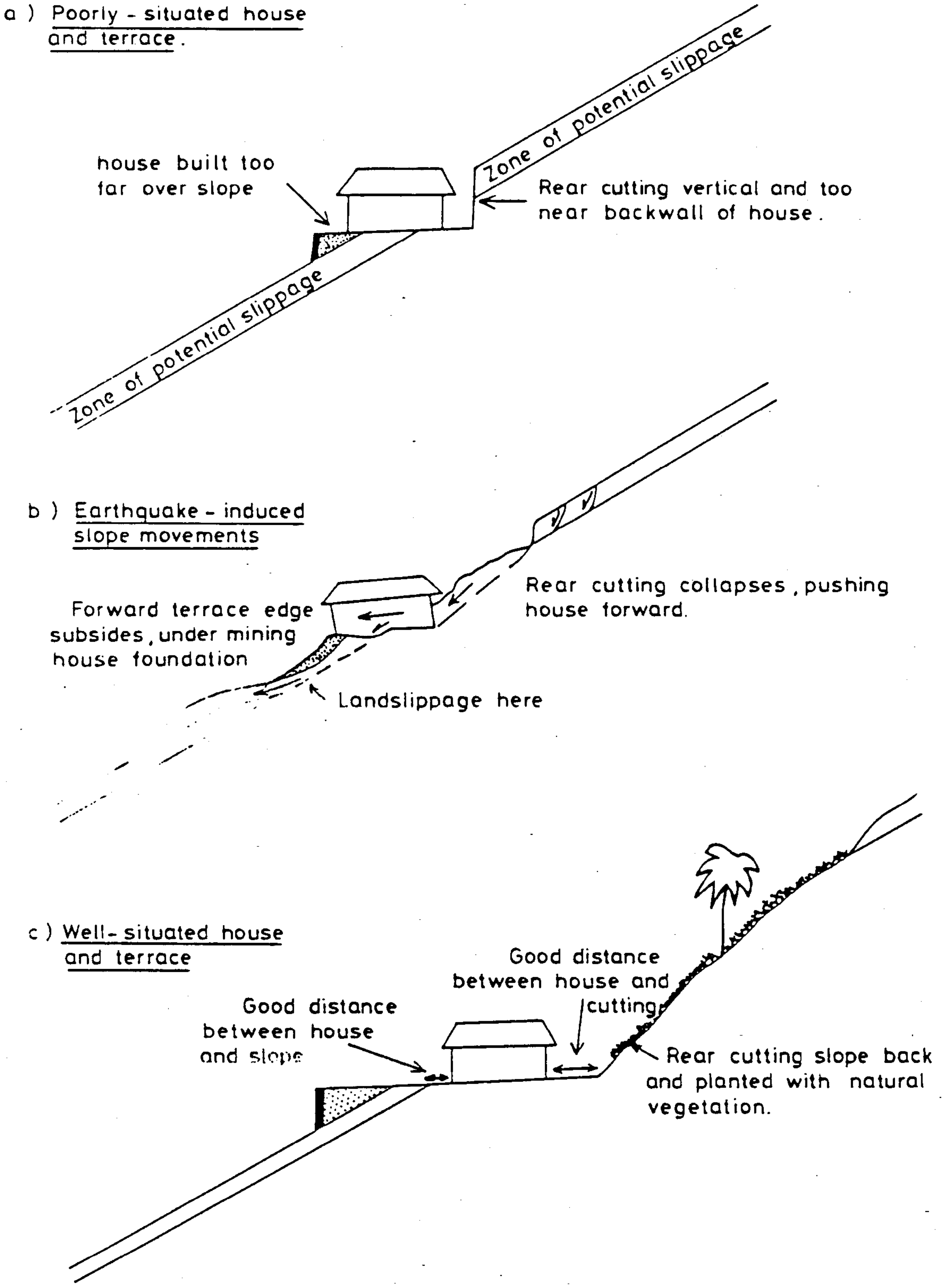


Figure 30. Schematic representation of causes of damage to poorly sited houses and suggestions for future house contruction in areas of loosely consolidated soil.

course, earthquake preparedness plans have much in common with hurricane or other natural disaster planning, but specific effects of earthquake occurrence must be considered: structural damage to multistory buildings, interruption of water supply, disruption of electrical and gas lines, secondary geological effects such as ground liquefaction or landslides in the near-source region; complicating effects of aftershocks in the days and weeks following a major earthquake. The primary structure for such civil defence plans already is in place in Tonga. Programs specific to the earthquake hazard may be added, following similar programs in Fiji, Papua New Guinea, and New Zealand.

Long-term Seismicity Observations

Fourth, long-term seismicity and strong motion observations should be continued. In the long-term, such information will help to refine estimates of seismic potential along the New Hebrides plate boundary; they will help to more directly and accurately assess the ground motion parameters of direct concern to engineers for building design in Vanuatu--ground acceleration, frequency spectra, horizontal and vertical components of ground motion, local amplification effects and so on. Furthermore, seismicity patterns may provide a key to long-term forecasting and short-term prediction of the location and size of future earthquakes that may affect Vanuatu's population.

International Cooperation

Fifth, international cooperation among the island countries of the Southwest Pacific and foreign agencies (e.g. U.S. Geological Survey, ORSTOM, etc.) may significantly help in Vanuatu's earthquake preparedness program. All of the countries affected by earthquakes (Vanuatu, Western

Samoa, Fiji, Tonga, Solomon Islands, Papua New Guinea, and New Zealand) have to varying degrees developed earthquake preparedness programs. Vanuatu may take advantage of the previous, current, and any future efforts of the other countries in the region.

References

Atkin, R. J. (1968). On volcanoes in the New Hebrides and Banks Islands, Quarterly J. of the Geological Society of London, 24, 305-307.

Calder, N., 1972. The Restless Earth, A Report on the New Geology, The Viking Press, New York, N. Y.

Carney, J. N. and A. Macfarlane (1979). Geology of Tanna, Aneityum, Futuna, and Aniwa, New Hebrides Geological Survey, Regional Report, 71 pp.

Carney, J. N. and R. Campillo (1980). An investigation into damage caused by seismic activity on Mere Lava during May 1980, Geological Survey Dept. Of Vanuatu Report.

Chase, C. G. (1971). Tectonic history of the Fiji Plateau, Geol. Doc. Amer. Bull., 82, 3087-3110.

Chase, T. E., B. A. Seekins, J. Daniel, and J. Y. Collot (1983). Topography of the Vanuatu region, map, U.S. Geological Survey, Alexandria, VA.

Chatelain, J. L., R. K. Cardwell, and B. L. Isacks, (1983). Expansion of the aftershock zone following the Vanuatu (New Hebrides) earthquake on 15 July 1981, Geophys. Res. Lett., 10, 385-388.

Chatelain, J. L., B. L. Isacks, R. K. Cardwell, R. Prévot, and M. Bevis (in press). Patterns of seismicity associated with asperities in the central New Hebrides Island Arc, J. Geophys. Res.

Chinn, D. S. (1982). Accurate source depths and focal mechanisms of shallow earthquakes in western South America and in the New Hebrides island arc, Ph.D. Thesis, Cornell University, Ithaca, N.Y.

Chinn, D. S., and B. L. Isacks, (1983). Accurate source depths and focal mechanisms of shallow earthquakes in western South America and in the New Hebrides island arc, Tectonics, 2, 529-563.

Chiu, J.-M. (1982). Structural features of subduction zone determined by detailed analysis of short period seismic waves from earthquakes recorded in the New Hebrides island arc, Ph.D. Thesis, Cornell University.

Collot, J. Y., J. Daniel, and R. V. Burne (1985). Recent tectonics associated with the subduction/collision of the D'Entrecasteaux zone in the central New Hebrides, Tectonophys., 112, 325-356.

Coudert, E., B. L. Isacks, M. Barazangi, R. Louat, R. Cardwell, A. Chen, J. Dubois, G. Latham, and B. Pontoise (1981). Spatial distribution and mechanisms of earthquakes in the southern New Hebrides arc from a temporary land and ocean bottom seismic network and from worldwide observations, J. Geophys. Res., 86, 5905-5925.

Dubois, J., J. Launay, J. Recy, and J. Marshall (1977). New Hebrides trench: Subduction rate from associated lithospheric bulge, Canadian J. Earth Sci., 14, 250-255.

Ebel, J. E. (1980). Source processes of the 1965 New Hebrides Islands earthquakes inferred from teleseismic waveforms, Geophys. J. Royal. Astron. Soc., 63, 381-403.

Everingham, I. B. (1984). Provisional list of felt earthquakes reports in Fiji, 1941-1981, Min. Resources Dept. Fiji, Note BP 33/8, 17 pp.

Falvey, D. A. (1978). Analysis of paleomagnetic data from New Hebrides, Bull. Austr. Explor. Geophys., 9, 117-123.

Geological Map of the New Hebrides Condominium, scale 1:1,000,000 (1975). Ministry of Overseas Development (Directorate of Overseas Surveys), D.O.S. 1196, British Residency, Port Vila, New Hebrides.

Gilpin, L. M., A. L. Bloom, B. L. Isacks, and M. Bevis, F. W. Taylor, and C. Jouannic (1982). Late Pleistocene coral reef terraces as tiltmeters on Santo Island, Vanuatu (New Hebrides), EOS, Trans. Amer. Geophys. Union, 63, 430.

Gutenberg, B. and C. F. Richter (1954). Seismicity of the Earth, 2nd ed., Princeton, N.J., Princeton University Press.

Habermann, R. E. (1984). Spatial seismicity variations and asperities in the New Hebrides seismic zone, J. Geophys. Res., 89, 5891-590.

Hamburger, M. W. (1986). Seismicity of the Fiji Islands and Tectonics of the Southwest Pacific, Ph.D. thesis, 312 pp., Cornell University, Ithaca, N.Y.

Hays, W. W., (1980). Procedures for estimating earthquake ground motions, U. S. Geological Surv. Prof. Paper 1114, 77 pp.

Ibrahim, A. K., B. Pontoise, G. Latham, M. Larue, T. Chen, B. Isacks, J. Recy, and R. Louat (1980). Structure of the New Hebrides arc-trench system, J. Geophys. Res., 85, 253-266.

Iida, K., D. Cox, and G. Pararas-Carayannis (1967). Preliminary Catalog of Tsunamis Occurring in the Pacific Ocean, H.I.G., University of Hawaii.

International Seismological Centre (ISC), 1978-1979. Bulletin of the International Seismological Centre, Newberry, Berkshire, United Kingdom.

International Seismological Centre (ISS), 1918-1963. International Seismological Summary, Newbury, Berkshire, U.K.

Isacks, B. L. and M. Barazangi (1977). Geometry of Benioff zones: Lateral segmentation and downwards bending of the subducted lithosphere in *Island Arcs, Deep Sea Trenches and Back-Arc Basins*, Talwani, M. and W. C. Pitman, ed., Maurice Ewing Series, 1, Amer. Geophys. Union, Washington, D. C., 99-114.

Isacks, B. L., G. Hade, R. Campillo, M. Bevis, D. Chinn, J. Dubois, J. Recy, and J. L. Saos (1978). Measurements of tilt in the New Hebrides island arc, in Proceedings of Conference VII, Stress and Strain Measurements Related to Earthquake Prediction, *U.S. Geological Survey Open-File Report 79-370*, 176-221.

Isacks, B. L., R. Cardwell, J.-L. Chatelain, M. Barazangi, J.-M. Marthelot, D. Chinn, and R. Louat (1981). Seismicity and tectonics of the central New Hebrides Island Arc, in *Earthquake Prediction, An International Review, Maurice Ewing Ser., 4*, edited by D. W. Simpson and P. G. Richards, AGU, Washington, D.C., 93-116.

Johnson, T. and P. Molnar (1972). Focal mechanisms and plate tectonics of the southwest Pacific, *J. Geophys. Res.*, *77*, 5000-5032.

Karig, D. E. (1971). Origin and development of marginal basins in the western Pacific, *J. Geophys. Res.*, *76*, 2542-2561.

Karig, D. E. and J. Mammerickx (1972). Tectonic framework of the New Hebrides island arc, *Marine Geology*, *12*, 187-205.

Kelleher J., J. Savino, H. Rowlett, and W. McCann (1974). Why and where great thrust earthquakes occur along island arc, *J. Geophys. Res.*, *79*, 4889-4898.

Kroenke, L. (1984). Cenozoic Tectonic Development of the Southwest Pacific, *United Nations Econ. and Social Commission for Asia and the Pacific*, *Technical Bull. 6*.

Lay, T. and H. Kanamori (1981). An asperity model of large earthquake sequences, in *Earthquake Prediction, An International Review, Maurice Ewing Ser. 4*., edited by D. W. Simpson and P. G. Richards, AGU, Washington, D.C., 579-592.

Luyendyk, B. P., W. B. Bryan, and P. A. Jezek (1974). Shallow structure of the New Hebrides Island Arc, *Geol. Soc. Amer.*, *85*, 1287-1300.

Louat, R., J. Daniel, and B. Isacks (1982). Seismicité de l'arc des Nouvelles Hebrides, in Equipe de Géologie-Géophysique du Centre ORSTOM de Nouméa, *Contribution à l'etude géodynamique du Sud-Ouest Pacifique*, Travau et Documents de l'ORSTOM, 1147, 179-186.

Mammerickx, J., T. E. Chase, S. M. Smith, and I. L. Taylor (1971). *Bathymetry of the South Pacific*, map, Scripps Inst. of Oceanogr., La Jolla, Calif.

Marthelot, J.-M. (1983). Patterns of seismicity in the Vanuatu (New Hebrides) arc: Regional variations and systematic evolution, Ph.D. Thesis, Cornell University.

Marthelot, J.-M., J.-L. Chatelain, B. L. Isacks, R. K. Cardwell, and E. Coudert (1985). Seismicity and attenuation in the central Vanuatu (New Hebrides) islands: A new interpretation of the effect of subduction of the D'Entrecasteaux Fracture Zone, J. Geophys. Res., 90.

McCann, W. R. (1980). Large and moderate size earthquakes: Their relationship to the tectonics of subduction, Ph. D. thesis, Lamont-Doherty Geol. Observ. of Columbia Univ., Palisades, N.Y.

McCann, W. R., S. P. Nishenko, L. R. Sykes, and J. Krause (1979). Seismic gaps and plate tectonics. Seismic potential for major boundaries, Pure Appl. Geophys., 117, 1082-1147.

McGuire, R. K., (1977). Effects of uncertainty in seismicity on estimate of seismic hazard for the East Coast of the United States, Bull. Seis. Soc. Amer., 67, 827-848.

Mitchell A. H. G. and A. J. Warden (1971). Geological evolution of the New Hebrides island arc, J. Geol. Soc. London, 127, 501-529.

Mogi, K. (1963). Some discussions on aftershocks, foreshocks and earthquake swarms--The fracture of a semi-infinite body caused by an inner stress origin and its relation to the earthquake phenomena (third paper), Bull. Earthq. Res. Inst. Tokyo Univ., 41, 615-658.

Monzier, M., J. Y. Collot, and J. Daniel (1984). Carte bathymetrique des parties centrale et meridionale de l'arc insulaire des Nouvelles-Hebrides, map, Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM), Paris.

Murphy, J. R. and L. J. O'Brien (1977). Analysis of a worldwide strong motion data sample to develop an improved correlation between peak acceleration, seismic intensity, and other physical parameters: Computer Sciences Corporation, Rept. NUREG-0402 to U.S. Nuclear Regulatory Commission, 68 pp.

Pascal, G., B. L. Isacks, M. Barazangi, and J. Dubois (1978). Precise relocations of earthquakes and seismotectonics of the New Hebrides island arc, J. Geophys. Res., 83, 4957-4973.

Preliminary Determination of Epicenters (PDE), 1961-1981. Monthly Bulletin, National Earthquake Information Service, U.S. Geological Survey, Alexandria, Va.

Prévot, R. and J. L. Chatelain (1983). Seismicity and seismic risk in Vanuatu, Report No. 5-83, Centre ORSTOM, Nouméa, New Caledonia.

Richter, C. F. (1958). Elementary Seismology, W. H. Freeman and Company, Inc., San Francisco.

Rothe, J. (1965). The Seismicity of the Earth, 1953-1965, Paris, UNESCO, 336 pp.
Santo, T. (1970). Regional study of the characteristic seismicity of the world, Part III, New Hebrides island region, Bull. Earthquake Res. Inst., Tokyo Univ., 48, 1-18.

SEAN (Scientific Event Alert Network) Bulletin, 9.

Taylor, F. W., B. L. Isacks, C. Jouannic, A. L. Bloom, and J. Dubois (1980). Coseismic and Quaternary vertical tectonic movements, Santo and Malekula islands, New Hebrides island arc, J. Geophys. Res., 85, 5367-5381.

Taylor, F. W., C. Jouannic, and A. L. Bloom (1985). Quaternary uplift of the Torres Islands, northern New Hebrides frontal arc: Comparison with Santo and Malakula Islands, central New Hebrides frontal arc, J. of Geol., 93, 419-438.

Trifunac, M. D. (1976). Preliminary analysis of the peaks of strong earthquake ground motion--dependence of peaks on earthquake magnitude, epicentral distance, and recording site condition, Bull. Seism. Soc. Amer., 66, 189-220.

Trifunac, M. D. and A. G. Brady (1975a). Correlations of peak acceleration, velocity, and displacement with earthquake magnitude, and site condition, Intl. J. Earthquake Engr. Struc. Dynamics, 4, 455-471.

Trifunac, M. D. and A. G. Brady (1975b). On the correlation of seismic intensity scales with the peaks of recorded ground motion, Bull. Seism. Soc. Amer., 65, 139-162.

Turcotte, D. L. and G. Schubert (1982). Geodynamics, John Wiley & Sons, New York.

U.S. Geological Survey, 1961-1985. Preliminary Determination of Epicenters, Denver, Colo..

Vidale, J., and H. Kanamori (1983). The October 1980 earthquake sequence near New Hebrides, Geophys. Res. Lett., 10, 1137-1140.

Wellington Seismological Observatory, Geophysics Division, 1953-1960. N.Z. Dept. Scientific and Industrial Research, Catalog of Earthquakes, 1953-1960.

Wray, S. T., R. K. Cardwell, B. L. Isacks, E. Coudert, and J.-L. Chatelain (1983). Detailed seismicity observations in the forearc region of a convergent plate boundary: Malekula Island, Vanuatu (abstract), EOS, Trans. Am. Geophys. Union, 62, 945.

Wyss, M., R. E. Habermann, and C. Heiniger (1983). Seismic quiescence, stress drops and asperities in the New Hebrides arc, Bull. Seismol. Soc. Am., 73, 219-236.

APPENDIX I. DEFINITIONS

Two measures of the size of an earthquake are magnitude and intensity. Magnitude is a measure of the energy from an earthquake source to indicate the strength of an earthquake. In comparison, intensity is a measure of the amount of ground shaking caused by the earthquake at a particular site. Thus, an earthquake of a given magnitude will produce a wide range of intensities, depending largely on distance from the source.

In general, a small earthquake, with a magnitude less than 5, may be felt only in the area near the source and a moderate earthquake, with a magnitude between 5 and 7, will be felt over a wider area, and may produce significant damage in the area very close to the source. A large earthquake refers to an earthquake with a magnitude greater than 7. Such events are often very destructive if they are located near population centers. A major earthquake refers to magnitudes between 7 and 7 3/4 and a great earthquake refers to magnitudes greater than 7 3/4. These great earthquakes cause widespread destruction and possible regional tsunamis. Generally, the potential damage from earthquakes is multiplied by the secondary effects of earthquake occurrence such as: ground faulting, generation of tsunamis, landslides, slumping, or liquifaction.

The depth of earthquakes range from the surface to approximately 700 km depth. Shallow earthquakes refer to those with depths between the surface and 70 km. Intermediate earthquakes refer to those with depths between 70 km and 250 km depth. Deep earthquakes refer to those with depths greater than 250 km (but less than 700 km). Intermediate depth earthquakes occasionally produce damage at the earth's surface only if the earthquake is very large. Deep events are generally not felt.

The seismic (earthquake) potential of a particular region is defined as the likelihood of that region to experience a (destructive) earthquake within a particular magnitude range within a particular time period. The seismic (earthquake) hazard of a particular location refers to the amount of ground motion that might be expected from an earthquake within or near that region. Adequate data on seismotectonic features, instrumental (strong-motion) and macroseismic (intensity) records of near-field effects of large earthquakes, source parameters of large earthquakes, earthquake spectra, and ground attenuation or amplification are necessary in order to reasonably evaluate earthquake hazard for any region. The seismic potential is the integration of all of these bits of information. The average length of time between earthquakes of a particular size (recurrence interval) and the amount of time elapsed since the last earthquake of that size help to define the probability of future earthquake occurrence along a particular seismogenic zone, hence the seismic potential of that zone.

Seismic risk of a particular region refers to the expected degree of losses of people and their property which result from the seismic hazard and the vulnerability in the region. One method that has been widely used for this risk determination (and is used here) involves the determination of a maximum probable earthquake (design earthquake) that is likely to occur in the immediate region. Calculations of seismic hazard which are based on design earthquakes generally yield conservative estimates of risk.

The most important conclusion of historical studies of seismicity is to define the seismogenic zones of a region and extrapolate what the future earthquake potential is for those zones. Seismically quiescent regions refer to regions with a lower level of seismic activity which are surrounded by more active regions. Portions of major plate boundaries that have not experienced a major or great earthquake during a particular time interval are <u>seismic gaps</u>. This time interval is taken to be a significant portion of the earthquake recurrence interval for a large earthquake. An estimate, to within several decades, of the location and size (magnitude) of a large earthquake constitutes a <u>forecast</u>. If a precise calculation of the time and probability of occurrence can be added to the location and size information, then the estimation is a <u>prediction</u>.

APPENDIX II. MODIFIED MERCALLI INTENSITY SCALE (1956 VERSION)[1]

Masonry A, B, C, D. To avoid ambiguity of language, the quality of masonry, brick or otherwise, is specified by the following lettering (which has no connection with the conventional Class A, B, C construction).

Masonry A. Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

Masonry B. Good workmanship and mortar; reinforced; but not designed in detail to resist lateral forces.

Masonry C. Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

DESCRIPTION (INTENSITY VALUES RANGE FROM I TO XII)

I. Not felt. Marginal and long-period effects of large earthquakes.

II. Felt by persons at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frames creak.

V. Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.

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[1] Original 1931 version in Wood, H. O., and F. Newmann, 1931. Modified Mercalli Intensity Scale of 1931, Bull. Seis. Soc. Amer., 53, 979-987. 1956 version prepared by Charles F. Richter, in Elementary Seismology (1958), 137-138, W. H. Freeman and Company.

VI. Felt by all. Many frightened and run outdoors. Persons walk un steadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle--CFR).

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments--CFR). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

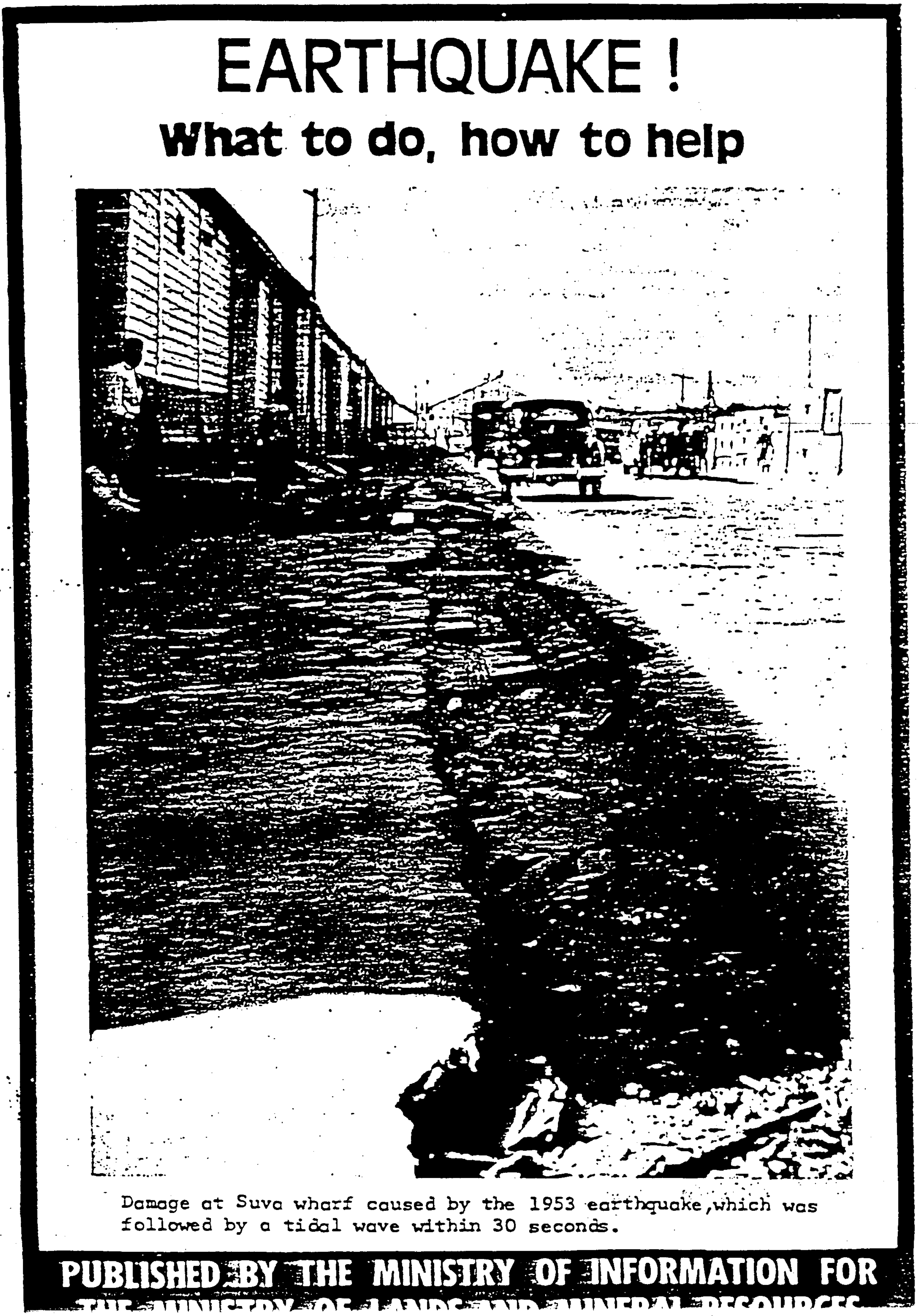
VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and steep slopes.

IX. General panic. Masonry D destroyed; masonry C heavily damaged, some times with complete collapse; masonry B seriously damaged. (General damage to foundations--CFR). Frame structures, if not bolted, shifted off foundations. Framed cracked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.

X. Most masonry and frame structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

APPENDIX III: EARTHQUAKE EDUCATION PAMPHLET PUBLISHED IN FIJI



EARTHQUAKE !

What to do, how to help

Damage at Suva wharf caused by the 1953 earthquake, which was followed by a tidal wave within 30 seconds.

PUBLISHED BY THE MINISTRY OF INFORMATION FOR THE MINISTRY OF LANDS AND MINERAL RESOURCES

A message from the Minister for Lands

Recent earthquakes in Waya Island and the even more recent one which rocked the city of Suva shortly after 9am on December 17,1975, and the ensuing panic reaction of the people are sharp reminders to us that although Fiji is situated in an earthquake zone, there is little information available to the public on earthquakes and tsunamis (tidal waves), which are often associated with the type of earthquakes we have experienced in Fiji.

It is hoped that the information pamphlet prepared by my ministry on earthquakes and tsunamis will allay some of the natural alarm which people experience during even the minor tremors.

It has been brought to my notice that at least one expert has predicted the chance of a serious earthquake in Fiji as 1/40 years, i.e., one earthquake every 40 years.

However, with the exception of the earthquake and tidal waves in 1953, we are fortunate not to have suffered a more serious earthquake.

They are probably the most terrifying and devastating phenomena known to man.

Unlike other natural disasters, such as hurricanes and flooding, the tragedy of earthquakes is that there is no forewarning of their coming.

The very recent earthquake disaster in Hawaii is an obvious indicator that the science of predicting earthquakes is still in the early stages of development.

Although the recent occurrence in Hawaii might not rank among the world's most serious earthquakes, we know from the experiences of other countries that earthquakes can be totally devastating.

However remote the possibility of a serious earthquake and tsunamis might be, the most effective means of mitigating the worst effects of a sudden calamity in these two potentially dangerous forms is to know more about them.

Indeed, the suddenness and the severity of a widespread disaster could disrupt all communications and paralyse even the most efficient and well-drilled emergency organisation.

Survival in those circumstances would depend on each individual's own knowledge and initiative.

Because we are in an earthquake belt, it would be prudent for people living in Fiji to make themselves thoroughly familiar with the information contained in this pamphlet.

I wish to take this opportunity to appeal for your full co-operation in answering the questionnaire on earthquakes and tsunamis which appears on page nine of this pamphlet as accurately as possible.

The aim of the questionnaire is to locate and map the fault-line zones from which it is suspected that most of our earthquakes originate.

The success and the efficiency of any kind of emergency relief system may depend on your co-operation in providing the information sought.— S.N.Waqanivavalagi, Minister for Lands and Mineral Resources.

Part of the damage to the Suva Harbour reef caused by the 1953 earthquake.

70 per cent from Fiji area

About 70 per cent of the world's deep earthquakes are recorded from the Fiji area. Most of them are not felt because they occur at great depths of about 400 to 600 kilometres (248.45 to 372.67 miles) beneath the surface of the earth.

These types of earthquakes are not dangerous or damaging because of the depths at which they occur. But they are scientifically interesting because they help geologists to deduce the structure of the crust.

The types of earthquakes which can be very damaging are those of large magnitude, which occur in the top 50 kilemetres (31.06 miles) of the earth's crust.

The 1953 earthquake which had an epicentre (origin) 15 miles west of Suva was of this type. That earthquake had an intensity of seven out of a Mercalli scale of 12 and resulted in a tsunami (tidal wave) which occurred 30 seconds after the quake and affected Suva and Kadavu. About seven people were killed by falling masonry, landslides or drowning in the tsunami.

Another earthquake with an intensity of four to five was experienced in Suva in 1961,but caused only minor damage to buildings. Several smaller shocks have been reported since then.

Other parts of Fiji where earthquakes are often felt are Rotuma, Labasa, Savusavu, Taveuni and, recently,the Waya - Nadi - Lautoka area.

Reports received after the 1953 earthquakes also show that several very strong earthquakes have been felt in the Fiji area since the early 1800s.

Although these may have caused little damage in the past, the increasing density of population and buildings would make the area more prone to damage unless buildings are properly reinforced to withstand strong lateral motions from earthquakes.

Quakes come in two main types

Volcanic earthquakes are associated with the movement of molten rocks underground, usually at depths of less than 30 kilometres near active or inactive (at surface) volcanoes.

These volcanic earthquakes are often called tremors, because they tend to occur frequently and almost continuously, and are often associated with possible forthcoming eruptions of volcanoes.

Fortunately, it has been over a million years since volcanoes erupted in most parts of Fiji, although the most recent volcano was probably active less than 2000 years ago in the Taveuni area.

Because of the long period of time since previous eruptions, volcanoes in most parts of Fiji can be considered extinct or at least inactive.

The possibility of another eruption occurring at some future time cannot be totally discounted. But it should be reassuring to note that with modern advances in instrumentation, it is becoming increasingly possible to predict the likelihood of impending volcanic activity.

Tectonic earthquakes, the other major (and more common) type, are due to the movements of relatively solid parts of the earth's crust against each other.

Such motions can be in the form of the "swallowing" of a large portion (or plate) of the crust into a trench area.

For example, the Eastern Pacific plate is postulated to be drifting westward at the rate of about 10 centimetres (roughly 3.94 inches) a year and is being "swallowed" or subducted under the Western Pacific plate in the Tonga trench area.

The subduction of one plate under another causes friction between the plates and causes numerous earthquakes fortunately at great depths — about 500 to 600 kilometres (310.56 to 372.67 miles).

Tectonic earthquakes occur also along fault lines which are zones of weakness in the earth's crust usually at fairly shallow crustal depth.

Geologists have mapped a number of fault areas in Fiji where it is apparent that one rock mass has been moved (or displaced) relative to an adjacent rock mass through the release of stresses and strains brought about during the geological development of the islands.

Fortunately, again, most of the faults which have been mapped are thought to be inactive.

But there are some fault zones which could be active and it is quite likely that the strong 1953 earthquake was caused by fault movement offshore from the Kalokolevu - Mau area.

The recent earthquakes felt in the Waya - Nadi - Lautoka area could be due to fault movements several miles offshore south-west of Waya.

In 1976, the Mineral Resources Division intends to do detailed mapping of these possibly active fault-zone areas near Suva and in the west of Waya.

Other plans are for the division to make greater use of instruments and become involved in the recording of earthquakes.

THE MAIN DANGERS

Collapse of buildings due to lack of reinforcement, poor building materials (e.g., adobe type) or unsatisfactory foundations.

Broken overhead power lines can occur quite easily and are particularly dangerous, because many people have the inclination to run outdoors when they feel a strong earthquake.

Landslides are possible along fault zones or very wet areas, particularly where hillsides are steep. One person was killed in the Namosi area by landslides during the 1953 earthquake.

Earth movements and chasms. People naturally tend to have a very strong fear that the earth will open up and swallow them during an earthquake. However there is only one properly documented case in recorded history of a person being crushed in a fissure. Basically, the danger of falling into chasms is minimal and the natural terror of people from this is apparently the result of exaggerated tales.

Fire can be one of the most dangerous effects of earthquake as evidenced by the disasters in San Francisco in 1906 and Tokyo in 1923. Perhaps the worst problem from fires caused by earthquakes is that water pipes are often broken and firemen are forced to use less accessible alternative sources, such as a river or the sea.

Tsunamis are a particular kind of sea wave which can build up following an earthquake. In the past they have devastated cities and small settlements along the coasts of Chile, Peru, Alaska, Hawaii, Japan and other countries. These waves travel across the Pacific Ocean at jet speed (more than 600 miles an hour).

In shallow waters, tsunamis become a threat to life and property because they can reach up to more than 100ft high at wave crest levels and strike with devastating force.

We have no official record of any extensive tsunamis in Fiji except for the one caused by the 1953 earthquake, which claimed some lives in Suva and Kadavu.

Other tsunamis are likely to have occurred in earlier times, but were not identified especially as tsunamis because of our lack of experience with them.

The barrier reef round much of the islands helps to dissipate some of the wave energy and, therefore, some of the dangers.

But we should realise that we can still be vulnerable to waves, especially from a southerly direction where our reef systems are less extensive.

If a very strong earthquake is felt in Fiji, you should prudently assume that it has originated within the Fiji group and is likely to have generated a tsunami.

In the 1953 case, the tsunami was about 50ft high when it hit the reef outside Suva within 10 seconds after the earthquake.

A 6ft wave then travelled across the harbour and hit the waterfront about three to four minutes later, causing only slight damage and leaving many fish on the low-lying areas.

But the tide was low at that time. If it had been high tide, the waves could have been about 9ft high and the effects could have been disastrous!

Waves 5ft to 6ft high also hit Lami, Deuba, Beqa Island and Koro Island, and a 15ft-high wave claimed two lives at Nakasaleka, Kadavu. Smaller waves were felt at Ovalau, the southern coast of Vanua Levu and in the western Lau Group.

Precautions to take

Because earthquakes occur suddenly and without warning, there are only a few precautions people can take, such as ensuring that houses are on firm foundations and are suitably reinforced to withstand earthquakes.

The following modified version of an earthquake notice is reproduced from a California Geology article published in October 1975:

When an earthquake occurs: For a minute or two, the earth may pitch and roll like the deck of a ship. The motion is frightening, but unless it shakes something down on you, it is probably harmless in itself. Keep calm and ride it out. Your chances of survival are good if you know how to act.

During the shaking: If indoors, stay indoors. Get under sturdy furniture, such as a table. Stay near the centre of a building and stay away from glass. Do not use candles, matches or other open flames.

Do not run through or near buildings, particularly concrete ones, where there is danger of falling debris. If outside, stay in the open away from buildings and power lines.

If in a moving car, stop, but stay inside.

After the shaking: Check your water and electricity.

If water pipes are damaged or electric wires are shorting, turn off at primary control point. If in a low-lying coastal area which can be affected by tsunamis, leave house and make for higher ground (see tsunami safety rules below). Turn on radio for emergency bulletins. Stay out of damaged buildings— aftershocks can shake them down.

In a 1961 study of earthquake risks in Fiji, R.Houtz estimated that the chance of a strong quake occurring here was about 1/40, i.e., once every 40 years. This figure should be reassuring. But one must remember that it is only an estimate — and that once in 40 years could be tomorrow!

Tsunami Safety Rules

Tsunamis follow no discernible pattern of occurrence. When you receive a tsunami warning, you must assume that a dangerous wave is on its way.

History shows that when the great waves finally strike, they claim those who have ignored the warning.

The following tsunami rules were extracted from a pamphlet prepared by the US Environmental Science Services Administration and they should be noted:

1. An earthquake in your area is a natural tsunami warning. Do not stay in low-lying coastal areas after a strong local earthquake.

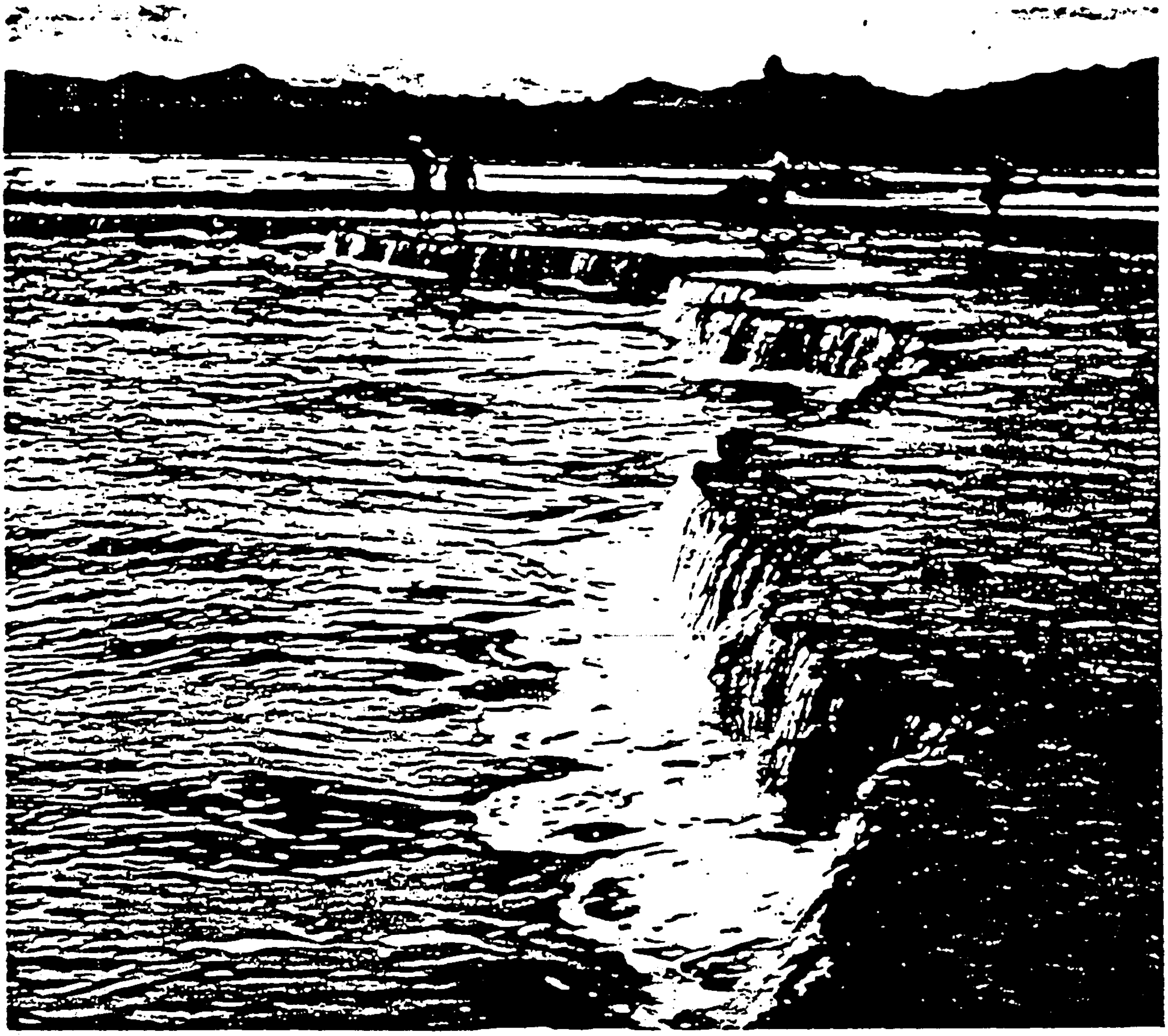
2. A tsunami is not a single wave, but a series of waves. Stay out of danger areas until an "all-clear" is issued by a competent authority.

3. Approaching tsunamis are sometimes heralded by a noticeable rise or fall of coastal water. This is nature's tsunami warning and should be heeded.

4. A small tsunami at one beach can be a giant one a few miles away. Do not let the modest size of one wave make you lose respect for what may follow.

5. All tsunamis — like hurricanes —are potentially dangerous, even though they may not damage every coastline they strike.

6. Never go down to the beach to watch for a tsunami.



When you can see the wave, you are too close to escape it.

7. Sooner or later, tsunamis visit every coastline in the Pacific. Warnings apply to you if you live in any Pacific coastal area.

8. During a tsunami emergency, your local emergency organisations will try to save your life. Give them your fullest co-operation.

Unless otherwise determined by competent scientists, potential danger areas are those less than 50ft above sea level and within one mile of the coast for tsunamis of any origin.

After 50ft wave hit Suva reef

A section of the Suva Harbour reef forced upwards by the 1953 earthquake. A tsunami (tidal wave) 50ft high hit the reef within 10 seconds after the quake and sent a 6ft wave to the shore. This struck the waterfront about three to four minutes later and caused minor damage — but only because it was at low tide.

Measuring their size

Earthquake magnitudes are measured on very sensitive seismological instruments. These are often referred to as the Richter scale and the largest shock known to date had a magnitude of 8.9 on Richter scale (compared to 6.75 for the 1953 Suva earthquake on the same scale).

Another scale that is in common use and depends on physical effects and observations is the modified Mercalli scale, which is reproduced here. It measures the intensity of earthquake and is graduated from one to 12 for measuring.

Modified Mercalli scale,1956 version

Earthquake intensity

1. Not felt except by a very few under especially favourable (for the earthquake!) circumstances.

2. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

3. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognise it as an earthquake. Standing motor cars may rock slightly. Vibration like passing truck. Duration can be estimated.

4. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows,doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

5. Felt by nearly everyone; many awakened. Some dishes, windows,etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.

6. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

7. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

8. Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys,factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbs persons driving motor cars.

9. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

10. Some well-built,wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed over banks.

11. Few, if any (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

12. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

FILL THIS IN TO HELP THE EARTHQUAKE STUDY

To enable an improved study of shallow local earthquakes, the co-operation of the public is required in filling out the following questionnaire whenever an earthquake is felt. Many earthquakes are very small and sometimes are not recorded on seismological instruments. This questionnaire system will enable the Mineral Resources Division to better determine the location of earthquake zones which can then be mapped in detail.

EARTHQUAKE QUESTIONNAIRE

1. An earthquake was felt on ....at..........am or pm.
   Place ....
2. What direction did the shock come from?......................
   ....
3. How many seconds did the quake last? ....
   ....
4. Was the shaking rapid or slow? ....
   ....
5. Where were you when the earthquake occurred? ....
   ....
6. Were you awake, asleep, or awakened? ....
   ....
7. Were you walking, working, standing, sitting or lying down? ...
   ....
8. Did the people around you feel the earthquake too? ....
   ....
9. Did people run outside? ....
   ....
10. Did cracks occur in the buildings you were in? ....
    ....
11. Was the building damaged in any other way? ....
    ....
12. What is the building made of?...........................
    ....
13. Did the windows, doors, dishes, rattle? ....
    ....
14. Did hanging objects, doors, etc., swing? ....
    ....

• Turn to next page

15. Did vases, small objects, furniture, overturn? ....

....

16. Did things fall off shelves? ....

....

17. Did you notice any unusual waves in the sea after the quake?.......

....

18. If so, how soon afterwards? ....

....

19. What were the waves like? ....

....

20. Did anything else unusual happen? ....

....

21. Any other remarks ....

....

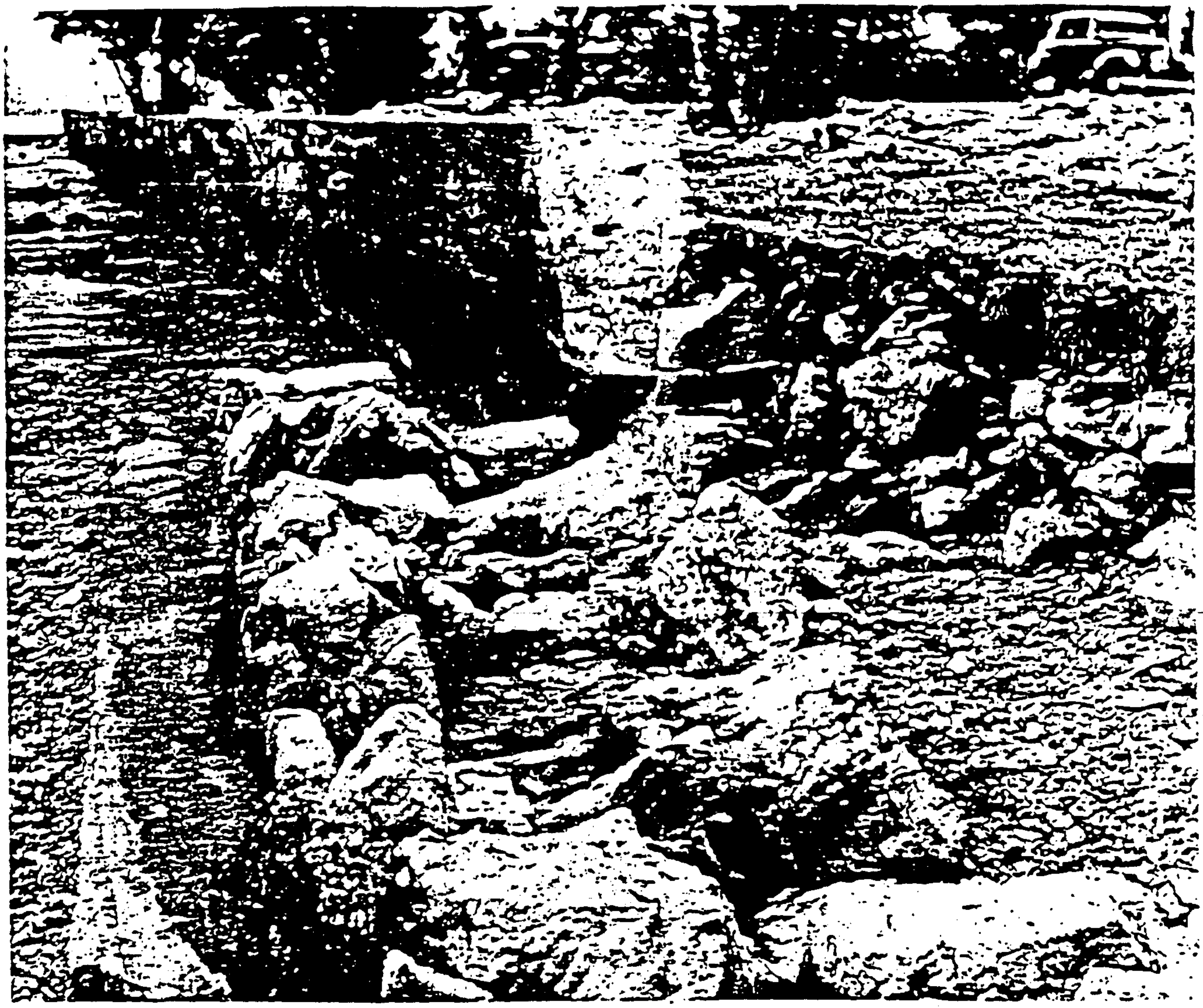
Name: ....Address: ....

Complete form, tear out this whole page and mail to:

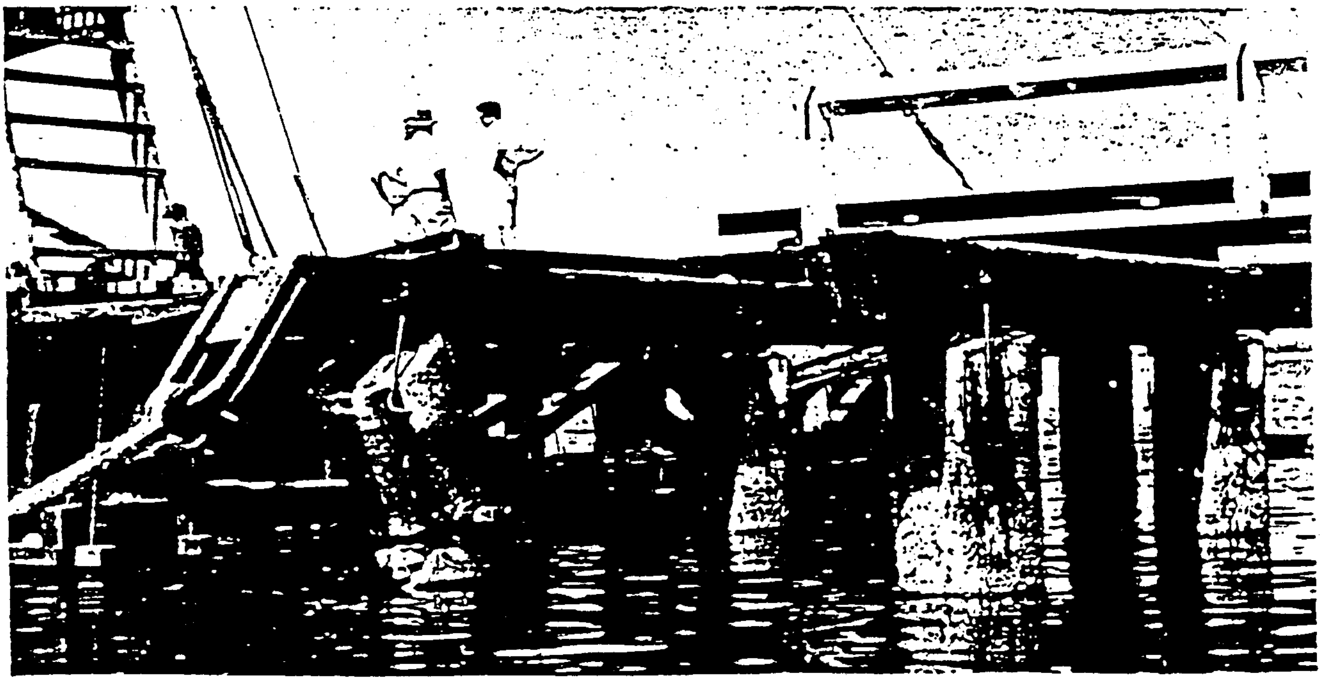
The Director of Mineral Development,
Mineral Resources Division,
Private Bag,
GPO, SUVA

- This special booklet is published by the Ministry of Information at Government Buildings in Suva for the Ministry of Lands and Mineral Resources.

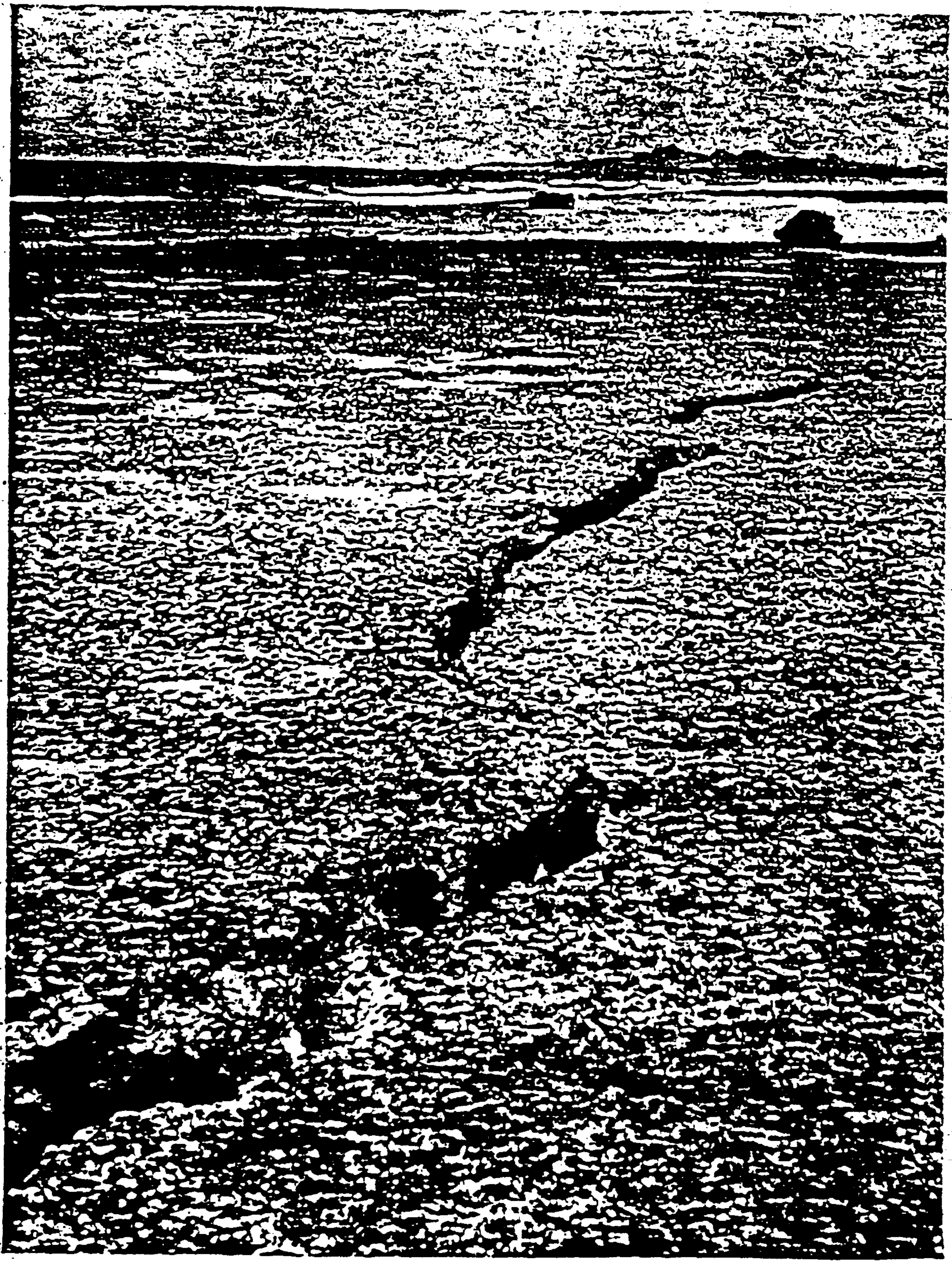
(JANUARY 1976)



In the wake of the 1953 quake



Crack in the coral



A crack in the main Suva reef after the earthquake and tidal wave in 1953.

T. SANERIVE, Government Printer, Suva, Fiji.

APPENDIX IV: SEISMOLOGICAL FACILITIES AND EARTHQUAKE HAZARD PROGRAMS IN THE SOUTHWEST PACIFIC

As part of our program of field investigations in Fiji, Tonga and Vanuatu, our researcher was able to visit the neighboring island countries of the Southwest Pacific region. During these visits he was able to meet with scientists and public officials involved with the earthquake hazard problem facing each country. In every case, the governments are aware of and have taken some action to mitigate the potential losses due to destructive earthquakes, but these governmental responses have varied widely from country to country. This report focusses on the seismological institutions and facilities in each of the countries and their capablities in assessing and planning for earthquake hazards. In the following sections, we consider each of the island countries of this area which face a severe earthquake risk: Fiji, Tonga, Vanuatu, Western Samoa, Solomon Islands, Papua New Guinea, and New Zealand.

FIJI

Seismological Facilities

Seismological observations in Fiji are conducted by the Mineral Resources Department, a subdivision of the Ministry of Energy and Mineral Resources. The government has made a major commitment to seismological work since the establishment of the AID-supported seismic network in 1979. In fact, seismological observations in Fiji have been carried out since the early part of this century, supported at first by the New Zealand scientific organizations, and subsequently strengthened by Lamont Geological Observatory's Upper Mantle Project in the 1950's and 1960's. In late 1979 the 8-station U.S. AID network was established to complement three permanent stations in Viti Levu. The network was significantly expanded by installation of a five-station telemetered network in 1981 supported by Japanese aid (Figure A1). Additional stations were installed in 1983 and 1984; the network has now expanded to an eighteen-station national network with excellent coverage of the Fiji region. In addition MRD now has available five MEQ-800 portable seismographs for occupation of temporary field sites, telemetered station testing, and special refraction experiments. While the Fiji network has experienced considerable technical difficulties it has recorded over 2000 earthquakes since its installation, and provides an invaluable basis for seismological study of the Fiji region.

Strong Motion Accelerographs

The Mineral Resources Department also operates a network of strong motion accelerographs, now numbering ten Kinemetrics SMA-1's (Figure A2). The initial six instruments of this network were granted to Fiji by AID; the remainder were purchased by the Fiji government. Since establishment of the SMA network, three accelerogram records have been obtained from moderate-sized earthquakes in Viti Levu. Records obtained from this network are expected, in the long run, to provide the basis for predicting

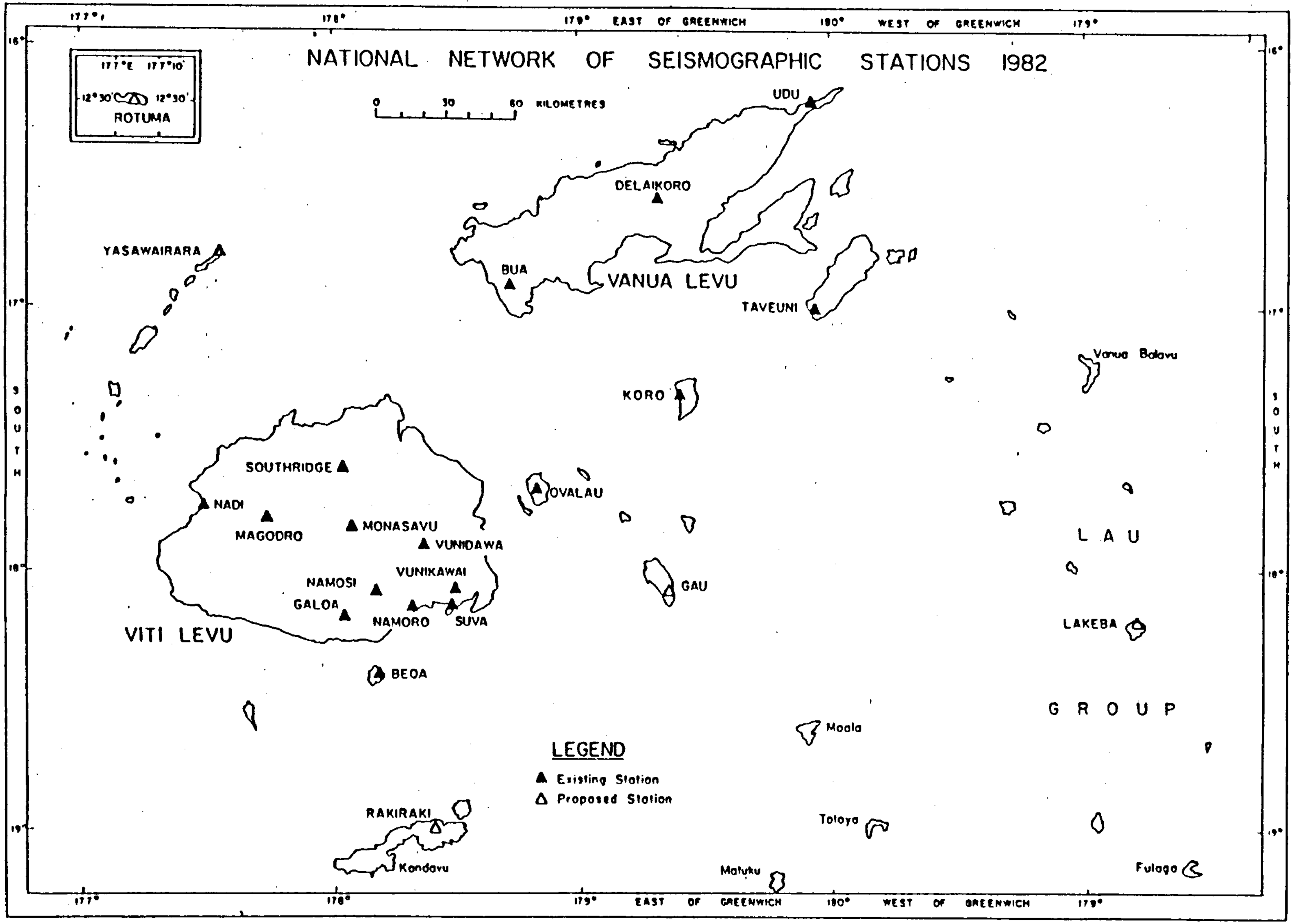


Figure A1. Network of seismic stations in Fiji, established through the assistance of U.S. A.I.D. and Japanese aid programs.

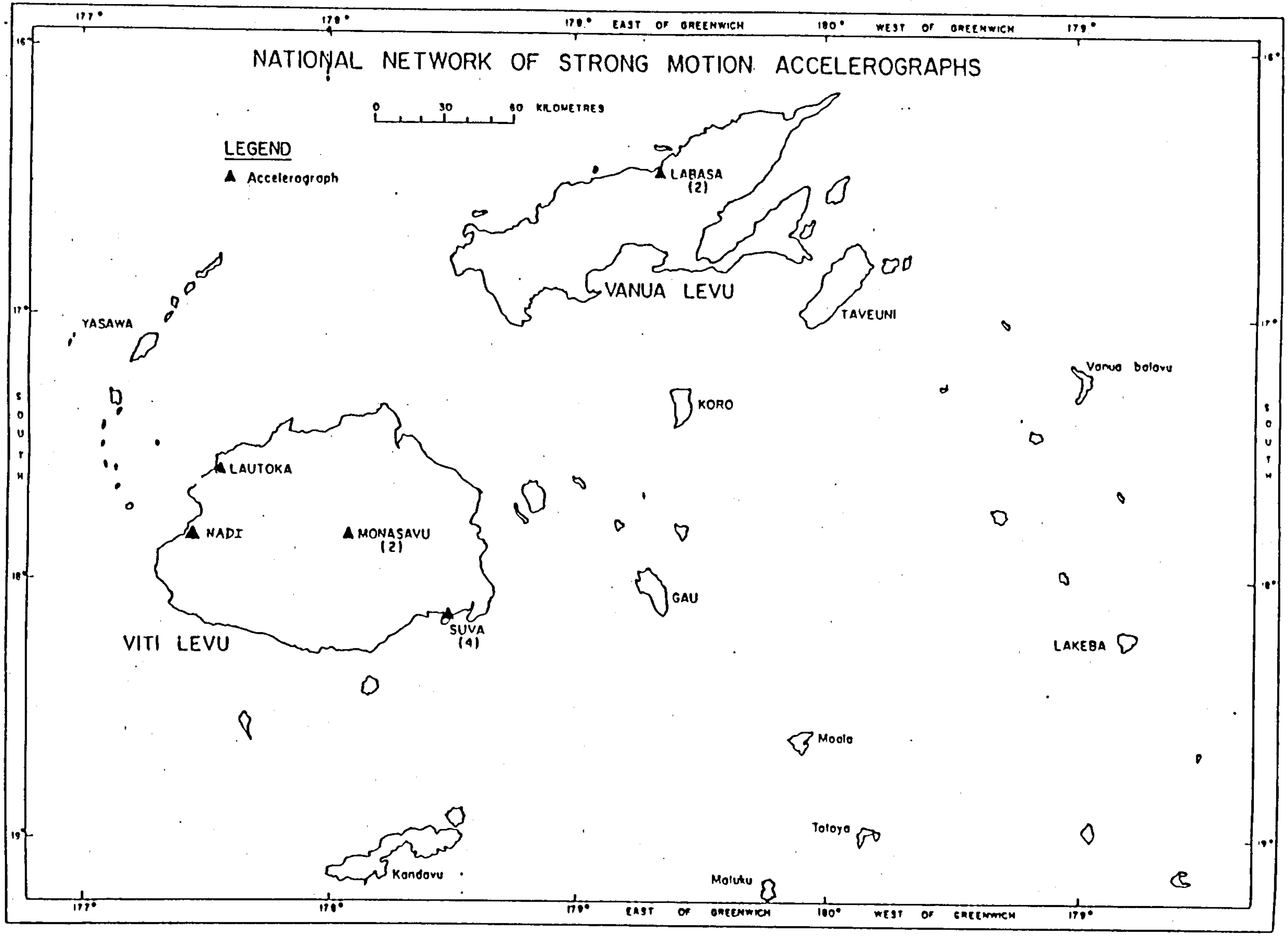


Figure 2A. Location of strong-motion accelerographs in Fiji.

ground accelerations, and thus for development of building codes specific to Fiji's tectonic setting.

Related Scientific Programs

The Mineral Resources Department includes an Offshore Geology section, which has an active program of marine geological and geophysical investigations, in and around Fiji waters. MRD also employs an engineering geologist, whose work includes microzonation of the Suva area, mapping of active faults in southeastern Viti Levu and investigation of soils subject to earthquake-induced liquefaction. An active program of geological mapping and structural studies is also carried out by MRD. They are supported by personnel assistance from Australia and Great Britain.

Suva is also the home of the United Nations Committee for Coordination of Offshore Prospecting in South Pacific Offshore Areas (CCOP/SOPAC). This organization coordinates much of the international marine research carried on in the region, and has been particularly helpful with Fiji's investigation of its offshore waters.

Critical Facilities

The major development in Fiji has been in and around the capital city of Suva. The population of the metropolitan area now exceeds 130,000, and most of the government, commercial and industrial operations are concentrated there. The city has become a major commercial, transportation, and regional political center and has developed rapidly in the past ten years. Development in this period has included construction of multistory buildings, a major electric power plant, expansion of the Suva harbor, and most recently, completion of the thirteen-story Central Monetary Authority building in downtown Suva. Much of this development has taken place on an area of filled land close to sea level, particularly vulnerable to earthquake and tsunami damage. This area was extensively damaged by the 1953 Suva earthquake and tsunami and is thus at significant risk from a repeat occurrence of an event of comparable size.

Other population centers with significant development include the towns of Lautoka (pop. 29,000), Nadi (13,000), and Ba (9,000) on the island of Viti Levu, and Labasa (13,000) on Vanua Levu. The tourist industry, which is a major part of Fiji's economy, is concentrated on the southern and western coasts of Viti Levu, and is also vulnerable to earthquake and tsunami damage. The major development project in Fiji is the 87-meter high Monasavu Dam in the interior of Viti Levu. The earthfill dam was completed in 1983, and is planned to provide most of the country's electric power needs through the end of the century.

Earthquake Preparedness Programs

In awareness of the serious earthquake risk to development in Fiji, the government has adopted New Zealand earthquake design codes for most of the urban areas of the country. Seismic zone "B" codes, applicable to areas of moderate seismic activity in New Zealand, have been chosen as appropriate, and are applied (in theory at least) to all domestic and commercial construction in urban areas. Considerable difficulty remains in enforcement of these regulations, particularly in construction of private dwellings. Major multistory building design is generally handled by overseas (Australia or New Zealand) engineers, and dynamic modelling tests are generally applied for earthquake loadings at least as large as those required by the New Zealand codes. The Monasavu Dam underwent dynamic testing by Australian consulting engineers.

Disaster preparedness is the responsibility of the Emergency Services Committee (EMSEC) and the Prime Minister's Relief and Rehabilitation Committee (PMRRC). EMSEC is responsible for coordination of disaster plans, maintenance of essential services, advice to the Cabinet on emergency measures, and direction of relief work. It is comprised of representatives of the related ministries and public agencies. PMRRC is chaired by the Prime Minister of Fiji, and has responsibility for long-term relief policy and rehabilitation programs. Fiji's experience with recurrent weather-related disasters has spurred efforts for emergency communication systems, supply distribution, temporary shelters, and so on. Much of this hurricane disaster planning is applicable as well to earthquake and tsunami damage. Fiji is also a participant in the International Tsunami Warning System.

Educational programs have been handled through the Fiji Broadcasting System, the Red Cross, and the school system. To a limited degree, the Public Works Department and the Mineral Resources Department have produced educational materials related to earthquake hazards in Fiji.

TONGA

Seismological Facilities

Seismological observations in Tonga are the responsibility of the Ministry of Lands, Surveys and Natural Resources. Due to fiscal constraints, however, these efforts have in the past been entirely dependent on foreign assistance. Seismological experiments began in Tonga in the mid-1960's with Lamont-Doherty's Upper Mantle Project. Seismic stations were operated by Lamont-Doherty, and subsequently by Cornell scientists through the early 1970's, when operations were suspended. In late 1983, as part of the present AID-supported seismic hazard program, Cornell reinstalled a three-component short-period seismograph in the capital, Nuku'alofa. The seismograph was installed upon the request of the government geologist, to be operated by the Tongan government, with technical assistance from Cornell. Unfortunately, after operation of the seismograph for eight months, Tonga's Cabinet decided that the drain on its resources and personnel was excessive, and the instruments were disconnected in May, 1984, with the components transferred to Fiji and Vanuatu, where they can be utilized. There are presently no plans to reinstall permanent seismographs in Tonga.

Strong Motion Accelerographs

Two strong-motion accelerographs, provided by the AID seismic hazard program, are presently operating in Tonga, one in Nuku'alofa and one in the northern Vava'u Islands. They have been in operation for one year, and have not to date recorded any large earthquakes. They require a minimum of maintenance and their operation will continue to be supervised by the government geologists with assistance from Cornell. A third accelerograph may be made available to tonga by the British Geological Survey, and could be installed on 'Eua Island, in a zone of high activity close to the Tonga Trench.

Related Research Programs

The Ministry of Lands, Surveys and Natural Resources employs a single government geologist, whose responsibilities include coordination of oil prospecting, geological mapping of the islands and assessment of earthquake and tsunami hazards. There has been considerable scientific study of the Tonga Trench subduction zone by research groups from the United States, Japan, New Zealand, Australia, Germany and the Soviet Union. More detailed marine geophysical data have been collected near Tongatapu Island by American petroleum exploration groups.

Critical Facilities

The capital city of Nuku'alofa has a population of only 20,000, but does include several three- and four-story buildings. The larger buildings have in general been designed by foreign engineers, and have included earthquake- resistant design specifications. Other significant development projects include the expansion of the government wharf in Nuku'alofa and development of tourist resorts on Tongatapu and several of the outer islands.

Earthquake Preparedness Programs

There are no building codes presently enforced in Tonga. However, construction of public buildings must be approved by the Ministries of Works and Health. The largest office buildings and hotels are designed by overseas engineering firms, and generally include some earthquake loading criteria. The Land and Environment Act, currently under consideration by the Tongan government, would require review of all development projects by the government planner; application of building codes, largely adapted from New Zealand codes, is expected to follow.

Disaster preparedness programs are the responsibility of the Cabinet's National Disaster Committee, including representatives from the related government ministries and departments. Subcommittees focus on disaster preparedness, action planning, and long-term relief and rehabilitation. There is no earthquake education program in Tonga.

WESTERN SAMOA

Seismological Facilities

One of the earliest seismic stations in the Pacific was established at the Apia Observatory in 1902 during the German colonial period through the University of Göttingen. In 1921, control of the observatory was transferred to the New Zealand Government. Weichert seismographs were operated continuously at Apia through 1957, when they were replaced by Benioff instruments at Afiamalu and by short-period Wood-Anderson instruments at Apia. Since Samoan independence in 1963, the Observatory has been operated jointly by the Samoan Government and the Department of Scientific and Industrial Research (DSIR), New Zealand. In 1963, a Worldwide Standard Seismograph Station was established at Afiamalu. Operation of this six-component station is supported by the U.S. Geological Survey. In 1980, the station was upgraded to allow digital recording equipment was added to upgrade the station to the status of a Global Digital Seismic Network station. Seismic records are sent to DSIR in Wellington for permanent storage.

Strong Motion Accelerographs

A simple strong motion instrument has been operating in Apia since 1979. It is an event-triggered low-gain seismograph, recording on an ink-stylus recorder. At the time of our visit to Western Samoa, the instrument had been out of service for several months. Only one event has, to date, triggered the instrument.

Related Scientific Programs

The Apia Observatory has also made continuous magnetic field measurements since 1905. Measurements are currently made using a Schultze earth inductor, an Askania declinometer and a proton magnetometer. The observatory maintains two tide guages as part of the Pacific Tsunami Warning System. Offshore resource studies have been carried out through CCOP/SOPAC, and by various international research groups. Much of the reconnaissance geological work in Western Samoa has been carried out by DSIR in New Zealand.

Critical Facilities

Like many of the other island countries of the Pacific, Western Samoa's development has been concentrated around the capital, Apia (pop. 34,000). A major, deep-water harbor and the country's tourist industry are based in Apia. Several multistory buildings have been erected in Apia in the past several years. A hydroelectric dam on Upolu Island was completed in 1978.

Earthquake Preparedness Programs

There is presently no disaster plan in effect in Western Samoa. The various agencies involved with emergency action are coordinated through the Police Commissioner. New Zealand seismic zone "B" codes are applied to construction in Western Samoa. Enforcement is handled by the Public Works Department. Modest educational materials have been prepared by the Apia Observatory staff, in English and Samoan, for distribution through schools and public agencies.

SOLOMON ISLANDS

Seismological Facilities

Seismological Observatories in the Solomon Islands are conducted by the Ministry of Lands, Energy and Natural Resources. They have operated a Worldwide Standard Seismic Station in Honiara since 1962; operation of the station is supported by funds from the U.S. Geological Survey. The station was augmented by two short-period telemetered seismic stations in 1982. This three-station network was provided through the British Geological Survey with the aim of identifying volcanic earthquakes associated with the active volcano Savo, located close to the capital.

In awareness of the high volcanic risk to population centers in the Solomon Islands, the Ministry has drawn up plans for two three-station telemetered arrays to be deployed around the active volcanoes on Simbo Island (New Georgia Group) and on Tinakula Island (Santa Cruz Group). They are presently seeking foreign aid in the form of seismic instrumentation and technical asistance to establish the network.

The Ministry also has responsibility for field surveys following major earthquakes in the Solomon Islands. Studies of ground deformation and cultural effects of the large 1977 and 1984 earthquakes were made by seismology officers.

Strong Motion Accelerographs

Two strong motion accelerogaphs were installed on Guadalcanal by the Ministry in late 1984. They will be responsible for maintaining the instruments, but have requested Cornell's assistance in analyzing accelerograms obtained during their operation. The high level of shallow activity near Guadalcanal suggests that a significant number of strong-motion records will be obtained during the lifetime of the instruments.

Related Scientific Programs

The Ministry also carries out related research programs in regional geology, minerals assessment, groundwater studies, and so on. Extensive marine surveys have been caried out in the Solomon Islands by the U.S. Geological Survey's Resource Assessment Program. Local offshore surveys have been carried out through CCOP/SOPAC. A tide gauge is maintained by the Solomon Islands Hydrographic Unit. Six proton-precession magnetometers are operated in the Solomon Islands by the Queensland University (Australia).

Critical Facilities

Over 90% of the Solomon Islands population remains in rural areas. The major development is in Honiara, the administrative and commercial center of the country. Honiara (pop. 15,000) is the major shipping center of the country, and now includes several multistory buildings.

Earthquake Preparedness Programs

The Solomon Islands implemented a National Disaster Plan in 1980, subsequently revised in 1982. The Plan gives the Ministry for Home Affairs and National Development overall responsibility for coordination of efforts in earthquake, volcanic and tsunami disasters. Operational relief efforts are carried out through the Disaster Operations Coordinator and the Provincial governments.

The government has adopted the most stringent earthquake building code (Zone "A") from New Zealand for multistory building construction in Honiara. Implementation of these guidelines continues to be a problem. One multistory building in Honiara (Australian High Commission Building) was severely damaged during the 1984 earthquake. Some efforts have been made to develop small-scale earthquake-resistant building techniques appropriate for rural areas. The Pacific Islands Development Program organized a model house construction and workshop during early 1984. A modest outreach program has developed through the school system, adult education programs, and the government broadcasting company.

PAPUA NEW GUINEA

Seismological Facilities

The government of Papua New Guinea has made an extensive commitment to earthquake and volcanic hazard mitigation through construction of a national network of seismographs and accelerographs (Figure A3). A ten-station national network of seismographs is monitored by the Port Moresby Geophysical Observatory (Department of Minerals and Energy). Three of the remote stations are telemetered to Port Moresby via microwave links; four stations operate as permanent field stations; and two are operated at temporary sites on outlying islands. Port Moresby is presently the site of a Worldwide Standard Seismic Station that has operated since 1958. The national network reports arrival times to the U.S. Geological Survey's Preliminary Determination of Epicenters and the International Seismological Centre, but does not routinely locate events independently.

In addition to the national seismic network, the Rabaul Volcanological Observatory operates seven seismic stations near active volcanoes around the country and a nine-station telemetry network around the Rabaul Caldera. Bougainville Copper Limited opeates a 5-station network on Bougainville Island (North Solomons Province).

Strong Motion Accelerographs

The Port Moresby Geophysical Observatory maintains a national network of thirteen strong motion accelerographs, distributed in the highly seismic areas of the country (Figure A3). This includes a closely spaced four-station network around the Rabaul Caldera. A single strong motion accelerograph is situated on Bougainville Island and is maintained by Bougainville Copper Limited. The network uses Kinemetrics SMA-1 and New Zealand DSIR MO-2 instruments and has recorded tens of accelerograms since its establishment in 1967. The Observatory is presently trying to to establish an engineering seismologist position to analyze the accumulating data, and to further upgrade the accelerograph network.

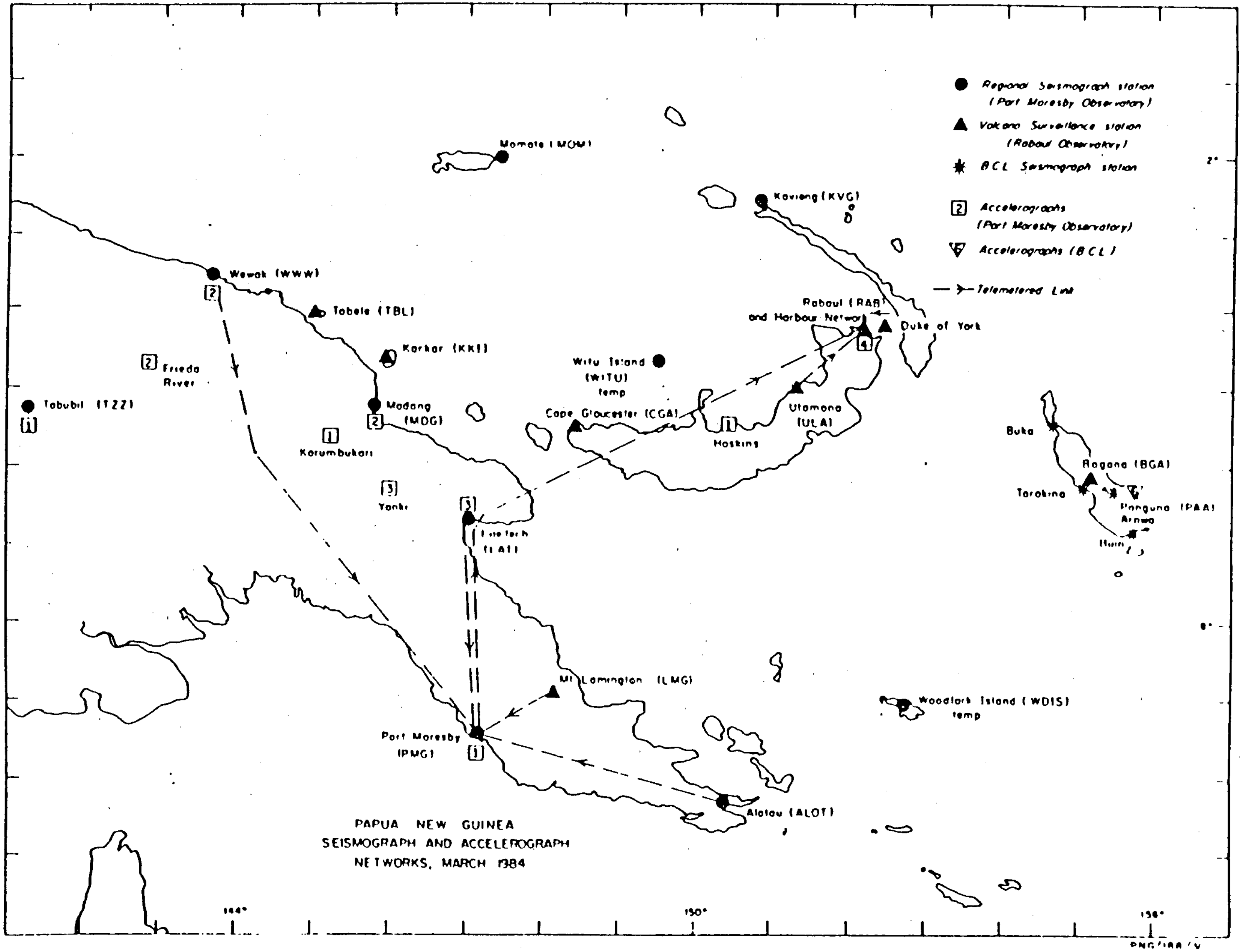


Figure A3. Papua New Guinea seismograph and accelerograph networks.

Related Scientific Activities

In addition to the Geophysical Observatory, the Department of Minerals and Energy includes the Geological Survey of Papua New Guinea. The Survey undertakes a wide range of geological investigations, including regional geological mapping, petroleum and mineral exploration, engineering and environmental geology, and energy resource development. Offshore surveys have been carried out through CCOP/SOPAC as well as American and Australian research vessels. Continuous monitoring of the magnetic field is carried out by the University of Queensland (Australia). Ten tiltmeters have been deployed by the Volcanological Observatory to monitor ground deformation near Papua New Guinea's active volcanoes. Four of these instruments are deployed around Rabaul Caldera.

Critical Facilities

Papua New Guinea is the most developed of the island countries of the Southwest Pacific, with a population of over 3,000,000 and extensive urban development. The capital city of Port Moresby has a population of over 130,000, with major multistory construction in the downtown area, a major deep water harbor and significant commercial and industrial activity in the Port Moresby area. There is significant development as well in the smaller towns of Rabaul, Lae, Madang, Wewak, Goroka, Mount Hagen, Wau, Bulolo, Daru, and Kerema. Major hydroelectric schemes have been established on the Ramu and Rouna rivers, with additional hydroelectric plans at various stages of evaluation and development. Extensive mineral development has taken place in the North Solomons, Morobe, and Western provinces of Papua New Guinea. Extensive natural gas and limited oil deposits have been located; these may become commercially exploited in the near future.

Earthquake Preparedness Programs

Papua New Guinea has a long history of earthquake and volcano-related disasters. A national disaster program was established in 1981, and provides for a National Disaster Emergency Committee, which formulates emergency government policy, and a Disaster Civil Defence Committee, which is responsible for implementation of short-term relief efforts. The provincial governments are given major responsibility for initial coordination and assessment of disasters; assistance is subsequently requested from the federal government for major disasters. Many of the provincial governments have not revised preparedness plans since the colonial period. However, particularly intense effort has been directed in East New Britain province, because of the imminence of a potentially destructive volcanic eruption in Rabaul Caldera.

The town of Rabaul (pop. 15,000) is a major commercial center for Papua New Guinea, and is situated directly within the caldera of an active volcano. A relatively small eruption took place at a secondary eruptive center near Rabaul in 1937, killing over five hundred nearby residents, and forcing the evacuation of the town. In order to avoid a repeat of such a disaster, the government established the Volcanological Observatory, with four full-time volcanologists and real-time earthquake location and analysis of tilt data. A drastic increase in volcanic seismicity in mid-1983 led to a volcanic hazard alert, and intensification of seismological and ground deformation studies around Rabaul. In addition, the alert allowed the provincial and national Disaster Emergency Committees to make extensive evacuation and relief plans for a possible eruption at Rabaul, including preparation of a new airstrip, improvement of roads and emergency water supplies, communications systems, detailed evacuation plans, education programs, and so on. To date, there has been remarkable cooperation of efforts by provincial, national and overseas officials to mitigate the potentially devastating effects of a volcanic eruption at Rabaul.

Papua New Guinea is the only country of the developing nations of the Southwest Pacific to have devised its own seismic zoning system (Figure A4).

The Nationwide Housing Code for Papua New Guinea sets up a four-level system of seismic loading oriented toward moderate-sized (to 8 stories) buildings. Major buildings require independent dynamic analysis, usually carried out by overseas engineering firms. Seismic Zone 1 of the Housing Code is among the most stringent earthquake loading codes in the world, and includes the town of Rabaul, and much of the East New Britain and North Solomons provinces. Seismic zone 2 includes the towns of Lae, Wewak, and Madang, and is approximately equivalent to New Zealand Zone "A" or California loading designs. The capital, Port Moresby, is in the lowest seismic zone (4), but buildings constructed there still require designs allowing for significant lateral loadings.

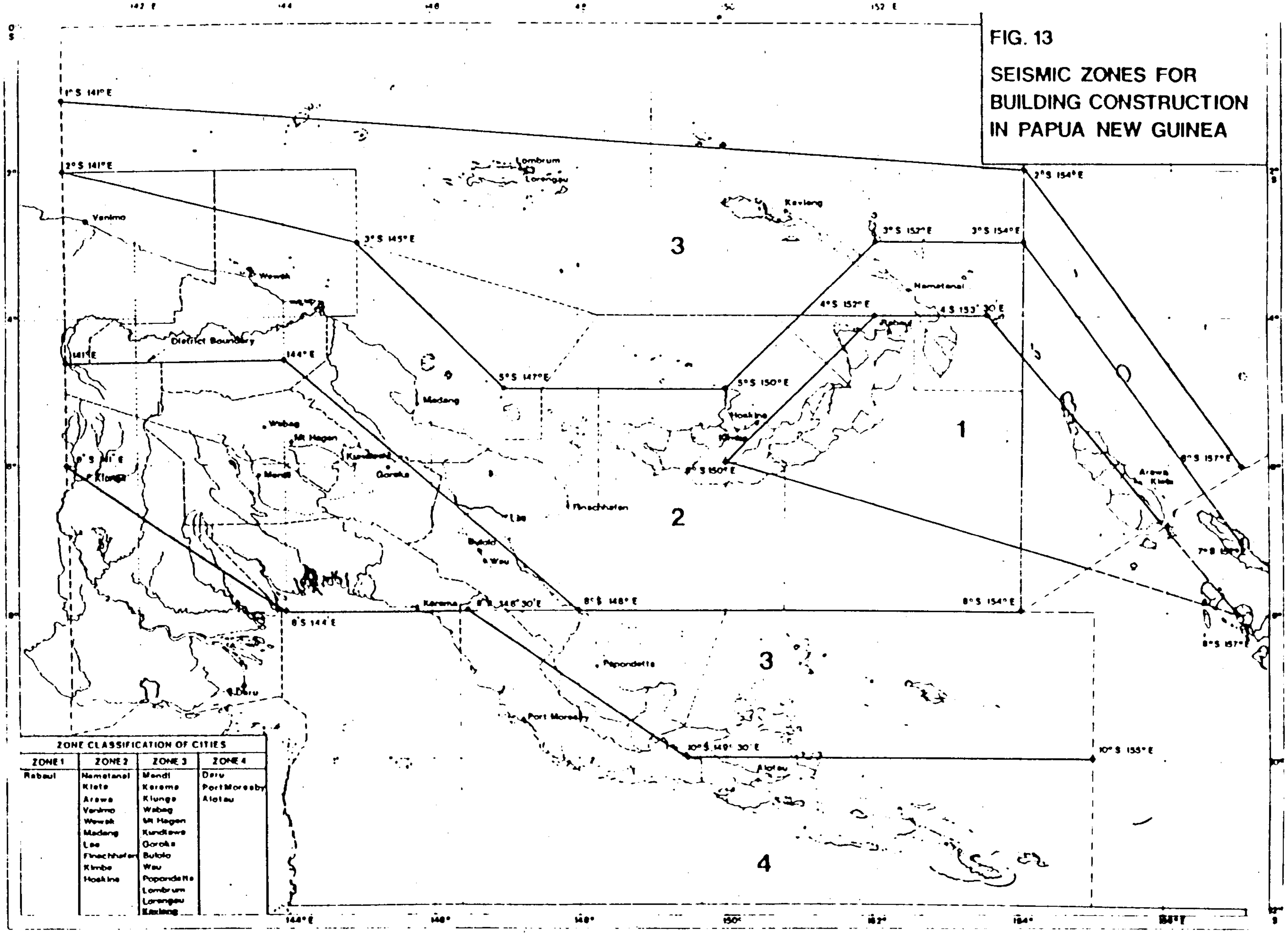
Earthquake education is handled through the National Radio, Government Printing Office the Civil Defence Department, and the school system, with information supplied by the Geophysical and Volcanological Observatories. A particularly intense education effort has been mounted in Rabaul, where educational materials have been produced and distributed in three languages, and public involvement in preparedness plans has been emphasized.

NEW ZEALAND

While New Zealand cannot be considered one of the developing countries of the Southwest Pacific, its seismology programs have been responsible for much of the observational data available for the entire region. Because of its importance to the other national seismology programs, we briefly review here the New Zealand's observational facilities. Its extensive programs in engineering seismology, its critical facilities and its earthquake preparedness programs will not be covered here.

National Seismic Network

Seismological facilities in New Zealand are maintained by the Geophysics Division of the Department of Scientific and Industrial Research (DSIR) in Wellington. The natioal standard seismograph network, presently consisting of thirty short-period stations, is shown in Figure A5. The network routinely locates all earthquakes of $M_L > 3.8$ within New Zealand, and earthquakes with $M_s > 5.0$ for the region within 10° of New Zealand. Arrival time data are routinely transmitted to the U.S. Geological Survey and the International Seismological Centre. The events located by the network are reported in the annual New Zealand Seismological Report. Several hundred earthquakes are located by the DSIR national network each year.



ZONE CLASSIFICATION OF CITIES			
ZONE 1	ZONE 2	ZONE 3	ZONE 4
Rabaul	Namatanai	Mendi	Daru
	Kieta	Kerema	Port Moresby
	Arawa	Kiunga	Alotau
	Vanimo	Wabag	
	Wewak	Mt Hagen	
	Madang	Kundiawa	
	Lae	Goroka	
	Finschhafen	Bulolo	
	Kimbe	Wau	
	Hoskins	Popondetta	
		Lombrum	
		Lorengau	
		Kavieng	

Figure A4. Seismic zones for building construction in Papua New Guinea (Jury et al., 1982).

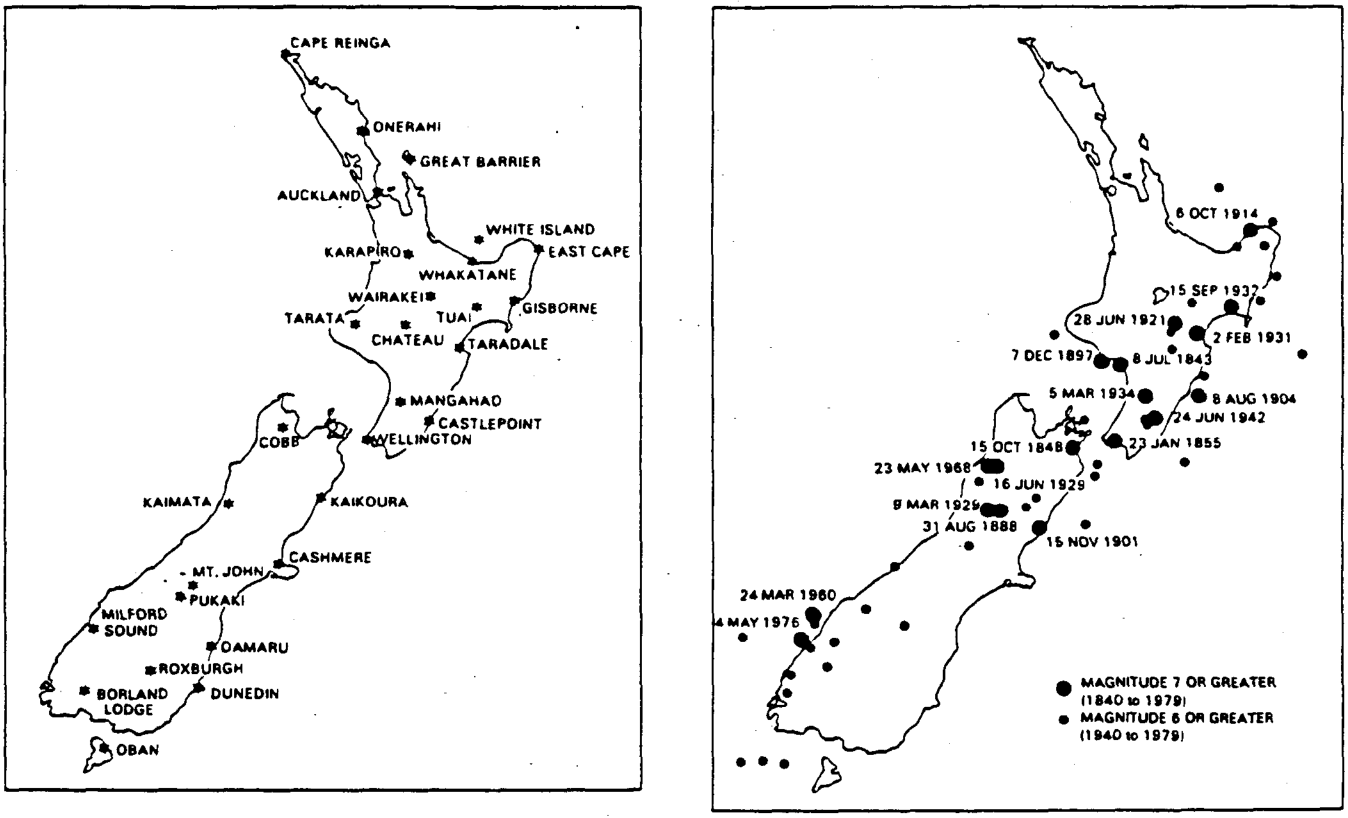


Figure A5. Seismograph stations of the national network (left) and the distribution of large, shallow earthquakes (right) in New Zealand. From Seismological Observatory, Wellington (1980).

The network is augmented by long-period instruments operating at Karopiro, Roxburgh and Wellington. DSIR also operates a three-component borehole seismometer in Wellington, as part of the Seismic Research Obseervatory network, supported by the U.S. Geological Survey.

Stations in Outlying Territories

New Zealand has also taken an important lead in operating seismograph stations in outlying areas of the Southwest Pacific. These stations have been extremely important in hypocentral control for the Tonga - Kermadec seismic zone, and for nuclear event detection in the Pacific. DSIR operates three 6-component Worldwide Standard Seismograph stations at Afiamalu (Western Samoa) Raratonga (Cook Islands) and Scott Base (Antarctica). Short-period stations operate at Apia (Western Samoa), Campbell Island (New Zealand), Chatham Islands (New Zealand), Nadi (Fiji), Nime, and Raoul Island (Kermadec Island, New Zealand). Readings from these stations are routinely reported to PDE and ISC for global earthquake location.

Wellington Network

A small-aperture, high-gain seismic network is operated around Wellington, an area of greatest seismic risk in New Zealand. The stations are telemetered by radio or telephone link to the central recording site. The network now consists of eleven stations. Earthquakes are presently detected by a microprocessor-based Automatic Seismic Monitor, and automated location processing is expected to follow. The network routinely locates events with $M_L > 1.5$.

Pukaki Network

A second microearthquake network has operated around Lake Pukaki, a hydroelectric project in the South Island, New Zealand. The network was established in 1975, to monitor reservoir-induced seismicity associated with impoundment of the reservoir. The network consisted of nine stations, and was intended to operate on a temporary basis. It has been closed since early 1984, with several of the stations continuing, to support the national network, and to monitor any future reservoir-related activity.

Related Seismology Research

In addition to its regular observatory seismology, the Geophysics Division has an active seismology research program. Their studies have focussed on theoretical seismology, earthquake prediction, crustal structure of New Zealand, historical earthquake studies, nuclear event detection, seismic risk in New Zealand, strong motion studies and volcanic seismology. The monitoring of active volcanoes is closely coordinated with crustal deformation monitoring, conducted by the Earth Deformation Section of the New Zealand Geological Survey.

The New Zealand strong motion accelerograph network now consists of 225 instruments, operated by the Physics and Engineering Laboratory of DSIR. Most of these instruments are of a New Zealand design (Mechanical and Optical Accelerographs), and analog records are made on photographic film. Three digitally recording accelerographs are now in operation in New

Zealand, and the M.O. records are digitized for computational analysis. Analysis of this empirical data is being used for a revision of New Zealand's building codes.

REFERENCES

Berryman, K., 1979. Seismotectonic zoning study of the Fiji Islands. Earth Deformation Section Report 70. Wellington, N.Z. Dept. Sci. and Indust. Research, 40 pp.

Everingham, I.B., 1983. Seismology section annual report, 1983. Min. Resources Dept., Fiji, Note 33/10, Suva, Fiji, 46 pp.

Franco, A.B., M.P. Hamnett and J. Makasiale, 1982. Disaster Preparedness and Disaster Experience in the South Pacific. Pacific Islands Developmental Program, Honolulu, 380 pp.

Geological Survey of Papua New Guinea, 1979. Information Booklet. Port Moresby, Dept. Minerals and Energy, 12 pp.

Government of Western Samoa, 1977. Apia Observatory, 1902-1977. Apia, Apia Observatory, 8 pp.

Jury, R.D., J.P. Hollings and I.A.N. Fraser, 1982. The development of seismic zones and the evaluation of lateral loadings for earthquake resistant design of buildings in Papua New Guinea. Bull. N.Z. Nat. Soc. for Earthq. Engr., 15, 123-140.

Lowenstein, P.L., 1982. Problems of volcanic hazards in Papua New Guinea. Geol. Surv. Papua New Guinea Rept. 82/7. Port Moresby, Papua New Guinea, 62 pp.

McCue, K.F. and I.D. Ripper, 1980. The Papua New Guinea Strong Motion Accelerograph Network. Geol. Surv. Papua New Guinea Rept. 80/7, Port Moresby, Papua New Guinea, 13 pp.

Mineral Resources Department Seismology Section, 1983. National activity report: Fiji. Submitted to Session IX, Intl. Coord. Group for Tsunami Warning System in the Pacific. Min. Resources Dept., Fiji, Note 33/3, Suva, Fiji, 4 pp.

Parliament of Fiji, 1984. Mineral Resources Department Annual Report for the Year 1982. Parliam. Paper No. 13. Suva, Fiji, 90 pp.

Power, C.A., 1978. Earthquake risk in Fiji and the problems of earthquake engineering. Presented to the Fiji Society, 17 pp.

Prevot, R., and J.L. Chatelain, 1983. Seismicity and Seismic Hazard in Vanuatu. ORSTOM Rept. 5-83, Nouméa, 51 pp.

Ripper, I.D., 1982. Accelerogram library. Geol. Surv. Papua New Guinea Rept. 1982/11. Port Moresby, Papua New Guinea, 44 pp.

Seismological Observatory, Wellington, 1980. The earthquake problem in New Zealand. Alpha, DSIR Extension Information. Wellington, N.Z., 4 pp.

Smith, W.D., 1979. Seismology and related research in New Zealand, 1975-1978. N.Z. DSIR Information Series No. 140, 30 pp.

Smith, W.D., 1983. Seismology and related research in New Zealand, 1979-1982, Seismol. Observatory, Wellington, Bull. 276, 32 pp.

Solomon Islands Government, 1982. National Disaster Plan, 1982. Honiara, Solomon Is., 14 pp.

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APPENDIX V. TSUNAMI SAFETY RULES

1. All earthquakes do not cause tsunamis, but many do. When you hear that an earthquake has occurred, stand by for a tsunami emergency.

2. An earthquake in your area is a natural tsunami warning. Do not stay in low-lying coastal areas after a local earthquake.

3. A tsunami is not a single wave, but a series of waves. Stay out of danger areas until an "all-clear" is issued by competent authority.

4. Approaching tsunamis are sometimes heralded by a noticeable rise or fall of coastal water. This is nature's tsunami warning and should be heeded.

5. A small tsunami at one beach can be a giant a few miles away. Don't let the modest size of one make you lose respect for all.

6. The Tsunami Warning System does not issue false alarms. When an ocean-wide warning is issued, a tsunami exists. When a regional warning is issued, a tsunami probably exists. The tsunami of May 1960 killed 61 people in Hilo, Hawaii, who thought it was "just another false alarm."

7. All tsunamis--like hurricanes--are potentially dangerous, even though they may not damage every coastline they strike.

8. Never go down to the beach to watch for a tsunami. When you can see the wave you are too close to escape it.

9. Sooner or later, tsunamis visit every coastline in the Pacific. Warnings apply to you if you live in any Pacific coastal area.

10. During a tsunami emergency, your local Civil Defense, police, and other emergency organizations will try to save your life. Give them your fullest cooperation.

Unless otherwise determined by competent scientists, potential danger areas are those less than 50 feet above sea level and within 1 mile of the coast for tsunamis of distant origin; or less than 100 feet above sea level and within 1 mile of the coast for tsunamis of local origin.