PN-ABF-389
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EVALUATION OF SEISMIC RISK IN THE TONGA-FIJI-VANUATU REGION OF THE SOUTHWEST PACIFIC

A COUNTRY REPORT: KINGDOM OF TONGA

Prepared by: Joyce L. Kruger-Knuepfer[1], Michael W. Hamburger[2], Bryan L. Isacks[1],
Muawia Barazangi[1], John Kelleher[3], George Hade[1]

[1]Department of Geological Sciences
Cornell University
Ithaca, New York 14853

[2]Department of Geology
Indiana University
Bloomington, Indiana 47405

[3]Redwood Research Inc.
801 N. Humboldt St. 407
San Mateo, California 94401

Report submitted to Office of U.S. Foreign Disaster Assistance; Grant No. PDC-0000-G-SS-2134-00, Evaluation of Seismic Risk in the Tonga-Fiji-Vanuatu Region of the Southwest Pacific

1986

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A. 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 results of our investigations included: (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 Tonga have been carried out through cooperative work with the Tonga Department of Lands, Surveys and Natural Resources.

Brief Summary of Work Completed

(A) Southwest Pacific Catalog. A subset of the master listing of teleseismically located earthquakes from the Southwest Pacific, comprising events larger than $m_b \geq 5.8$ for the Tonga region, was compiled from twelve major data sources (Appendix VI). The earthquakes are sorted chronologically and are organized into a systematic format allowing easy access to hypocentral data selected by data source, location, depth, magnitude, and location quality.

(B) Tonga Seismic Observatory. A three-component short-period seismograph was established in Nuku'alofa, Tonga. This station operated for eight months before monetary constraint on the Tongan government forced its closure. While it was operating, the station complemented existing stations throughout the region, as well as providing critical constraint on hypocentral locations of earthquakes throughout the Southwest Pacific.

(C) Strong-motion Seismology Program. Two new accelerographs were installed in Tonga, one in Nuku'alofa (Tongatapu) and the other in Neiafu (Vava'u). These instruments complement a 10-station network established in Fiji and a 5-station network in Vanuatu. To date, only one record has been obtained from these instruments, but it provides valuable information concerning accelerations from intermediate depth earthquakes. These two instruments are still operational.

(D) Significant Earthquakes Near Tongatapu. We have examined the effects of the largest earthquake in Tonga since 1948, which occurred approximately 200 km south-southwest of Tongatapu on 23 June 1977. The local intensities on Tongatapu from this event indicate that a future major earthquake in the nearby subduction zone could produce locally severe shaking in the main population centers of Tonga.

Seismic Potential

Because of the paucity of local network data and long-term historical observations in Tonga, our earthquake hazard assessment is largely based on the teleseismic and historical record (twentieth century) of earthquakes along the plate boundary. The earthquake hazard from the plate boundary zone is generally very high because of the relative motion of the two plates (10 cm/yr). We propose that the maximum size of earthquake that might occur in the immediate vicinity of Tongatapu could be as large as $M_s = 8.3$ within the interplate zone and perhaps as large as $M_s = 7.3$ from the interplate zone close to the island arc. However, in addition to large and great earthquakes along the plate interface, moderate to large magnitude events can occur within either plate. The local effects of a large intraplate event near the Tonga islands may exceed those generated by a great earthquake at a larger distance.

Tsunami Hazard

The shallow seismic zone of the Southwest Pacific has a history of earthquake-generated tsunamis, of which a significant number have originated in the Tonga region. The potential for tsunamis is of particular importance in view of low-lying topography of many of the islands of Tonga. Significant local and possibly regional-scale tsunamis may be expected from large to great earthquakes occurring along the Tonga plate boundary.

Volcanic Eruption Hazard

Volcanic eruptions pose a problem to the inhabitants of the islands of Tonga, particularly for those people who are living on the flanks of an active volcano.

Conclusions and Recommendations

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

B. 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. 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 force. A discussion of some of the definitions of 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 one 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).

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.

Evaluation of Seismic Hazard

The seismic hazard in any region is a function of the frequency of occurrence and magnitude of destructive earthquakes, while seismic risk is a function of the proximity of the earthquake foci to population and industrial centers. The Kingdom of Tonga is located close to a major seismic zone of the Southwest Pacific (Figure 1A and 1B) which is along a plate margin with an instrumental history of earthquakes with magnitudes greater than 8.0 (Gutenberg and Richter, 1954; McCann, 1980). Although the country is not heavily populated or industrialized, its proximity to a seismic zone leaves it particularly vulnerable to the risk of earthquake damage. The capital city of Nuku'alofa 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 loss of life in the Southwest Pacific 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.

Historical Earthquakes in Tonga

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 in the determination of the frequency of occurrence and possible effects of future earthquakes. The portion of the Tonga Arc in the vicinity of Tongatapu has experienced 3 great earthquakes since 1900 (1902, 1919, and 1948) and 6 major earthquakes (1913, 1917, 1921, 1943, 1946, and 1949; Figure 2).

The relative motion of the two convergent lithospheric plates in this region (Pacific and Indo-Australian) is accumulated over a time period of tens to hundreds of years and then released

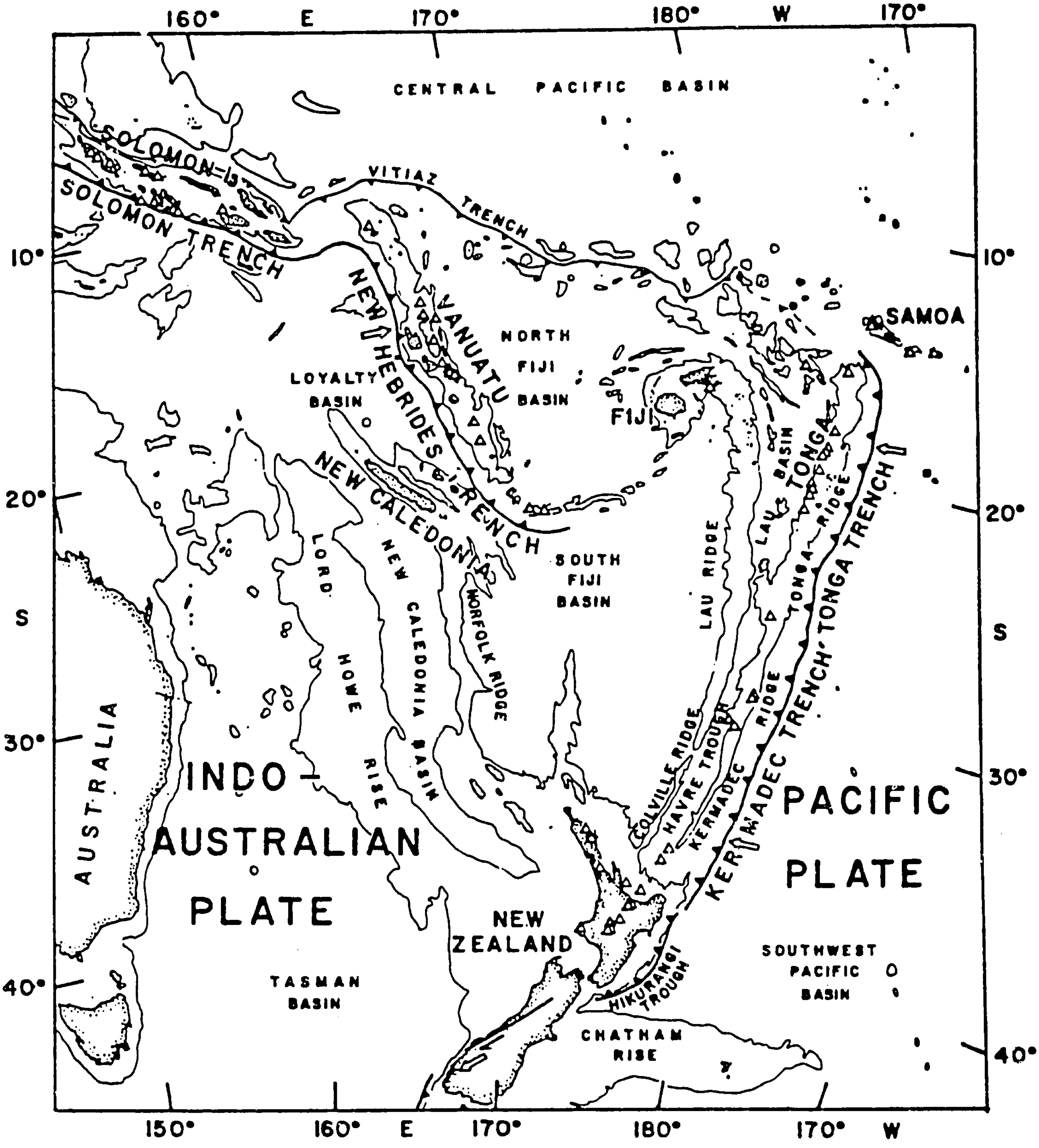


Figure 1. (A) Regional setting of the Southwest Pacific. Tectonic and morphologic features of the Pacific/Indo-Australian plate boundary. Open arrows indicate direction of relative plate convergence. Contour line shows 2-km isobath. Holocene volcanoes are indicated by open triangles. Data on bathymetry, seismicity, volcanoes, and plate motions are taken from the Circum-Pacific Council for Energy and Mineral Resources (1981) map.

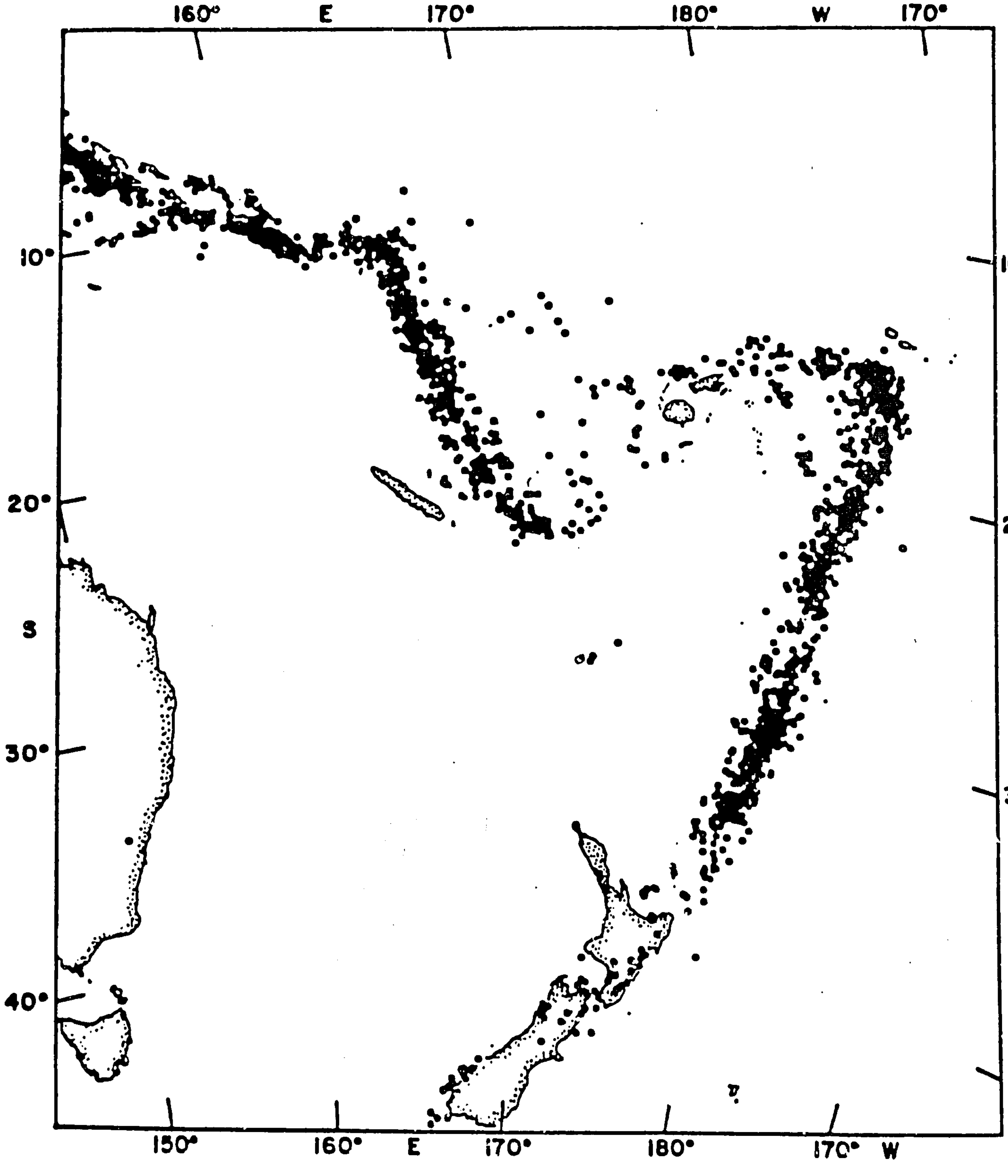


Figure 1. (B) Regional setting of the Southwest Pacific. Shallow seismicity associated with the plate boundaries in this region.

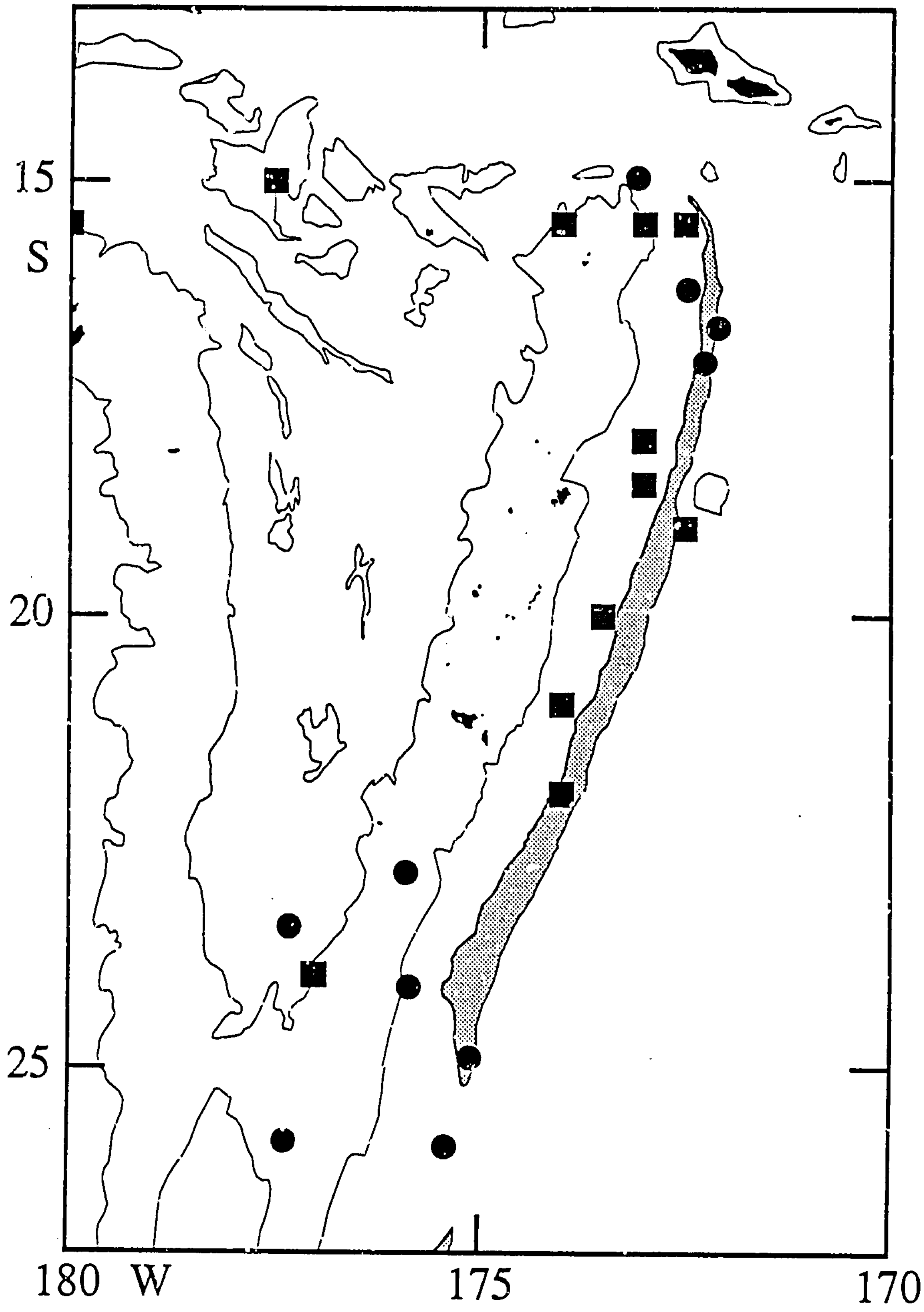


Figure 2. Map showing locations of large and great historical earthquakes along the Tonga Trench for the time period 1900 to 1980. Large earthquakes ($M_S > 7$) are shown as circles, and great ones ($M_S \geq 7\ 3/4$) are shown as squares.

in large earthquakes. The area over which the descending and over-riding plates interact, the age of the sea floor, and 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.

Tsunamis in Tonga

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 3). A few tsunamis have originated in the Tonga region. Five notable ones occurred in 1865, 1917, 1919, 1928, and 1948 (Soloviev and Go, 1975). While major Pacific-wide tsunamis such as those generated along the South American or Alaskan plate margins apparently do not take place near Tonga, significant local tsunamis may be generated by large shallow earthquakes. The potential for tsunamis is of particular importance in view of low-lying topography of many of the islands of Tonga.

Volcanic Eruptions in Tonga

Volcanic activity is concentrated near the middle portion of the Tonga island arc. Bryan et al. (1972) have identified at least nine centers of volcanism that are presently active. Six of these loci are associated with submarine volcanoes which may form temporary islands (e.g. Home Reef eruptions of 1984; SEAN Bull., 1984). The duration of the eruptions from Tongan volcanoes has been short, lasting from a few months to approximately a year. Bryan et al. (1972) has calculated the average time of recurrence for volcanic eruptions and found that one eruption is observed approximately every four years.

In general, the potential effects of a volcanic eruption on the inhabitants of the islands of Tonga 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.

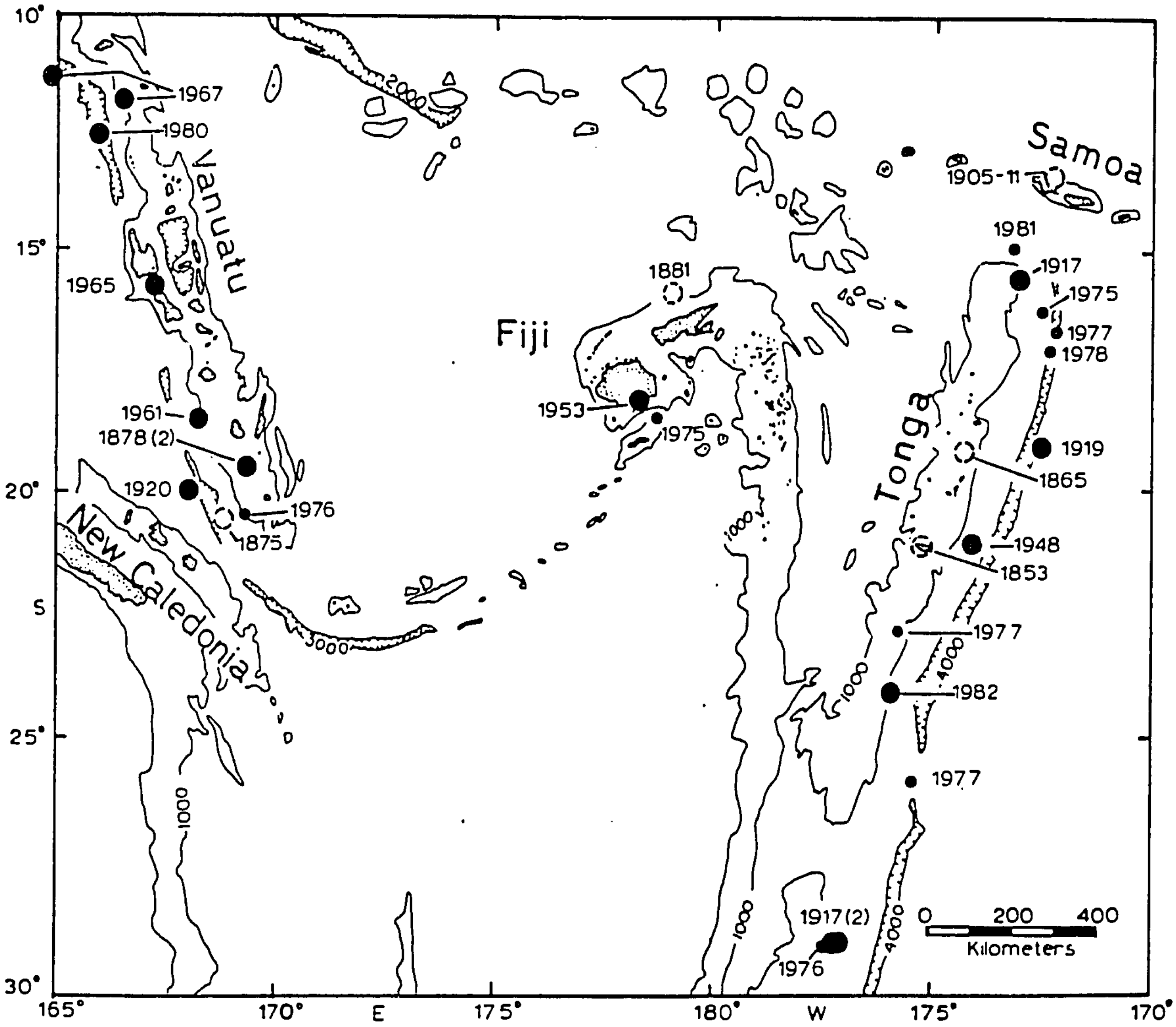


Figure 3. Tsunami history of the Southwest Pacific. Filled circles indicate locations of tsunamigenic events; dashed circles indicate inferred locations of tsunamigenic events.

For example, 1200 inhabitants of Niuafo'ou were evacuated from the island when the volcano erupted in 1946 (Macdonald, 1948). The eruptions at Home Reef during March 1984 produced large quantities of pumice which rafted across large portions of the Southwest Pacific. The floating pumice piled ashore locally and caused problems with shipping in the region (SEAN Bull., 1984).

C. ACTIVITIES SUMMARY

Seismological Facilities

Seismological observations are necessary for the accurate location, study, and ultimate prediction of earthquakes. These observations in Tonga are the responsibility of the Ministry of Lands, Surveys and Natural Resources. However, due to fiscal constraints, in the past these efforts have been entirely dependent on foreign assistance. Seismological experiments began in Tonga in the mid-1960's with the Lamont-Doherty Geological Observatory (Columbia University) Upper Mantle Project. Seismic stations were operated by Lamont-Doherty, and subsequently by Cornell University scientists through the early 1970's, when operations were suspended. The absence of a seismic station near the Tonga-Kermadec seismic zone has been a major limitation on the accuracy of epicentral and depth determinations of earthquakes in this region.

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 (Figure 4). Seismic station NUK began operating on 2 September 1983 and recorded an average of 5-6 earthquakes per day. A close-up view of an earthquake that occurred near the station is shown in Figure 5. This station complemented existing regional stations in the Cook Islands (RAR), Western Samoa (AFI, API), Niue (NUE), Fiji (17-station network), Vanuatu (19-station network), Solomon Islands (6-station network), Papua New Guinea (17-station network), and New Zealand (51-station network). The addition of a permanent observatory in this critical location filled a major void in seismic observatories of the Southwest Pacific. The seismograph

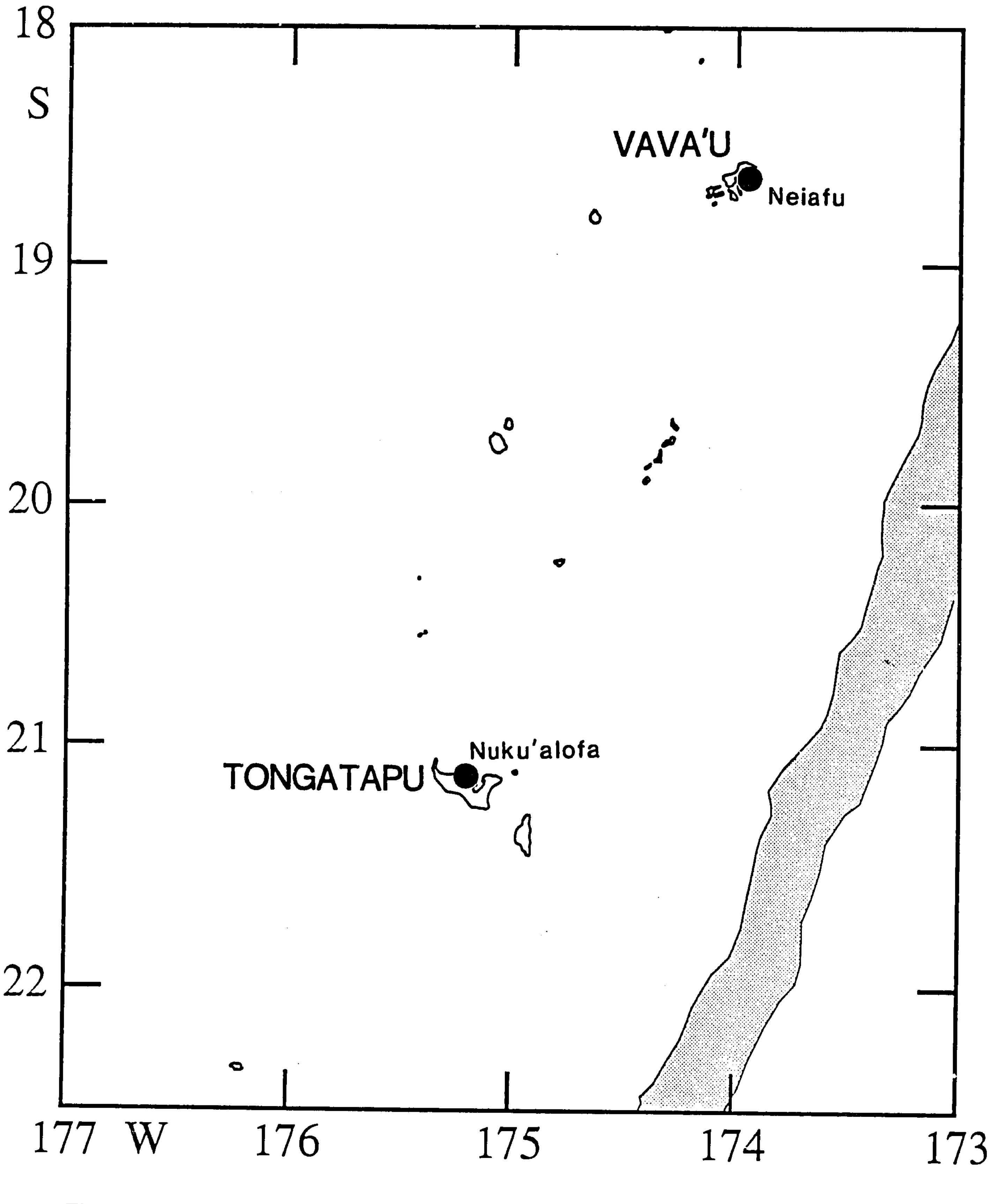


Figure 4. Locations of accelerographs in Tonga shown by filled circles. Shaded zone is the 6 km contour of Kroenke et al. (1983) for the Tonga Trench.

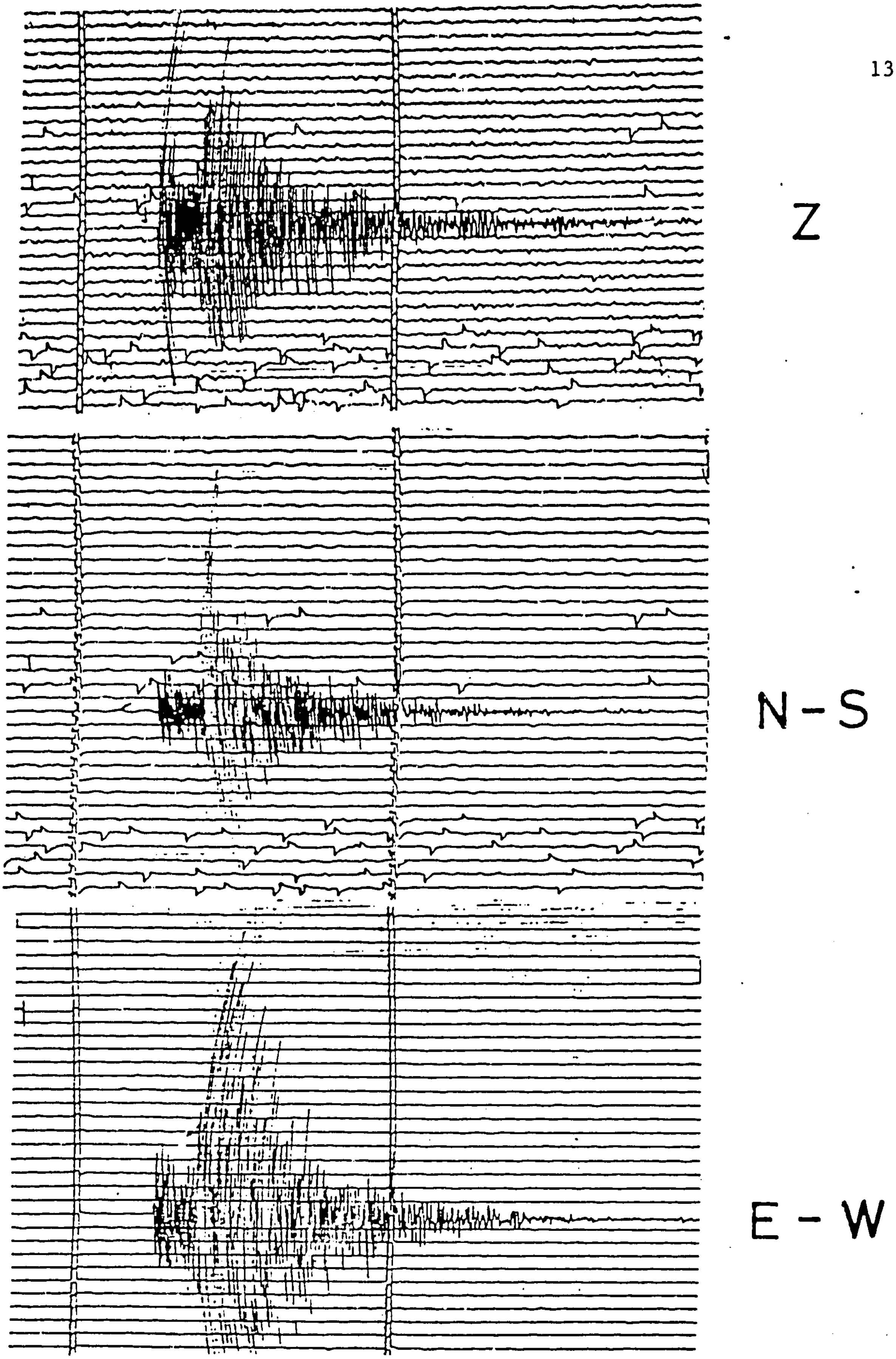
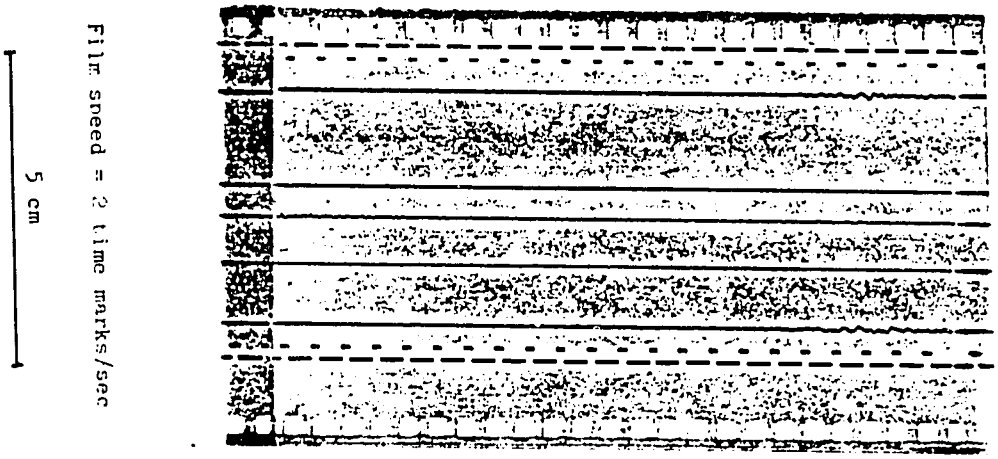


Figure 5. Representative seismograms from Tonga observatory. Example of a local earthquake near Nuku'alofa: 26 Sept. 1983, 0409 U.C.T., distance approximately 60 km. Three components of ground motion are shown. Vertical tick marks are separated by one minute.

was installed upon the request of the government geologist, to be operated by the Tongan government, with technical assistance from Cornell University. Unfortunately, monetary considerations forced the closure of the Nuku'alofa station in May 1984, after eight months of seismograph operation. For the brief period of observation, the seismic station recorded some 1200 earthquakes. During that period, the global network locations of Tongan and regional earthquakes were significantly improved. Data for this time period are available for detailed wave propagation studies, attenuation estimates, etc. There are presently no plans to reinstall permanent seismographs in Tonga. We are hopeful that future conditions will permit seismological observations to resume in Tonga on a permanent basis. The only seismological observations since NUK ceased operating, have been temporary experiments which were conducted by scientists from the (University of Colorado) Cooperative Institute for Research in the Environmental Sciences (CIRES; Bowman and Ando, in press). These experiments involved collecting a specialized set of data for examinating detailed wave propagation of shear-waves from intermediate and deep earthquakes near Tonga.

Strong-Motion Accelerographs. Two strong-motion accelerographs, provided by the AID seismic hazard program, are presently operating in Tonga, one in Nuku'alofa (Tongatapu) and one in Neiafu (Vava'u Islands, Figure 4). The Nuku'alofa instrument has been moved from its original location to the records vault at the Department of Lands, Surveys and Natural Resources. The accelerographs require a minimum of maintenance and their operation will continue to be supervised by the government geologist with assistance from Cornell University. Since installation of the instruments two years ago, only one accelerogram has been recorded by the Tonga instruments (Figure 6).

A single strong-motion accelerogram was recorded by the Nuku'alofa SMA-1. The most likely triggering event is an intermediate-depth earthquake that occurred on 17 August 1984, at 1042 UTC (9:42 PM local time). The earthquake was located nearly directly beneath Tongatapu at a depth of 114 km, and had a magnitude of 5.5. There are no reports of felt effects of the



SOUTHWEST PACIFIC STRONG-MOTION NETWORK	DIRECTION	CONSTANTS
Station NUK 21.13S, 175.21W Nuku'alofa, Tongatapu I., Tonga (Cornell U)	0°	Sens. = 1.86 cm/g Per. = .039 sec Damp. = 0.6 crit
SMA-1 No. 5511 EARTHQUAKE OF 17 August 1984 1042 UTC	Up	Sens. = 1.98 cm/g Per. = .039 sec Damp. = 0.6 crit
	90°	Sens. = 1.74 cm/g Per. = .039 sec Damp. = 0.6 crit

Figure 6. Accelerogram from Tonga observatory. The ticks at top and bottom are time marks. The first trace is the N-S component, the third trace is the vertical (Z) component, and the fifth trace is the E-W component.

earthquake in Tonga. The earthquake produced a peak acceleration of 0.027 g (26.5 cm/sec^2) on the east-west component (Figure 6) and similar peak accelerations of 0.023 g (22.5 cm/sec^2) on both the north-south and vertical components. These peak accelerations are close to those predicted by empirical relations obtained elsewhere (e.g. Donovan, 1973 and McGuire, 1977).

The vertical record is characterized by a single strong pulse (approximately 10 Hz frequency) followed by a high-frequency (25 Hz), low-amplitude coda that continues for 2-3 seconds after the initial pulse. The horizontal components show very little acceleration until the S-arrival, about 9.5 seconds following the trigger. They are characterized by similar, relatively low-frequency arrivals (4-7 Hz) that continue for about 3 seconds. The relatively short trigger-to-S time indicates either (1) incorrect computation of the earthquake's depth (by approximately 20 km) or (2) that the accelerograph was triggered by a secondary phase following the P-arrival (see Mitronovas et al., 1969).

This accelerogram, though very small in amplitude, suggests that intermediate-depth events at 70-150 km directly beneath the islands of the Tonga Ridge may produce significant accelerations there. The low frequency, high amplitude horizontal vibrations following the S-wave are of greater concern for the structural stability of buildings in developed areas. Because intermediate-depth earthquakes with magnitudes greater than 7.0 are not uncommon in the Tonga region (e.g., Gutenberg and Richter, 1954), accelerations up to 0.2 g might result from a large event directly beneath Tongatapu, if scaling laws derived elsewhere are applicable to the Tonga region.

Related Research Programs. The Ministry of Lands, Surveys and Natural Resources employs a single government geologist, whose responsibilities include coordination of all 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 petroleum exploration groups such as the Tonga Oil Exploration Consortium (Tongilava and Kroenke, 1975) and CCOP/SOPAC (Committee for the Coordination of Joint Prospecting for Mineral Resources in the South Pacific; Scholl et al., 1983). A new cooperative Japanese/New Zealand study of the marine geology of northernmost Tonga was undertaken in late 1984 and those data are not yet available (see Lewis, 1985).

Critical Facilities

The capital city of Nuku'alofa had a population of 20,357 people in 1982 (up from 18,400 in 1979), and has several three- and four-story buildings. In general, the larger buildings have been designed by foreign engineers and have included earthquake-resistant design specifications. Other significant development projects include the expansion of the government wharf (Queen Salote Wharf) in Nuku'alofa and development of an industrial estate (Small Industries Centre) and tourist resorts on Tongatapu and several of the outer islands (Pacific Isands Yearbook).

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, under consideration by the Tongan government, as of early 1984, would require review of all development projects by the government planner; application of building codes, largely adapted from New Zealand or other foreign 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 and is chaired by the Prime Minister. Subcommittees focus on disaster preparedness, action planning, and long-term relief and rehabilitation. However, there is no formal earthquake education program in Tonga.

D. GENERAL BACKGROUND INFORMATION

Plate Tectonic Setting

This paragraph is meant to give a brief introduction to the general geologic and plate tectonic setting of the Kingdom of Tonga for the reader who is unfamiliar with the region. The Kingdom of Tonga lies along a portion of what is commonly called the "Pacific Ring of Fire." The concentration of earthquakes (Figure 7A) and volcanoes (Figure 7B) along this trend were used to establish the boundaries of the lithospheric plates in the modern view of plate tectonic theory (Figure 7C). 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 8 shows sketches of the 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.

The Tonga island arc is a component of the Melanesian Borderlands that form the boundary between the Pacific and Indo-Australian lithospheric plates (Figure 1A). The tectonics of this region are dominated by the presence of a well-developed subduction zone which is expressed at the surface as the Tonga Trench. The Pacific Plate is being subducted westward under the Indo-Australian Plate at a rate of ten centimeters per year (McKenzie, 1969; Minster and Jordan, 1978) in a direction perpendicular to the trench (Isacks et al., 1969; Johnson and Molnar, 1972). Relative to other convergent plate boundaries (e.g., Chile and Alaska) the width of the zone of interaction between these two plates is rather limited in extent because of the steepness of the subducting slab (70°).

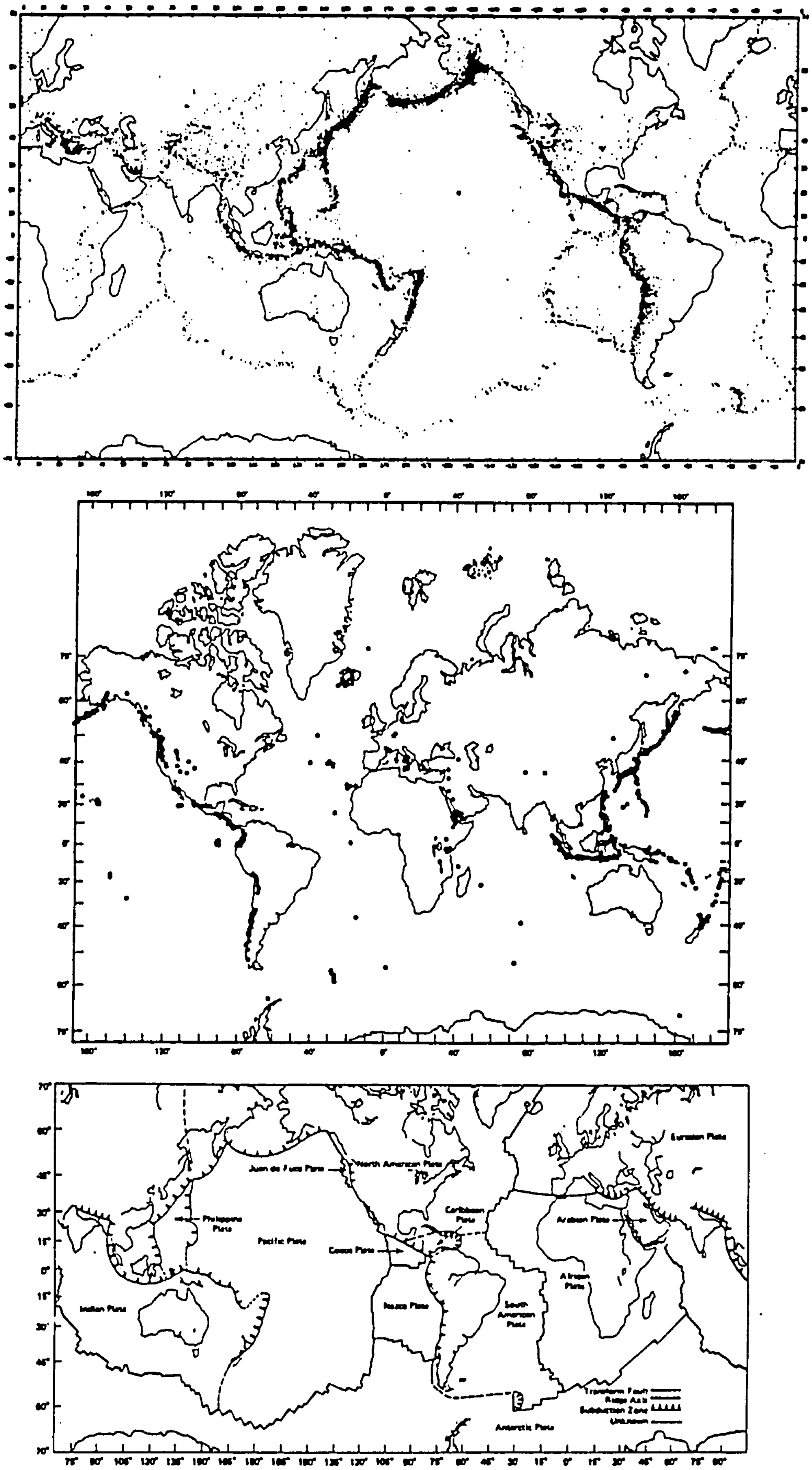


Figure 7. World distribution of (A) earthquakes and (B) volcanoes. (C) Configuration of the major tectonic plates on the earth's surface (Turcotte and Schubert, 1982).

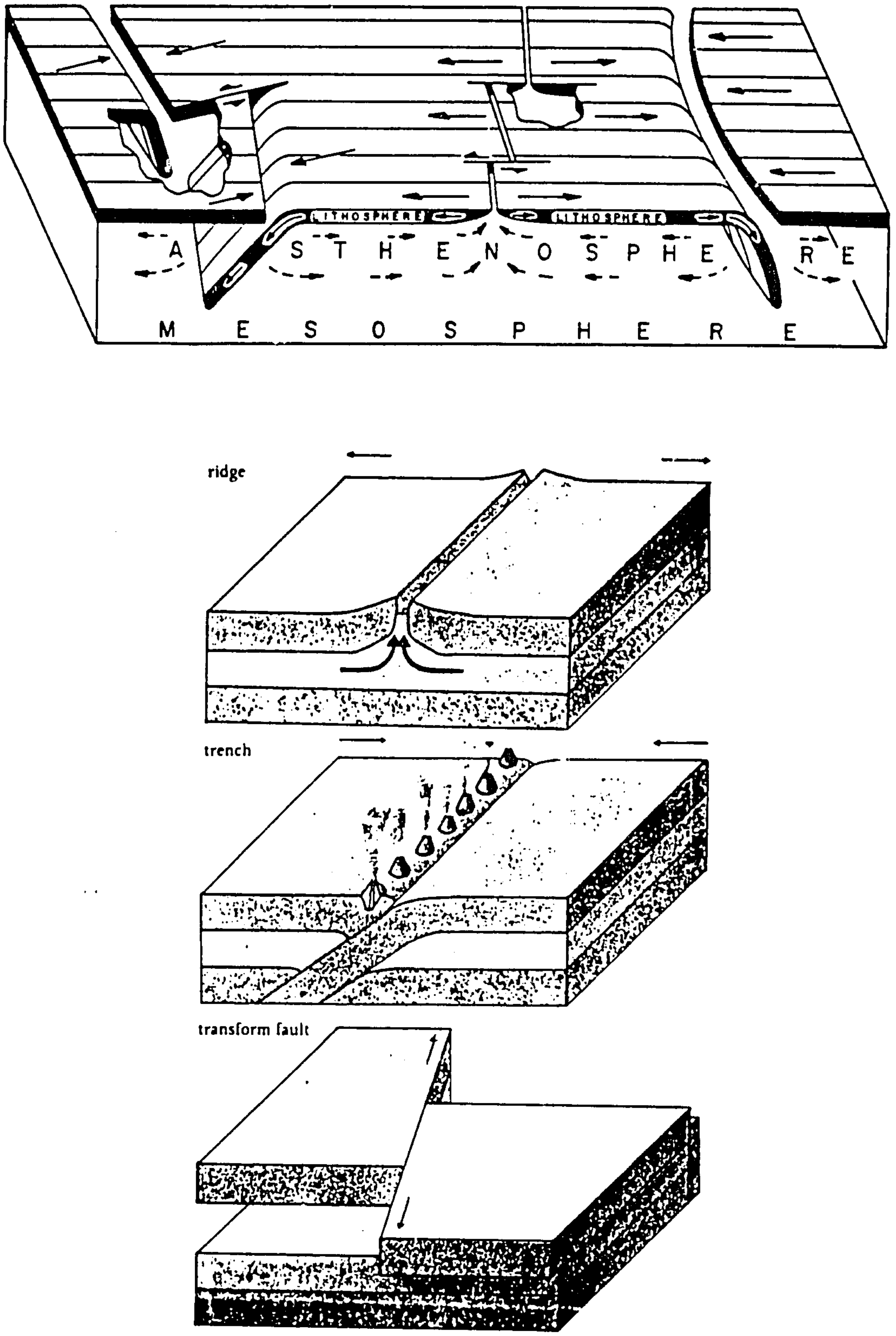


Figure 8. (A) Sketch of the different types of plate tectonic boundaries and their relationships (Isacks et al., 1968). (B) Diagrams of the three types of boundaries in three dimensional view (Calder, 1972).

Geological Setting

The islands of Tonga are volcanic in origin and can be divided into two groups (Figure 9): (1) the western volcanic arc which contains active aerial and subaerial volcanoes of the Tofua Ridge and (2) the eastern coralline arc which consists of reefal limestones overlying volcanic rocks of an older volcanic arc which produced the Tongatapu Ridge (Bryan et al., 1972).

The Tonga Trench, Tonga Ridge, and Tofua Ridge have been produced as the island arc has been built up by the extrusion of basaltic and andesitic lavas from the sea floor. These erupted materials are derived from the wedge of asthenosphere above the descending plate and the partial melting of the crust and sediments of the descending plate. Behind and westward of of the Tonga Arc lies the Lau Basin (Figure 10) where the presence of shallow seismicity, fresh basalts, and little sedimentation indicate active back-arc spreading of the Lau Basin.

In a study of uplift rates on Tongatapu and Eua, Taylor and Bloom (1977) have used bathymetry to identify five crustal blocks along the Tongan frontal arc (Figure 11). Whether or not these blocks are continuous into the lower crust is unknown. Using altitudes and radiometric dates from coralline limestones, they did not observe large contemporary tectonic tilting along the frontal arc such as the Quaternary tilting and uplift observed in Vanuatu (Taylor et al., 1978; Gilpin, 1982). These results do not resolve whether the absence of major uplift indicates (1) lower seismic potential or (2) no net tectonic uplift along the Tonga plate boundary.

E. SEISMOTECTONIC SETTING

Earthquakes in the Tonga Region

Most Tonga earthquakes are located in the **interplate** zone between the two plates. They are associated with slippage of the Pacific Plate as it descends beneath the Indo-Australian Plate at an average rate of ten centimeters per year (Minster and Jordan, 1978). The southern end of the

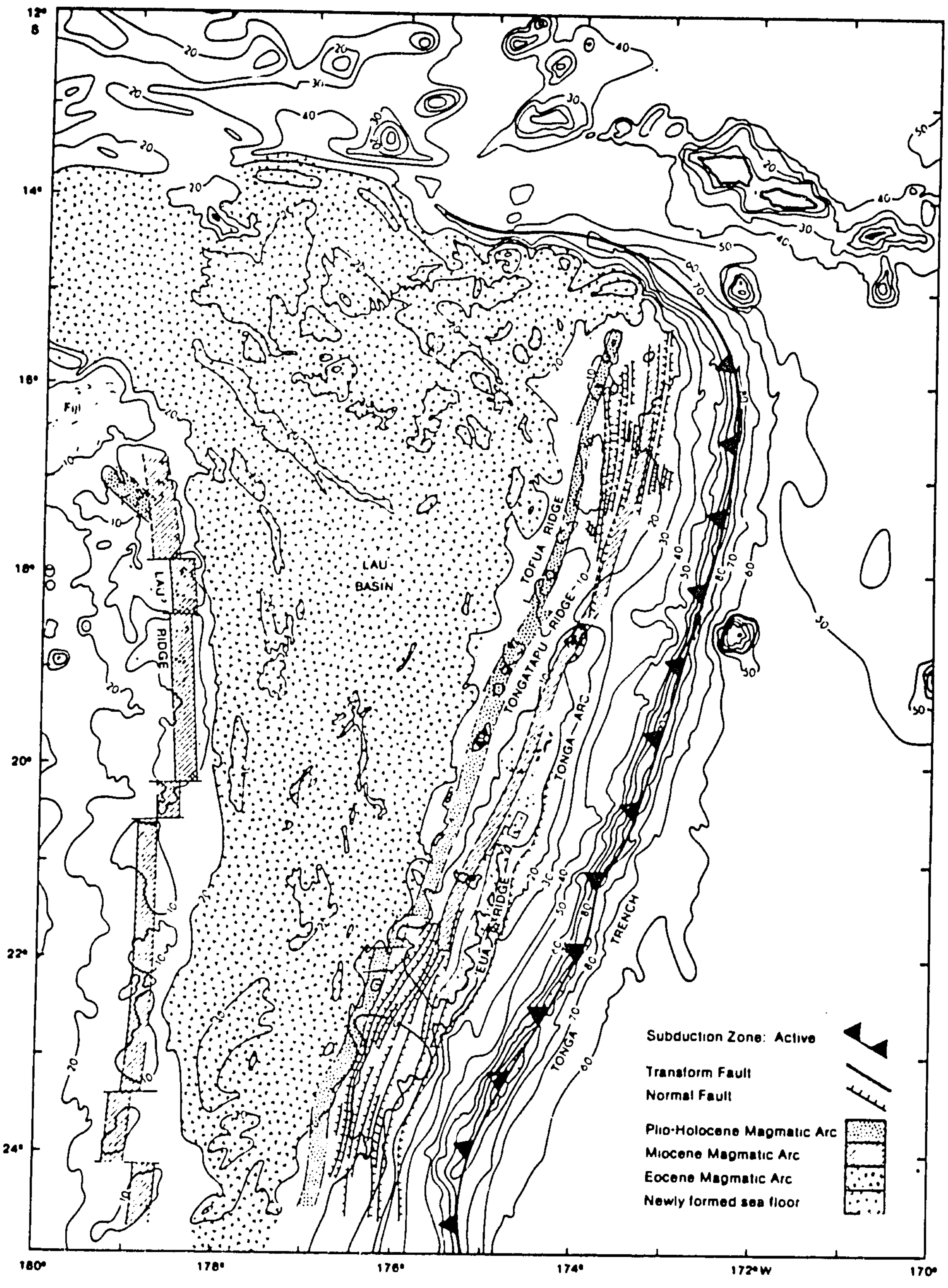


Figure 9. Structural geology of the Tonga Arc and surrounding regions (from Kroenke, 1984).

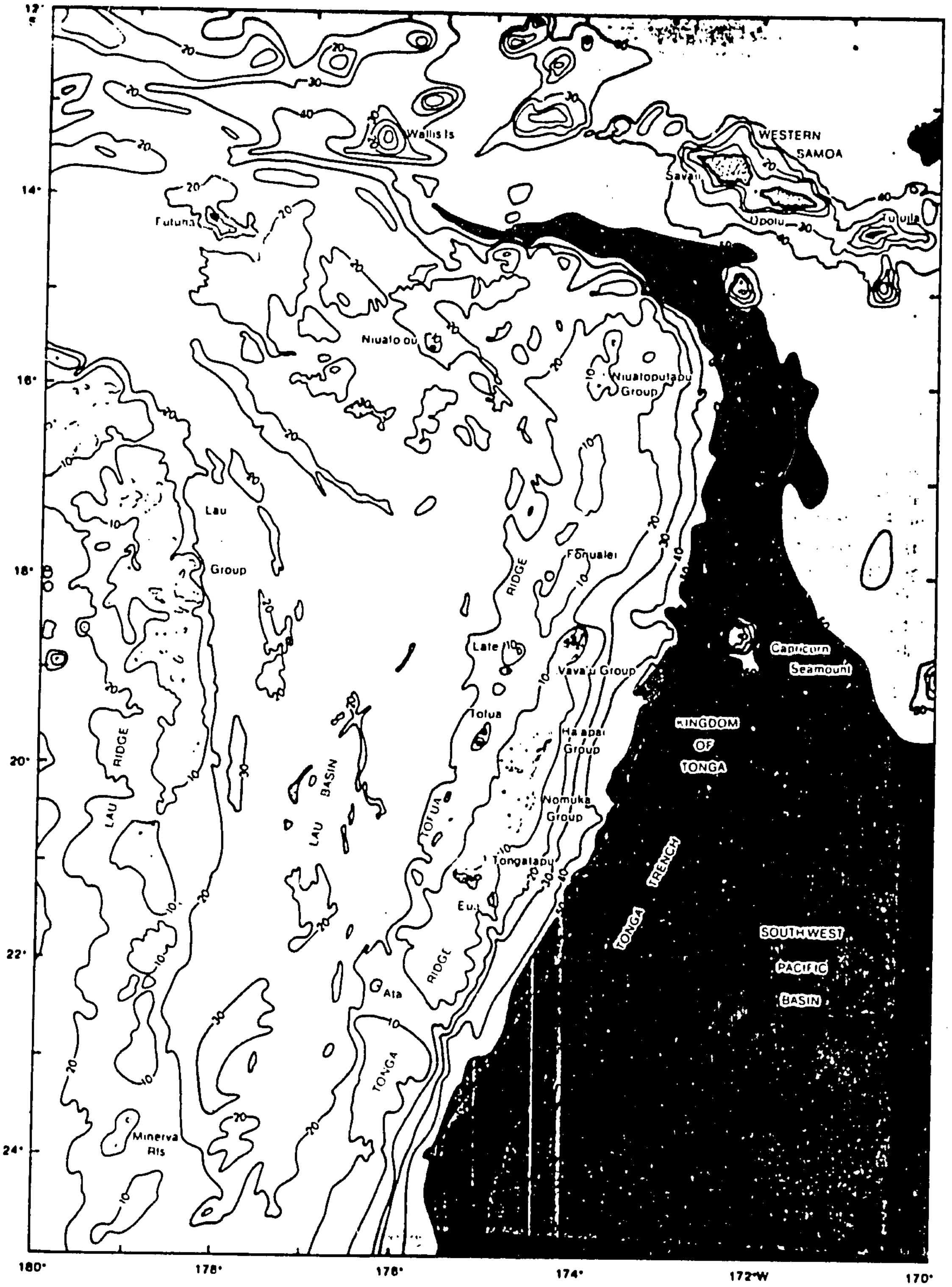


Figure 10. Physiographic setting of the Tonga Region showing the main island groups and major physiographic features (Kroenke, 1984).

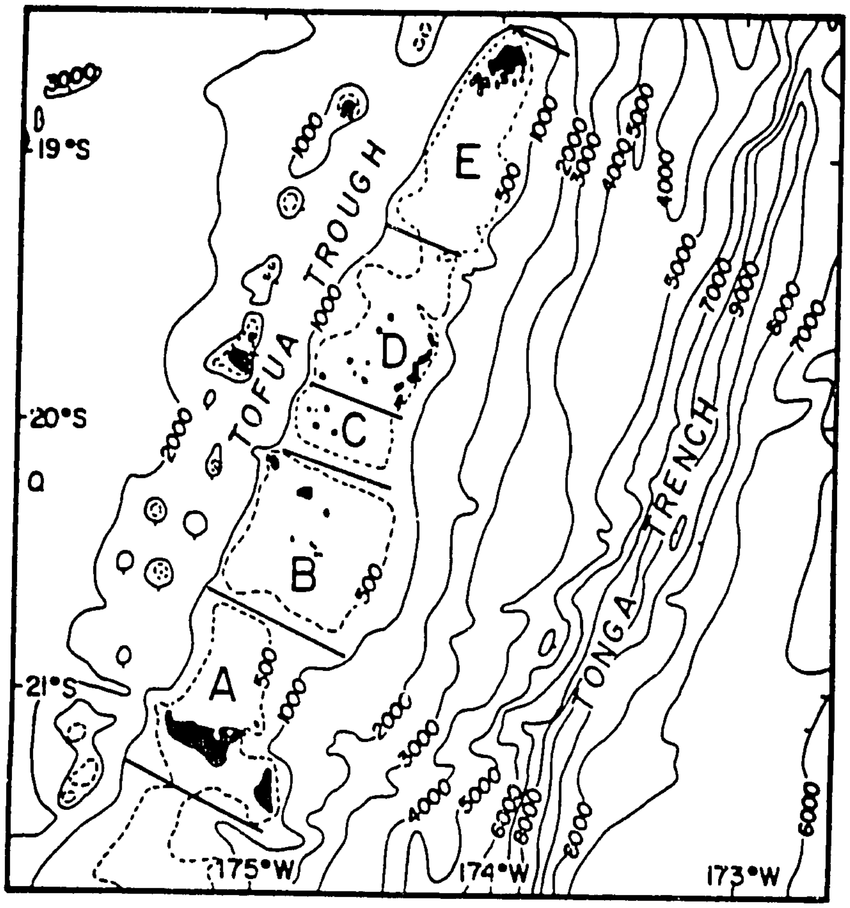


Figure 11. Bathymetry, Tonga island arc (contour interval = 1000 m + supplemental 500 m contour). Tectonic blocks: (A) Tongatapu; (B) Nomuka; (C) southern Ha'apai; (D) northern Ha'apai; (E) Vava'u (Taylor and Bloom, 1977).

Tonga subduction zone is seismically quieter where the Tonga Trench shoals against the Louisville Ridge (trending 330°) at approximately 27°S. **Intraplate** earthquakes also occur within the descending and overlying plates in the trench region and behind the volcanic island arc in what is known as the back-arc region. A schematic, though representative, vertical cross section near Tongatapu, perpendicular to the trend of the arc, shows the relationship of the seismicity to the trench, islands, and back-arc (Figure 12). In the vicinity of Samoa, large, destructive earthquakes result from an unusual combination of subduction of the Pacific Plate in the northernmost Tonga Trench (south of 15°S), and tearing of the Pacific Plate to accommodate subduction, with westward translation along transform faults west of the "Samoa Corner" (north of 15°S; Isacks et al., 1969; Figure 13).

Teleseismically located earthquakes occur from the near surface to approximately 700 km of depth. The earthquakes systematically deepen westward, from the Tonga Trench, forming a narrow dipping plane (**Benioff zone**) which is represented by the contours in Figure 14. Thus shallow, potentially destructive earthquakes generally occur just east of the Tonga Islands, and intermediate and deep earthquakes occur progressively farther west. Events at 500-700 km depth are located just east of the Fiji Islands, 500 km west of Tonga. Large earthquakes have occurred along the entire length of the Tonga-Kermadec arc, where subduction of the Pacific Plate is taking place.

Because shallow earthquakes are of greatest concern for earthquake hazard, in this report we have focussed on shallow earthquakes near Tonga. We have compiled maps of shallow seismicity (depth ≤ 70 km) of the Tonga region, based on the U.S. Geological Survey's Preliminary Determination of Epicenters (PDE) catalog for the period 1961-1984. Figure 15 shows reliably determined shallow earthquakes, recorded at 20 or more stations of the global network. This figure illustrates the dense concentration of interplate events close to and landward of the Tonga Trench. The capital city, Nuku'alofa, is located on Tongatapu Island at about 21.5°S, 175°W, and is located near another concentration of (interplate) events at that location. Zones of

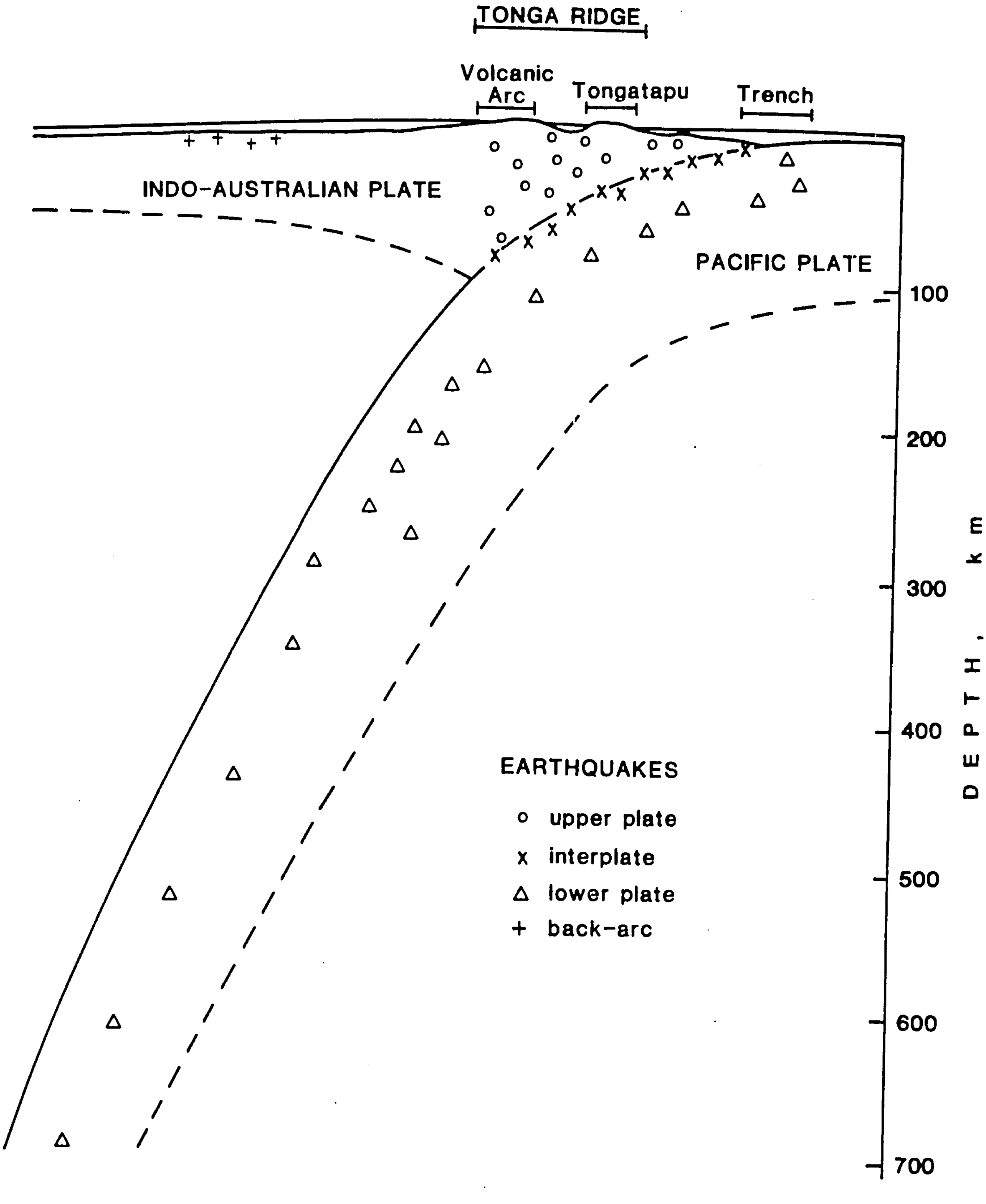


Figure 12. Schematic east-west cross sectional view of the Tonga region showing earthquake locations and the relationship to the two tectonic plates (modified from Billington, 1980).

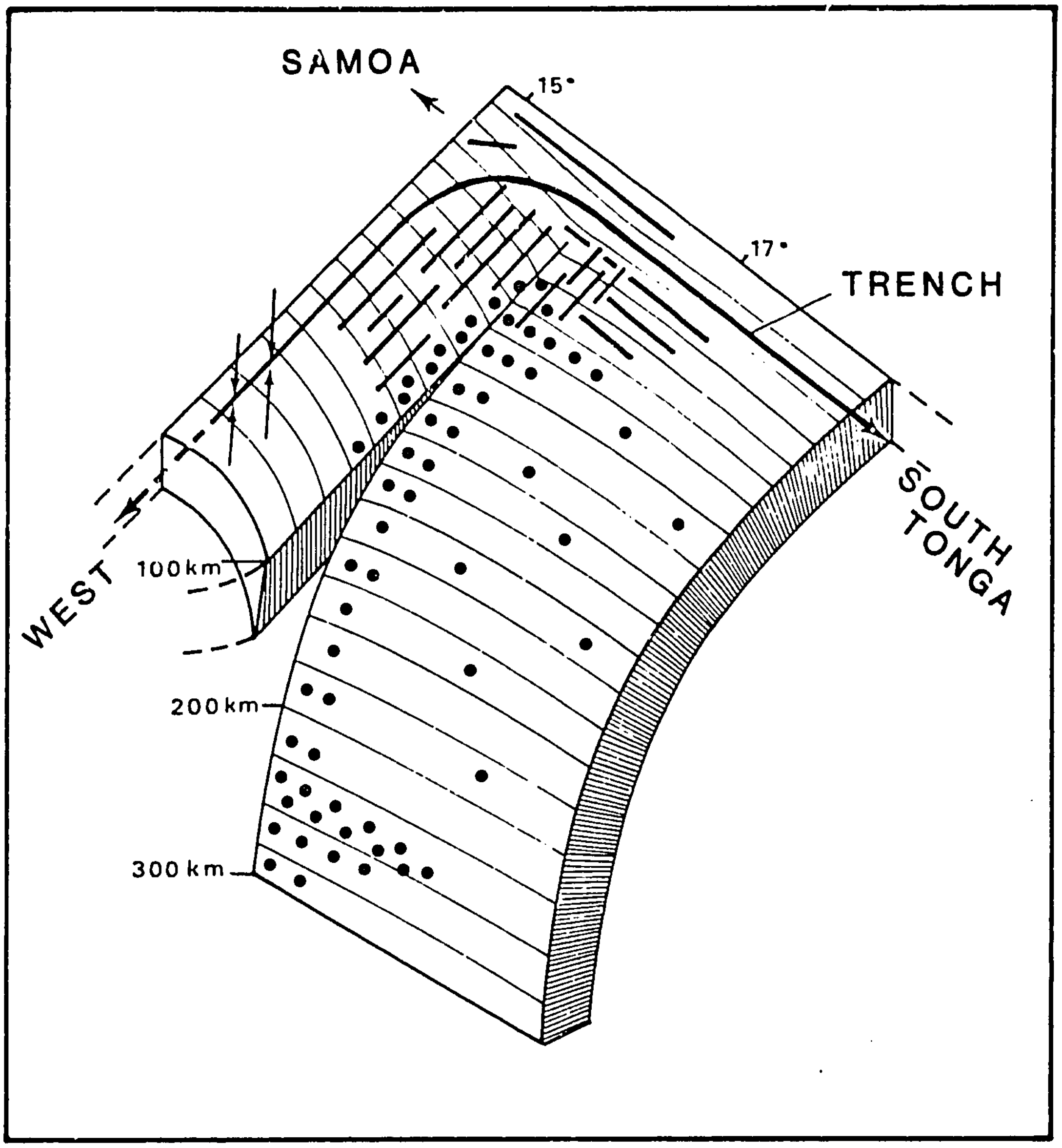


Figure 13. Schematic diagram of the Benioff zone at the "Samoa Corner." The opposing arrows indicate where compressional motion occurs between the Pacific and the Indo-Australian plates and filled circles indicate representative earthquake foci.

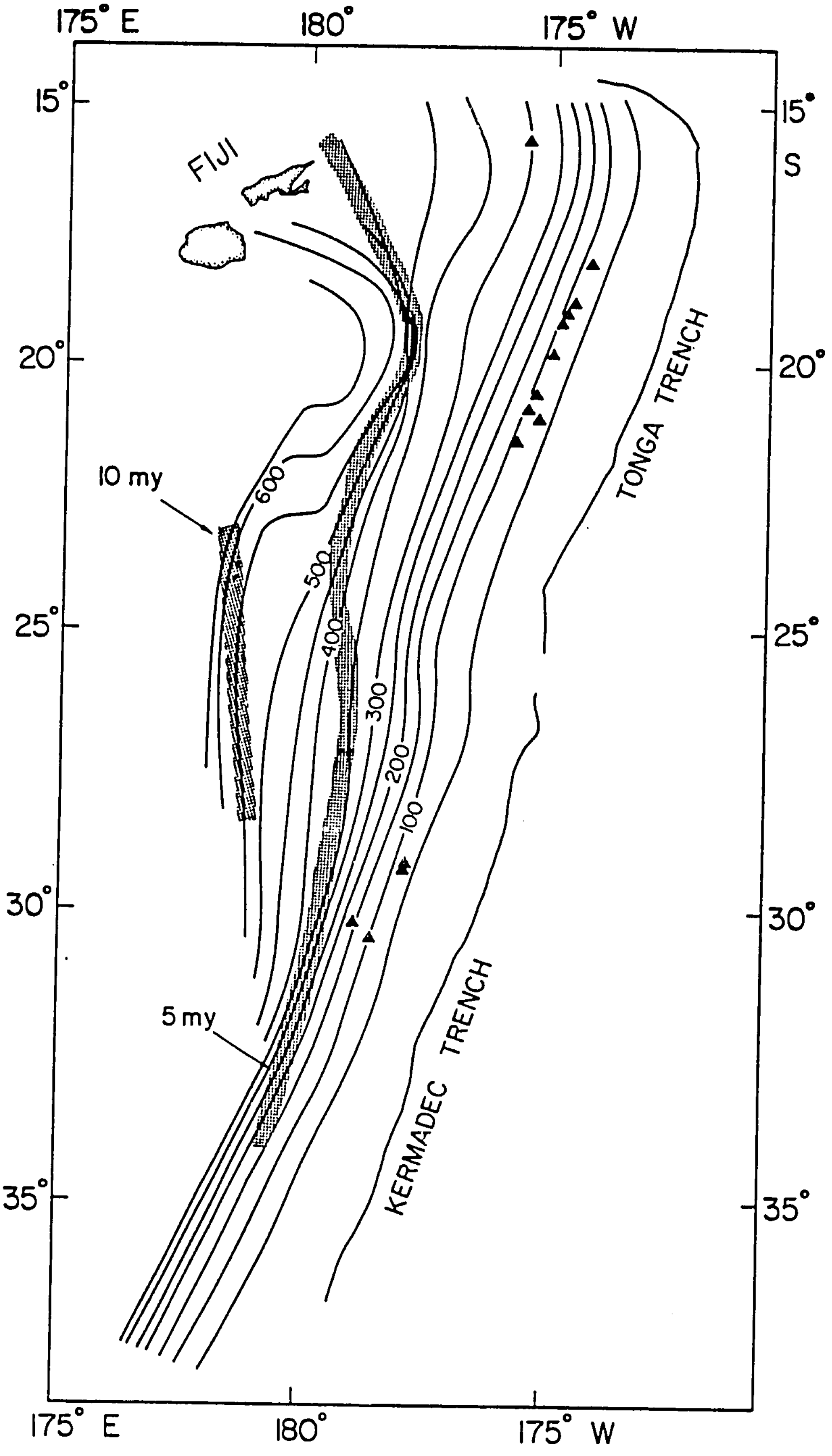


Figure 14. Map of contours of the depth in km to the top of the Benioff zone. Triangles are active volcanoes. (Billington, 1980).

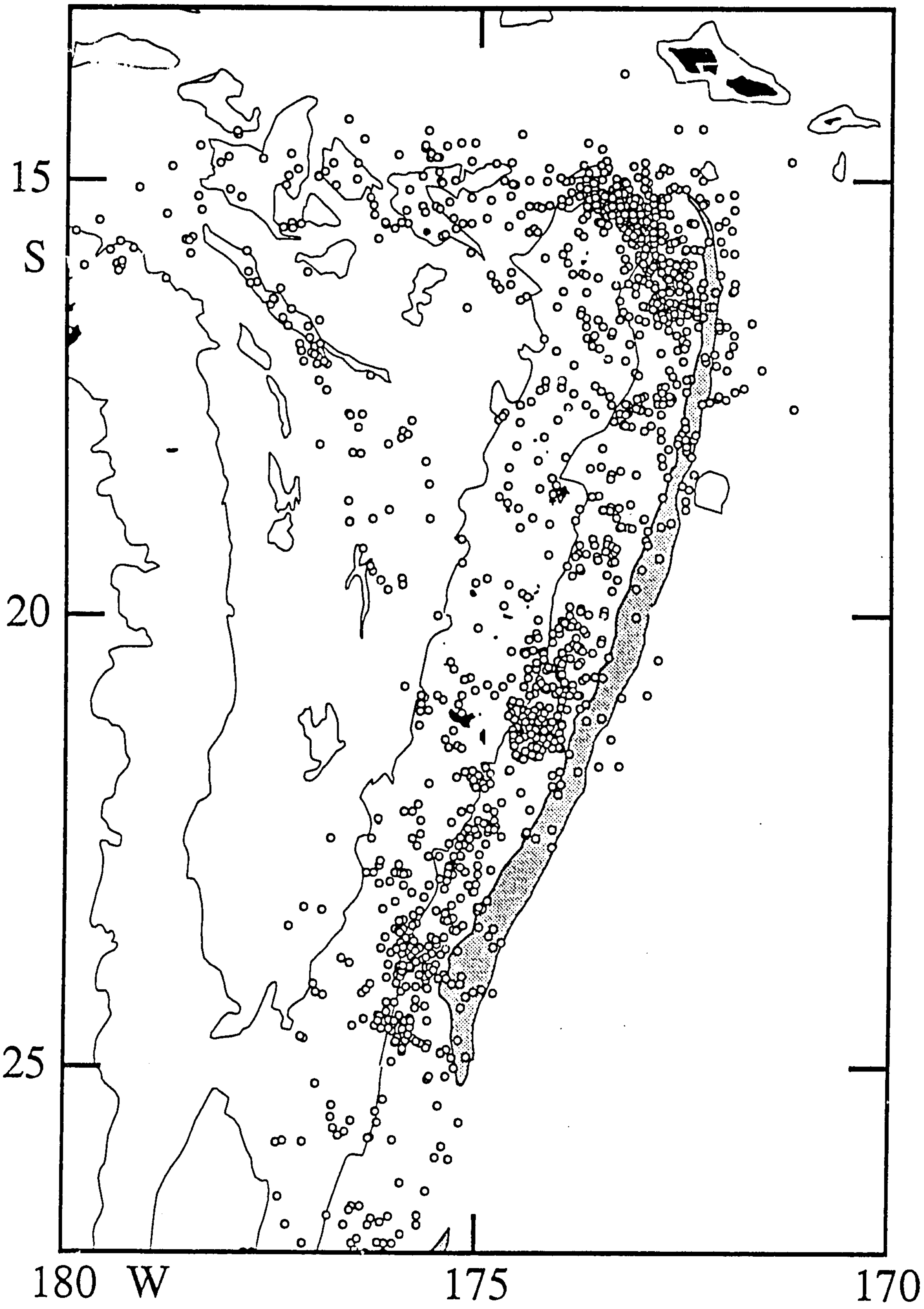


Figure 15. Shallow seismicity in Tonga (h ≤ 70 km) from the PDE catalog. All earthquakes located by more than 20 stations of the global seismic network are included. Shaded area shows Tonga Trench, and thin solid line indicates 2-km isobath, from Kroenke et al. (1983).

shallow (intraplate) seismicity can also be seen within the Lau Basin (west of the Tonga Ridge) and along the Fiji Fracture Zone, the transform fault which extends westward from northernmost Tonga.

Instrumental records show that while the moderate-sized earthquakes are distributed throughout the arc (Figure 16), it is clear that the larger, and potentially destructive, events have concentrated at the northern and southern ends of the arc. Thus, the seismicity record for the past 23 years might suggest relatively low hazard to development in Tongatapu. However, the seismicity record covering the time period since the beginning of the twentieth century indicates a rather different pattern of large earthquakes such that the entire arc may experience large or great earthquakes.

Large historical earthquakes in the Tonga region for the period of time 1900-1978 are shown in Figure 17 (from McCann, 1980). It is clear that the pattern of large earthquakes occurring between 1951 and 1978 (Figure 17A) is confined to the ends of the arc. However, the previous period, 1900-1950 (Figure 17B), shows a concentration of large events in the central portion of the arc. This pattern suggests that the recent gap in large earthquakes in central Tonga may be a temporary one. Thus, over the long term the earthquake potential for the portion of the plate boundary near Tongatapu is as high as the remainder of the arc.

23 June 1977 Earthquake

In trying to determine the earthquake hazard for a given region, it is important to consider the effects of a particular earthquake in the region (such as the largest and closest recent event) in order to evaluate the response of a region to a particular size of earthquake at a particular distance. One such earthquake with a surface wave magnitude (M_s) of 7.2 shook the southern islands of the Kingdom of Tonga on 23 June 1977. The tremor was also felt on Ha'apai and Vava'u. Personal injuries were relatively small from this earthquake which was located approximately 200 kilometers to the south-southwest of Tongatapu (Figure 18). Many people were affected by the damage to

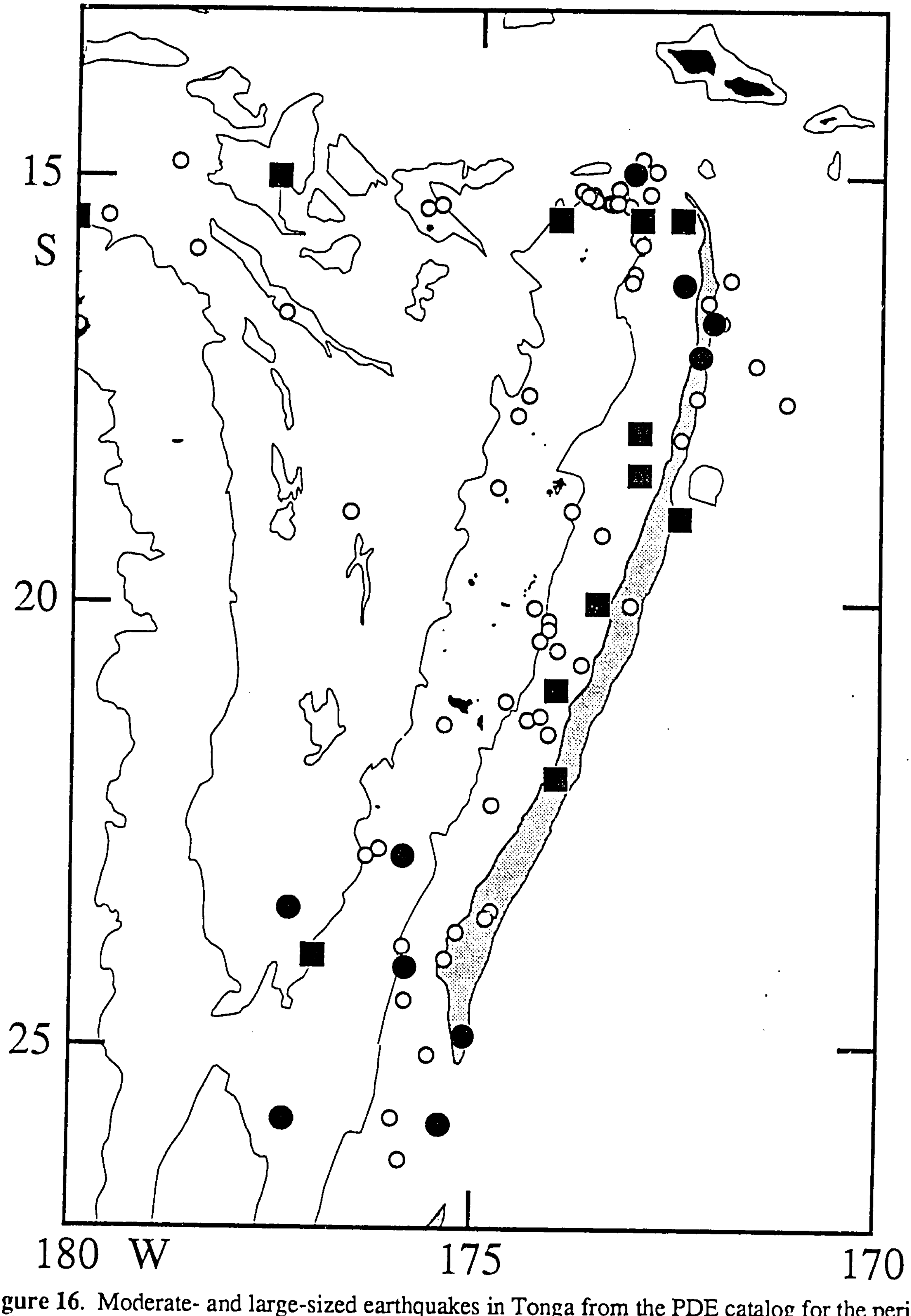


Figure 16. Moderate- and large-sized earthquakes in Tonga from the PDE catalog for the period 1961-1984. Small open circles indicate moderate-sized earthquakes with body wave magnitude (m_b) ≥ 5.8, large shaded squares and circles indicate earthquakes with surface wave magnitudes (M_s) between 7.0 and 7.5 and large filled squares and circles indicate those earthquakes with $M_s \geq 7.5$. Circles indicate instrumentally recorded epicenters, while squares represent historical epicenters (pre 1950). The June 1977 earthquake is shown as a large shaded circle approximately 2° south-southwest of Tongatapu. Bathymetry as before.

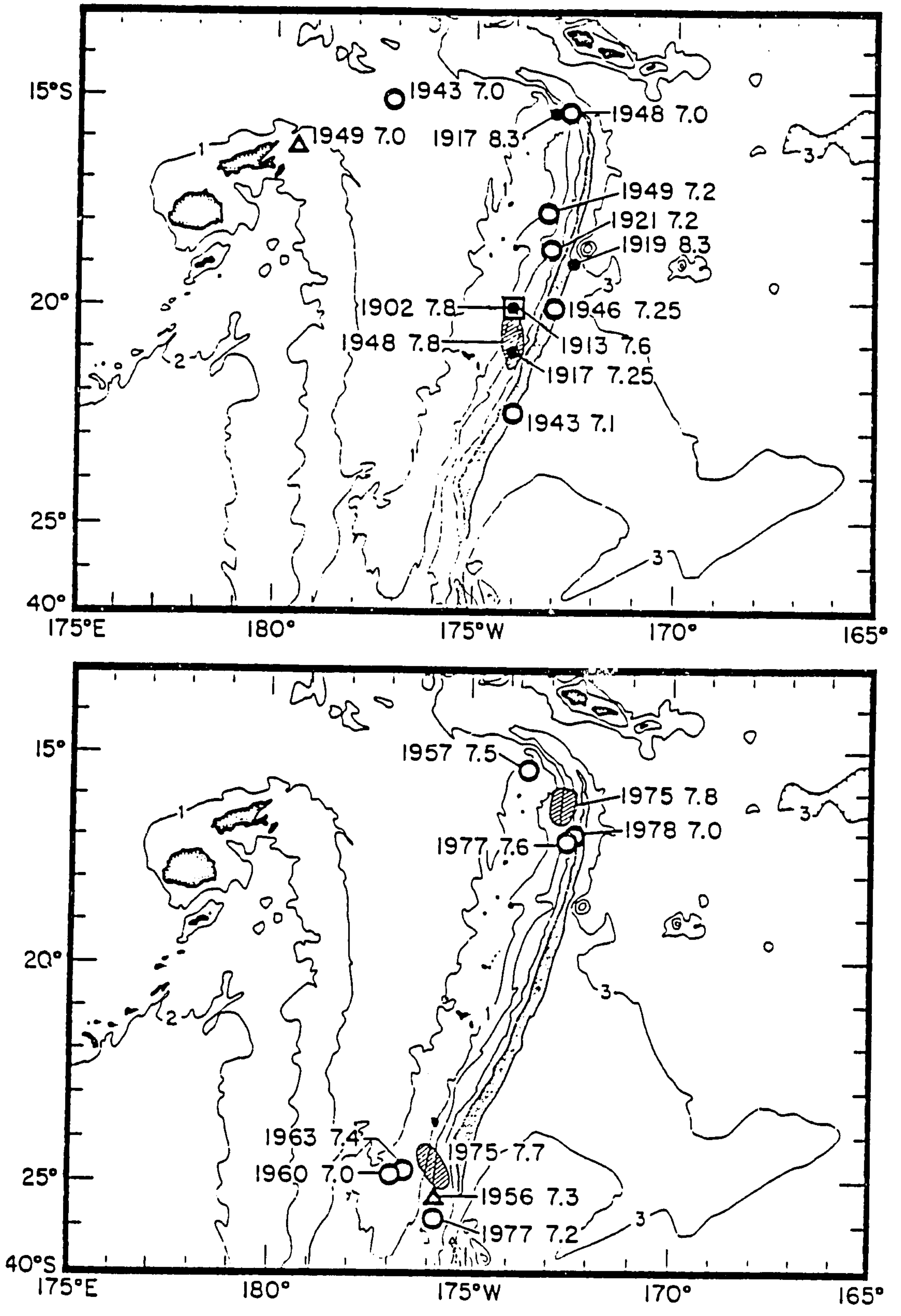


Figure 17. Large earthquakes in Tonga since the beginning of the century (from McCann, 1980). Hachured areas represent aftershock zones, open circles are relocated shocks, solid circles and squares are epicenters taken from Gutenberg and Richter (1954) and Richter (1958), respectively. The time period is shown for (A) 1900-1950 and (B) 1951-1978.

homes, churches, and public works. The Vuna Wharf was badly damaged at Nuku'alofa when the floor of the customs shed collapsed. *The Tonga Chronicle* published pictures of the damage to the wharves and various buildings. A small tsunami was generated by this earthquake and recorded at Suva, Fiji (40 cm) and Papeete, Tahiti (12 cm; ISC report).

The International Seismological Centre (ISC) hypocentral data for this earthquake are as follows:

Time: 12h 08m 33.7s, 22 June 1977 Universal Coordinated Time (0h 08m, 23 June Local Time)
Location: 22.91°S latitude, 175.74°W longitude
Depth: 69 km

The epicenter was located about 190 km to the south-southwest of Tongatapu and Eua. Figure 18 shows the ISC locations of this mainshock as well as three weeks of aftershock activity. The aftershock zone has been demarked.

Modified Mercalli intensities of shaking (see Appendix II for descriptions of these values) ranged from MMVII and MMVIII on Eua to MMVI and MMVII on Tongatapu to less than MMV on the northern island groups of Ha'apai and Vava'u (Campbell et al., 1977). Considerable damage to structures resulted from this earthquake . This may be the result of one or more of the following: (1) The focussing of seismic energy in the vicinity of the main islands or (2) poor quality of construction, design, or building materials, (3) lower than average attenuation of seismic waves, or (4) limited attenuation resulting from the geometrical effects of the relatively long, thin interplate zone. In any of these cases, structural damage would be higher than expected. Because this earthquake was of moderate to large size (M_S 7.2) and because it was so far from Tongatapu (190 km), we suggest potentially devastating effects could result from a large to great size earthquake close to the population centers in Tongatapu, Ha'apai, and Vava'u.

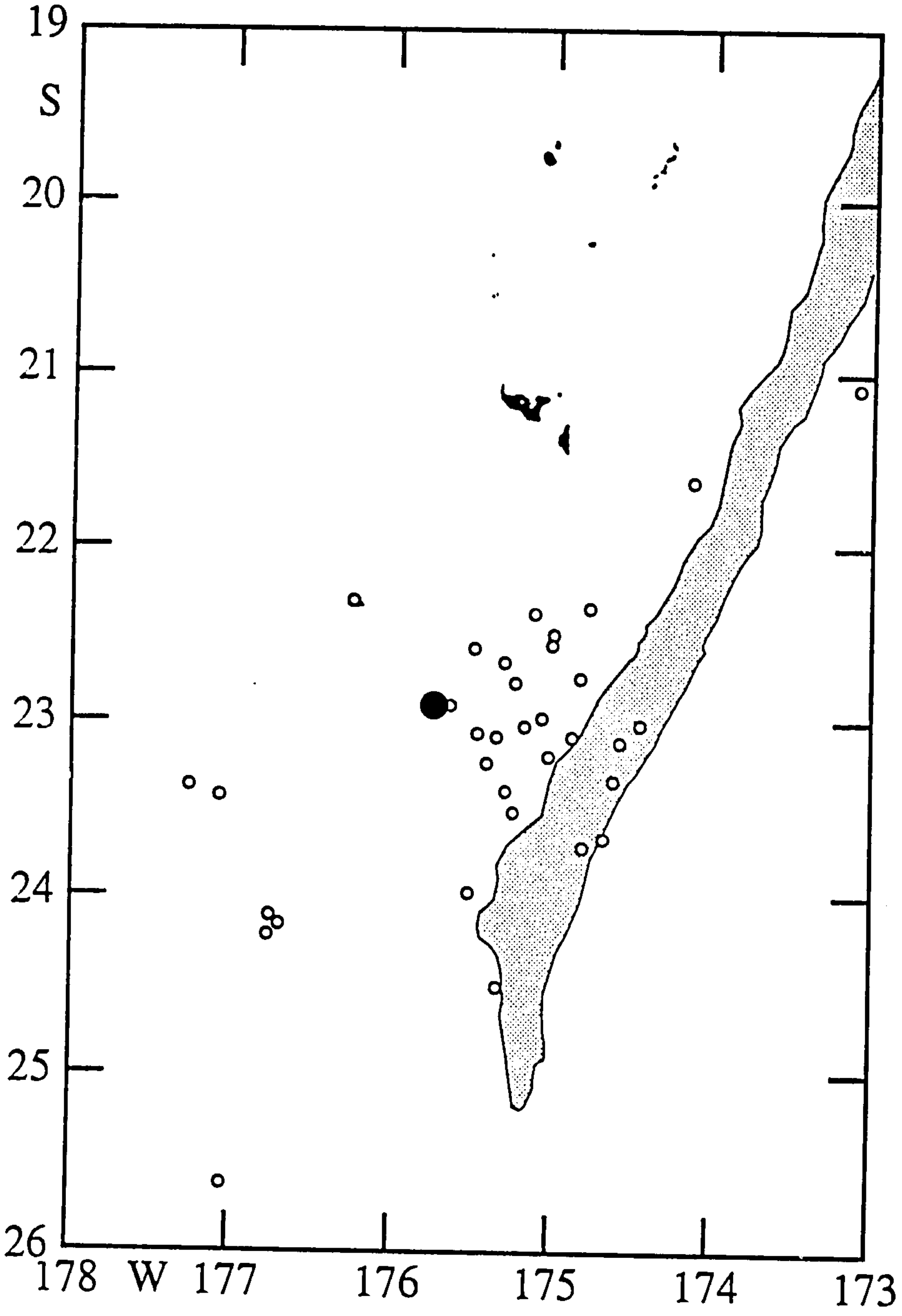


Figure 18. The 22 June 1977 earthquake location (large filled circle) and three weeks of aftershock activity (small open circles within the heavy line).

Stewart and Given (unpublished data, 1982) obtained a focal mechanism from first motions that showed normal faulting (slip angle -63°) on a steeply dipping (73°W) fault plane trending S20°W (ϕ, in Figure 19). Since no local seismic observations are available to constrain the fault plane of this earthquake, aftershock locations have been used to delineate the rupture zone (Silver and Jordan, 1984). The characteristics of the focal mechanism (normal versus thrust faulting) and conflicting depth information indicate that this event is not a typical subduction earthquake but a complex rupture within the upper plate. However, studies of the effects of this earthquake can provide valuable information about site response for the region.

F. PREVIOUS STUDIES

Seismic Potential Studies Along the Tonga Arc

Because of the paucity of local network data or historical observations in Tonga, our earthquake hazard assessment is largely dependent on the teleseismic record of earthquakes along the plate boundary. We have used the available information to assess the earthquake hazard for Tonga. The earthquake hazard from the interplate zone is generally high because of the rate of relative motion of the two plates (10 cm/yr). 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.

Available data necessary to address the recurrence history for Tonga are sketchy at best. The rupture zones of major and great earthquakes occurring along the trenches of the Southwest Pacific are usually less than 150 km in the maximum dimension (McCann, 1980). More extensive ruptures are possible when multiple events occur in adjacent areas within a few hours or days (McCann, 1980). Little information is available to determine rupture dimensions of the historical earthquakes such as those of 1902, 1917, and 1919.

Instrumental historical records exist for the period 1910 to the present. McCann et al. (1979) and McCann (1980) have used these records to analyze aftershock zones of large shallow

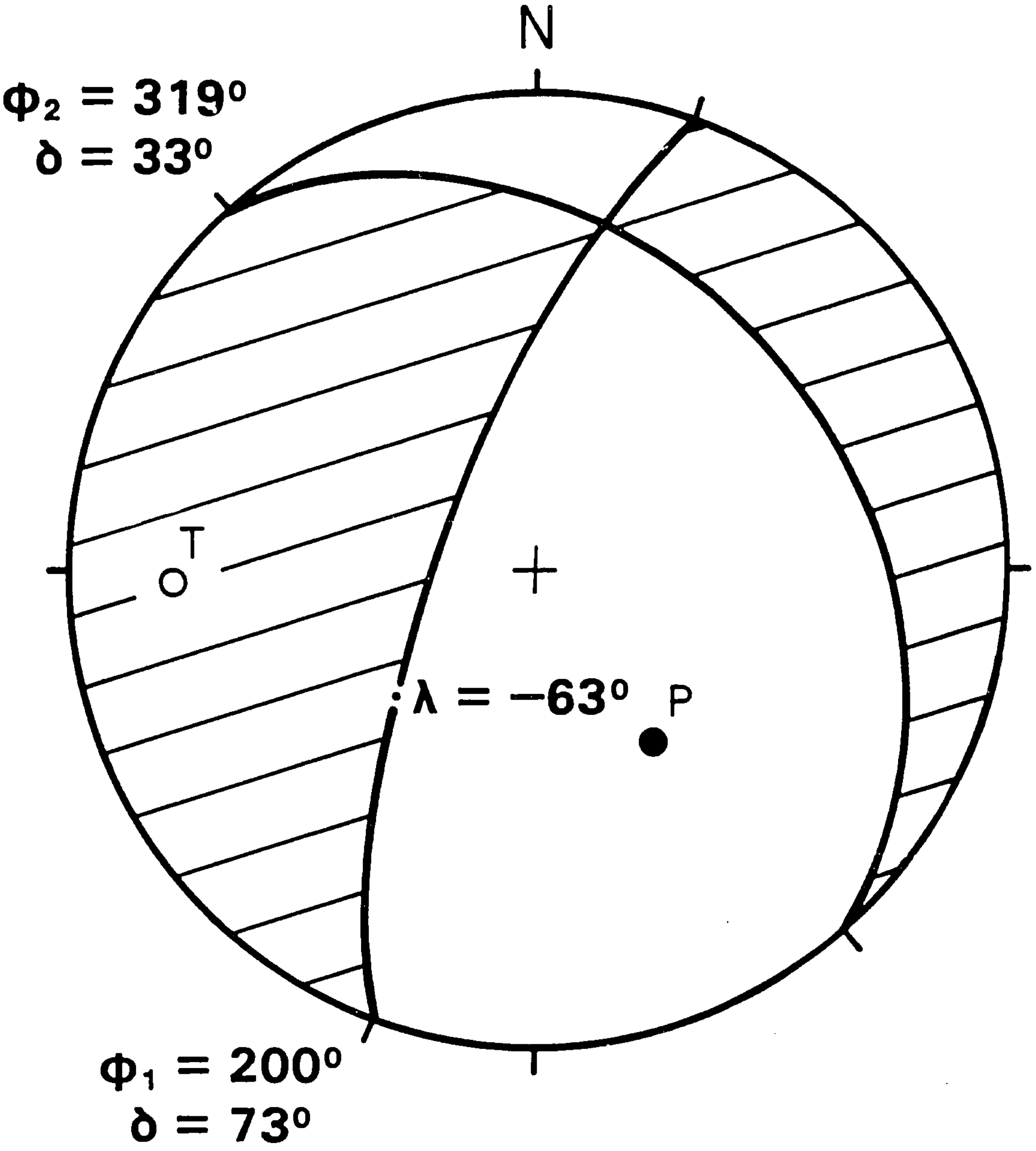


Figure 19. Lower hemisphere projection of the normal focal mechanism of the long period first motions for the 22 June 1977 earthquake (Stewart and Given, unpublished data, 1982). This normal mechanism exhibits oblique slip and is atypical of subduction zone thrust faulting.

Tongan earthquakes to map the rupture zones and the seismic gaps that separate them (Figure 17). They have also noted that the segments of the arc from 17° to 22°S and 25° to 28°S are locations of lower rates of historical seismicity. They concluded that most of the northern portion of the Tonga seismic zone has the potential for a large earthquake even though the historical record is incomplete. This conclusion is based upon the dominance of the tear faulting of the Pacific plate in that region. They also concluded that the southern portion of the Tonga seismic zone near the Louisville Ridge might not have the potential for a great earthquake since none is present in the historical record. Figure 20 shows McCann's (1980) breakdown of the Tonga arc and assignment of seismic potential. Lateral changes in the seismic nature of this plate boundary reduce the confidence of these assignments of seismic potential. It is clear from these data that relatively recent seismicity patterns (e.g. 1950 to present) may lead to incorrect conclusions.

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, although the historical record may be incomplete or too short to accurately determine which option is correct.

Recurrence relations which are dependent upon the observations of seismograph networks cannot be used for the Tonga region. Local networks have operated only periodically and not continuously, so no basis exists for this analysis. Indirect evidence of large earthquakes can sometimes be found in the geologic record in the form of uplift rates. However, the ages of coral reefs on uplifted terraces of Tongatapu and Eua do not resolve whether or not the 2.2 m of

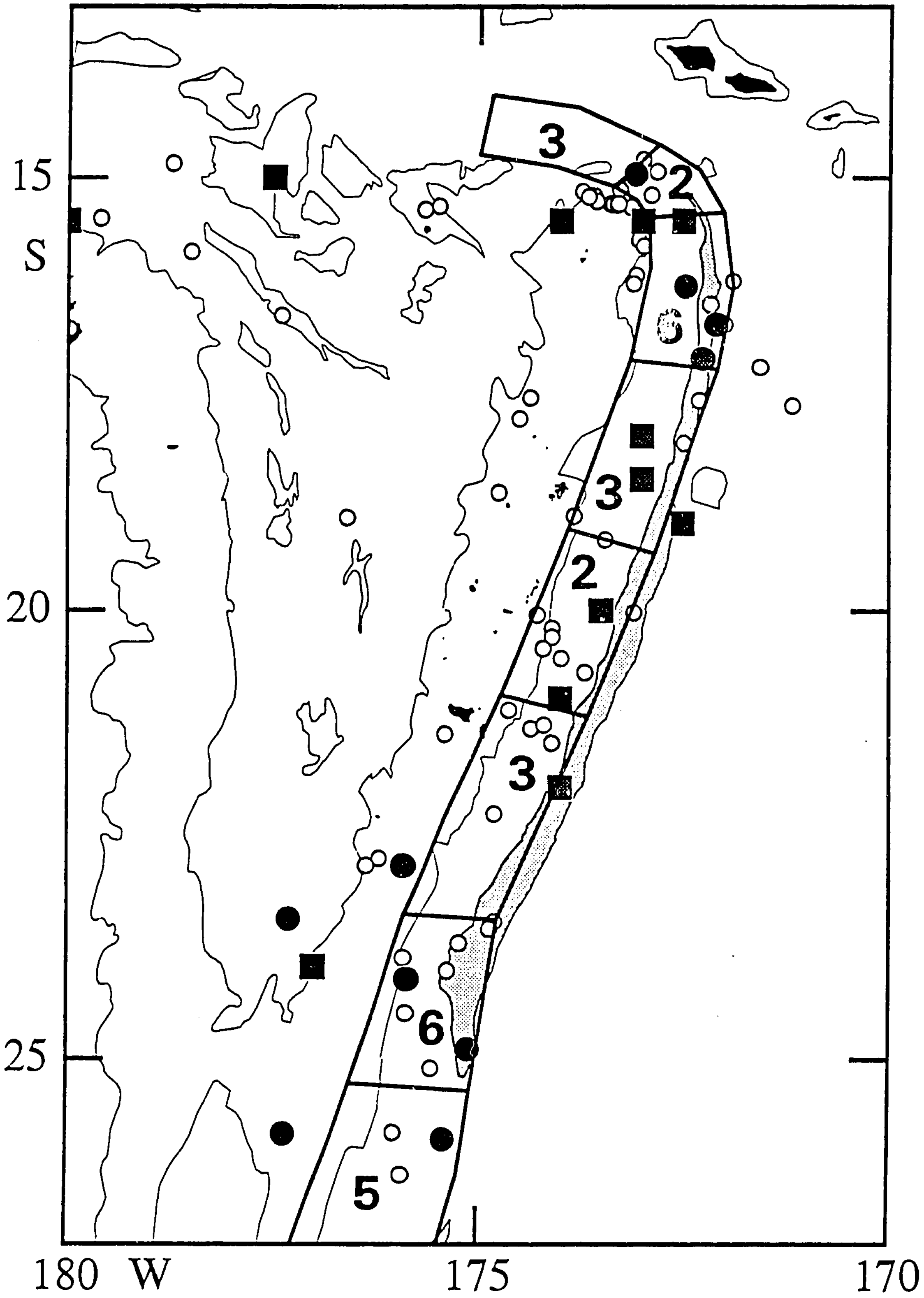


Figure 20. Assessment of seismic potential for the Tonga Arc by McCann (1980). On a scale of 1 to 6, the lower numbers represent regions of higher seismic potential for large earthquakes in the next few decades. These values are derived from studies of rupture zones of historical earthquakes.

emergence is the result of tectonic uplift or eustatic sea level fluctuations within the last several hundred thousand years (Taylor and Bloom, 1977). In any case, the tectonic uplift rate is lower than the Vanuatu (New Hebrides) arc where high tectonic uplift rates were obtained for this same period of time.

Earthquake Prediction

Wyss et al. (1984) have also studied the shallow Tongan seismicity in order to (1) identify areas of high 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. Areas of activity near Tongatapu and at the northern end of the Tonga Trench and quiescence near the Capricorn Seamount and the Louisville Ridge were identified. Based on their analyses, Wyss et al. (1984) propose that a "major asperity exists on the plate interface near 21°S and that future large ruptures may emanate from or terminate at this location."

The technique that Wyss et al. (1984) employed, detected a statistically significant reduction in the seismicity of the region around the June 1977 mainshock during the 2 years prior to the earthquake. Figure 21A shows the distribution of seismicity in the region of the June 1977 event between 1963 and 1970 and Figure 21B shows the quiescence of this region during the 2 years preceding the June 1977 earthquake (from Wyss et al., 1984). In the future, such observations may be critical to development of preparedness measures in areas of precursory seismicity signals. The work of Wyss et al. (1984) suggests that one way to update the estimate of seismic potential for the Tonga Arc is to monitor the significant changes in the rates of seismicity for the region. However, the rates of seismicity do not completely describe the nature of an asperity nor do they pinpoint when a large, destructive earthquake will occur. Because of the concentration of the population in Tongatapu, this is the most important region to understand in terms of earthquake hazard. The availability of continuous earthquake monitoring in Tonga is an important component of any such earthquake study.

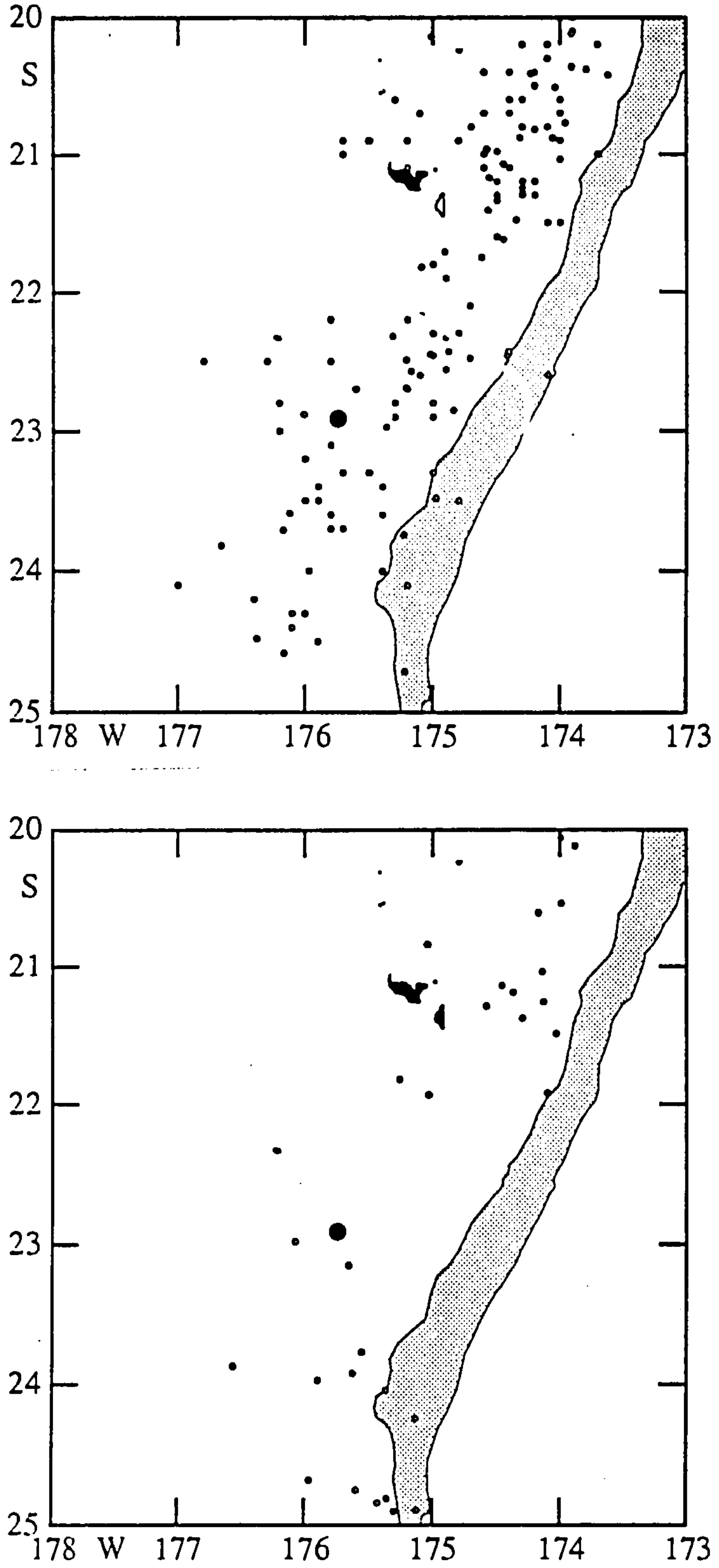


Figure 21. Seismicity maps of the Tonga arc segment between 20° and 25°S, surrounding the epicenter of the 1977 Tonga earthquake of M = 7.2 (filled circle). (A) Time period (June 1963 to July 1970) with relatively even distribution of seismicity density contrasts with (B) the precursory two year time period with a clear lack of earthquakes in the central segment of the map, around the 1977 mainshock epicenter (Wyss et al., 1984).

G. ASSESSMENT OF EARTHQUAKE HAZARD

Basis for Hazard Evaluation

Evaluation of the recurrence history of a particular region can be investigated using: (1) Teleseismically recorded instrumental history of earthquakes, (2) recurrence relations of smaller earthquakes recorded by seismograph networks; (3) preinstrumental historical records of large earthquakes; and (4) evidence of prehistoric large earthquakes observable in the geological record.

Seismotectonic Provinces

From our knowledge of the plate boundaries and shallow seismicity in the Tonga region, we have defined six major seismotectonic provinces that may have very different tectonic setting, seismic regime, and earthquake potential: (1) The northern end of the Tonga Trench, (2) the linear portion of the Tonga Trench, (3) the back-arc, (4) the Lau Basin, (5) the Lau Ridge, and (6) the Fiji Fracture Zone (Figure 22). The first province is characterized by the complex mixture of large thrust earthquakes associated with underthrusting of the Pacific Plate, tear-faulting earthquakes associated with the tearing of the Pacific Plate, and transform faulting along the Fiji Fracture Zone. This region is one of the most active seismogenic zones in the world, and exhibits high seismic potential. The linear portion of the plate boundary (segment 2) is characterized by large thrust-type earthquakes and is the source area for all great earthquakes along the arc. The character of seismic activity varies along the arc and allows us to further subdivide segment 2 into: (a) moderately active northern Tonga Trench, (b) active central Tonga Trench, (c) moderately active southern Tonga Trench with increasing activity to the south, (d) relatively quiescent Louisville Ridge segment, and (e) moderately active northern end of the Kermadec Trench. The third province, located behind the volcanic arc includes both shallow activity in the Tonga back-arc and deeper activity along the plate interface. Lack of depth resolution from teleseismic data prohibits us from discriminating these two very different source areas. Because of its proximity to the Tongan

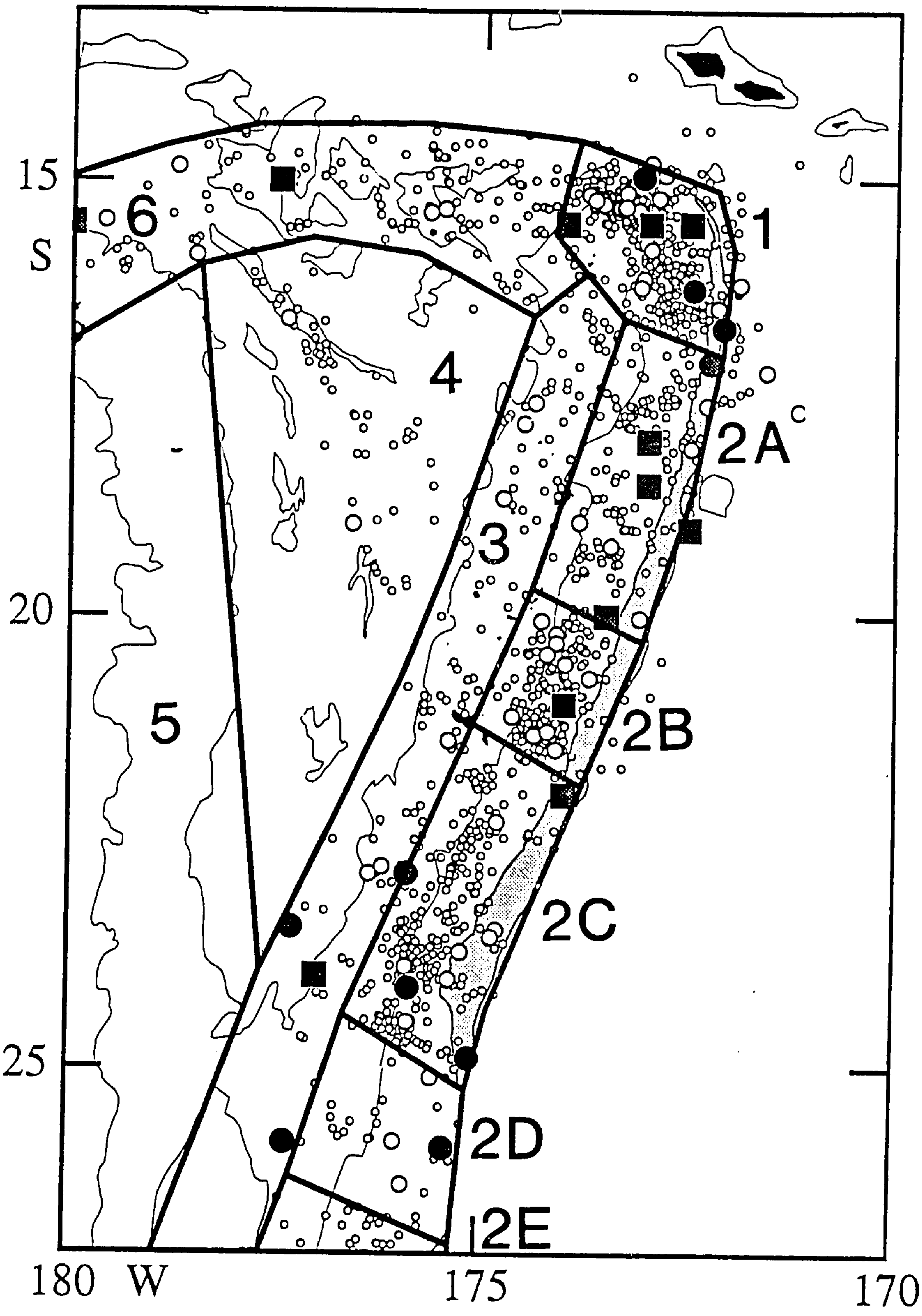


Figure 22. Shallow seismicity (h ≤ 70 km and $m_b \geq 5.8$) and seismotectonic provinces in Tonga: (1) "Samoa Corner" (2) Tonga Trench, (3) Back-arc, (4) Lau Basin, (5) Lau Ridge, and (6) Fiji Fracture Zone. Seismicity and morphology as in Figures 15 and 16. See text for description of individual zones.

islands, moderate to large earthquakes in province 3 are of particular concern for seismic hazard. The Lau Basin (province 4) contains shallow activity associated with the back- arc spreading taking place in that region. The Lau Ridge (province 5) is seismically quiet but small events are occasionally recorded there (Hamburger et al., in prep.). The Fiji Fracture Zone (province 6) is a region dominated by strike-slip faulting between the northern end of the Tonga Trench and Fiji.

We propose the following maximum sizes of earthquakes be considered for the provinces outlines in Figure 22 when considering a design earthquake for these regions. (1) Since tear-faulting occurs at this "Samoa Corner" and the historical record contains earthquakes of this magnitude for province 1, a great earthquake (M_s 8.3) is possible for this region. (2) The Tonga Arc (province 2) is really one tectonic unit and as such a great earthquake ($M_s = 8.3$) for sections 2a-2c and 2e is based on the historical record that earthquakes of this magnitude range have occurred in the past. However, in the region where the Louisville Ridge intersects the Tonga Trench, great earthquakes do not seem to occur, and a large earthquake (M_s = 7 3/4) may occur in section 2d. In any case, this region is also far from land and therefore represents less danger to the islands of Tonga than the other portions of province 2. (3) M_s = 7 1/4, similar to the 1977 earthquake, could occur in this back-arc region of province 3 as the result of deformation within the island arc. (4) The back-arc spreading in the Lau Basin could produce moderate (M_s = 6 1/2) earthquakes in province 4. (5) The Lau Ridge (province 5) is similar to intraplate and related area to the south and west, but the historical record does not indicate much activity. However, a moderate $M_s = 6$ could result from intraplate earthquakes in this region. A few small earthquakes have been recorded in Fiji from this region. (6) The Fiji Transform System (province 6) has the potential for a M_s = 7 1/2 earthquake. The historical record contains $M_s = 7.0$ events occurring along this boundary. Figure 23 summarizes the proposed provinces and the maximum magnitude earthquake that might be expected for each zone.

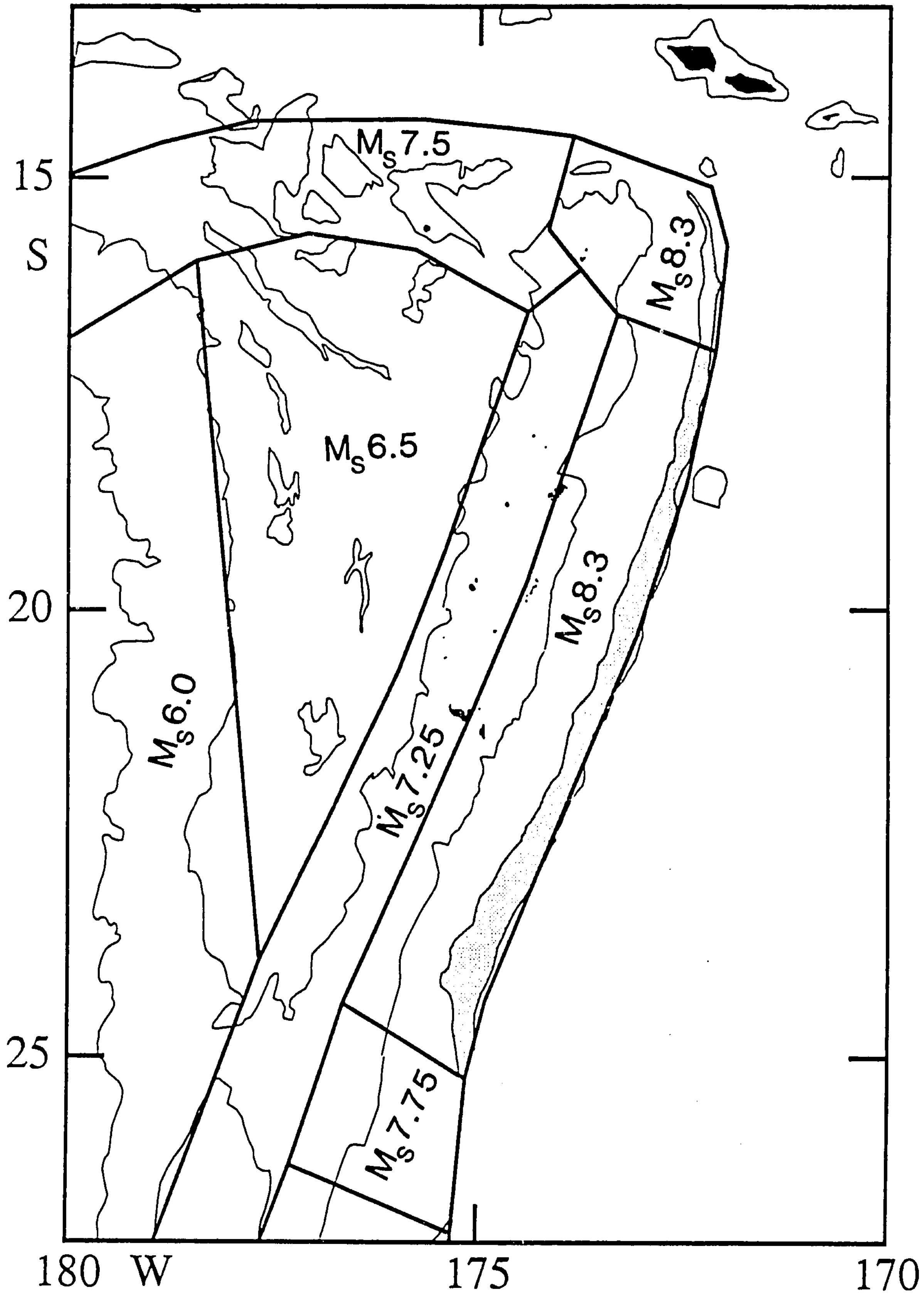


Figure 23. Seismic potential for the Tonga region. Maximum magnitude earthquake most likely to occur within each seismotectonic province described in Figure 22. Bathymetry as in Figures 15 and 16.

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 is accomplished by the consideration 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. 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 Tonga. 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 building 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 acceleration (PGA). Figure 24 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 acceleration 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

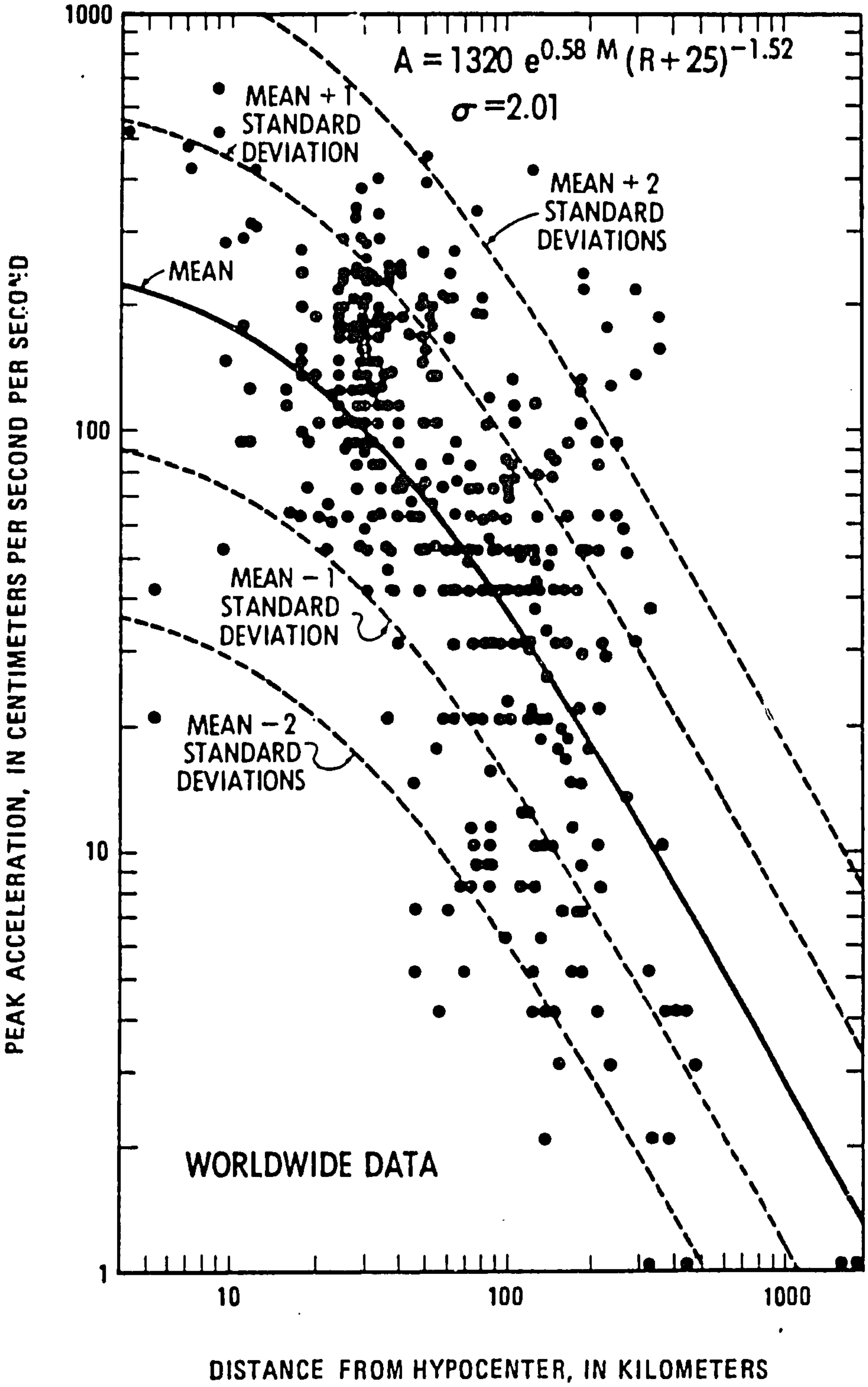


Figure 24. Relationship between acceleration and attenuation for worldwide earthquakes (from Hays, 1980).

acceleration and Modified Mercalli intensities have been developed (Table 1). Two of these proposed relationships are shown in Figure 25. For worldwide data, Murphy and O'Brien (1977) have proposed some statistical correlations between Modified Mercalli intensity values and ground accelerations (horizontal and vertical). The resultant relationships and the geometrical standard deviation (σ) are:

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

$$\log A_h = 0.24\, I_{mm} + 0.26 \qquad \sigma = 2.19$$

where A_v = peak vertical ground acceleration

A_h = peak horizontal ground acceleration

I_{mm} = Modified Mercalli intensity

Using only the relationship of earthquake intensities to distance and size of Fiji earthquakes Everingham (1984) has produced a plot for the Fiji region (Figure 26). Comparison of these values with results from studies in the eastern United States (Figure 27) indicate similar curves. Although the intensity values for Fiji may be lower than for values for a given Tonga distance (e.g. 22 June 1977 Tonga earthquake shown on Figure 26), the decreasing of the intensities with distance is evident.

Application to Earthquake Hazard

Scientists have reached different conclusions regarding the region near Tongatapu. The consensus is that it would seem most prudent to assume that a great thrust earthquake could occur at a shallow depth directly trenchward of Tongatapu; therefore, such an event is likely to occur in the future and recommendations should be made accordingly. The damage from such an event should be considered to be comparable with the devastation resulting from meteorological disturbances such as tropical cyclones.

Table 1. 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

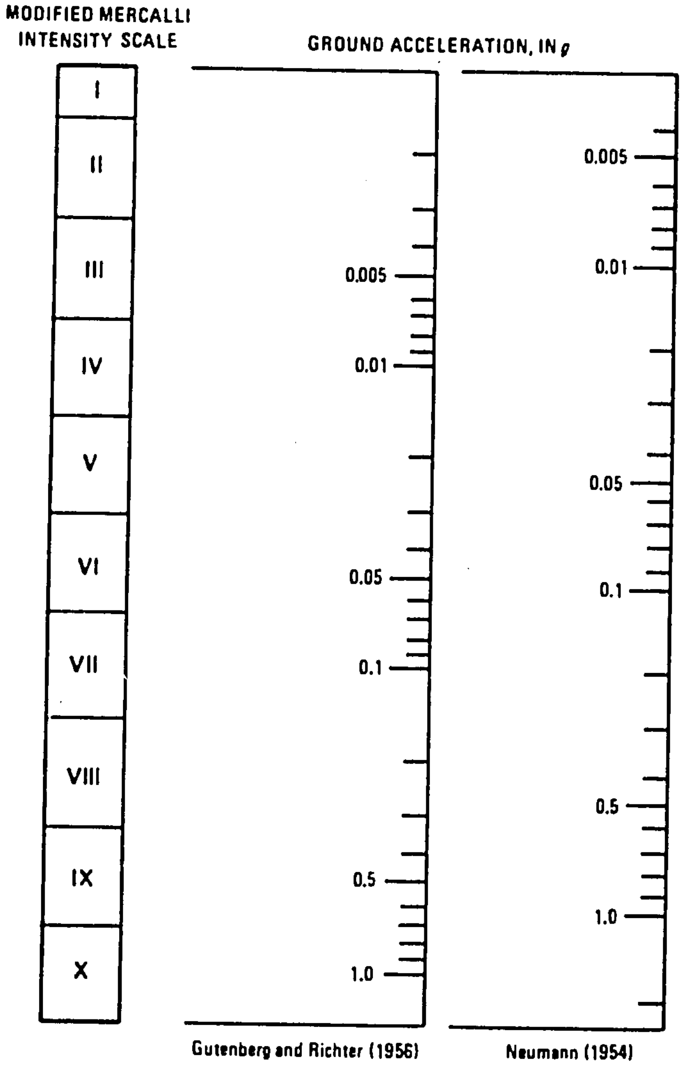


Figure 25. Proposed relationships between earthquake intensities and peak ground accelerations.

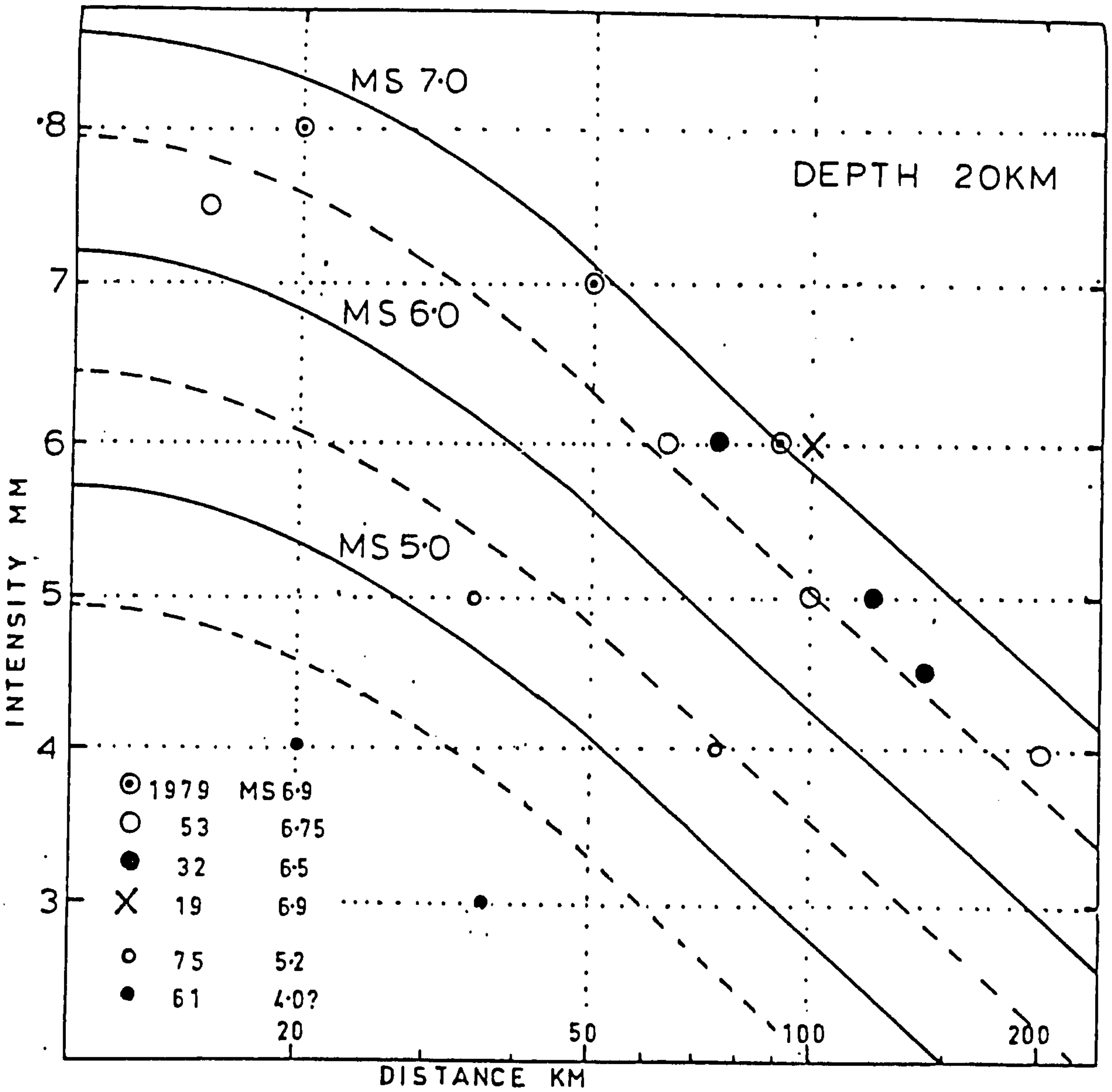


Figure 26. Earthquake intensities (Modified Mercalli) observed in Fiji as a function of magnitude and epicentral distance. From Everingham (1984).

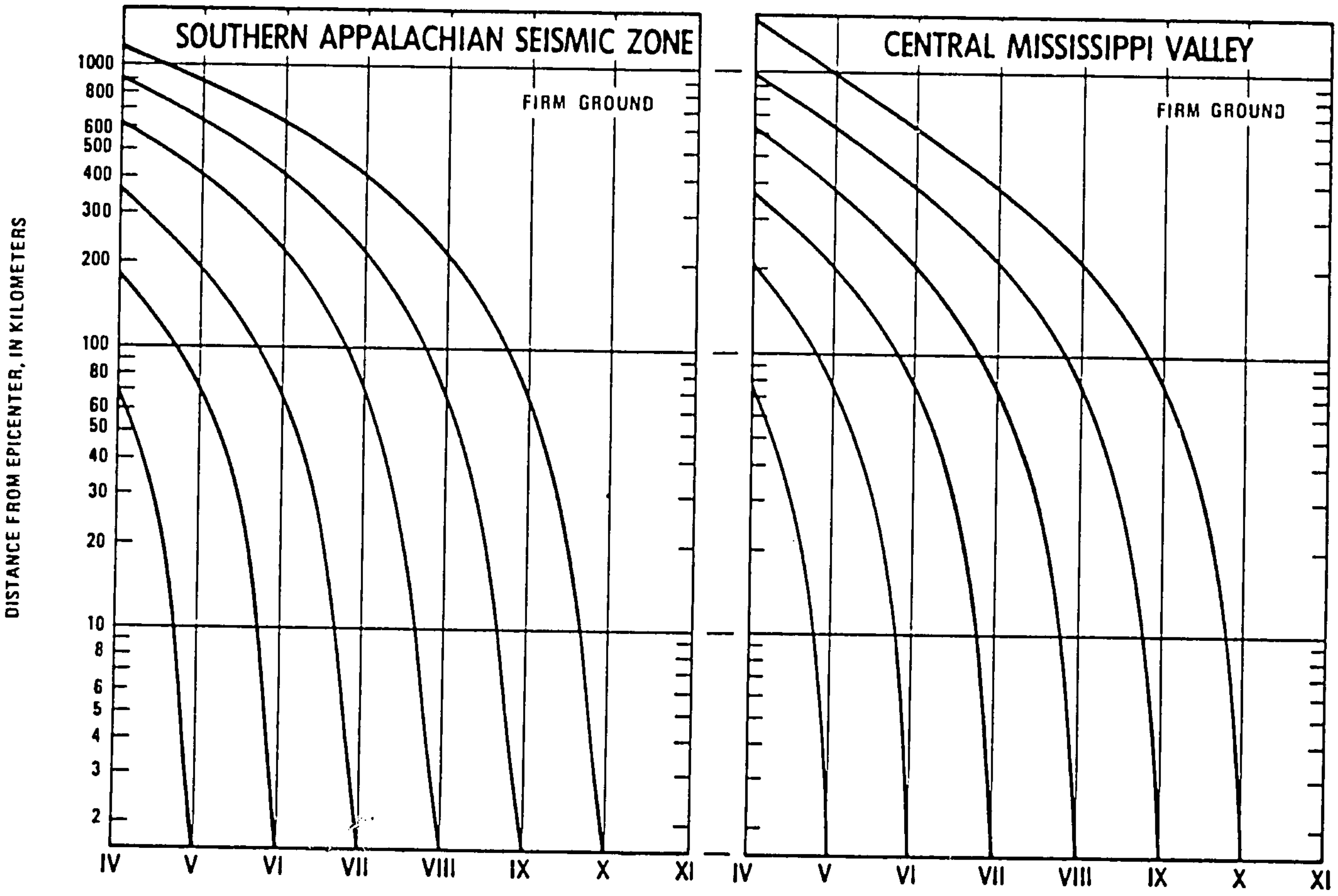


Figure 27. Empirical intensity—attenuation curves proposed from the Southern Appalachian seismic zone and the central Mississippi Valley (Hays, 1980).

Application to Tsunami Hazard

In addition to the direct damage from ground shaking in the vicinity of an earthquake, large earthquakes in the southwest Pacific can cause considerable damage, at both regional and global distances by earthquake-generated tsunamis. A tsunami education program for the residents of Tonga is recommended (Appendix III contains a listing of safety rules from the National Oceanic and Atmospheric Administration (NOAA) which operates the Pacific tsunami warning system in Hawaii, U.S.A.).

Application to Volcanic Hazard

Volcanic eruptions have occurred on the average every four years in Tonga since the beginning of the century. Most of these eruptions have been short-lived, lasting a few months to approximately a year (Bryan et al., 1972). Floating rafts of pumice can also cause disruption of local and regional shipping operations. However, general education is recommended concerning volcanic hazards since some people do live on the flanks of the active volcanoes (e.g. village of Fata'ulua on Niuafo'ou Island).

H. IMPLICATIONS FOR MITIGATION OF EARTHQUAKE RISK

Several important steps should be taken to significantly mitigate the loss of life and property from future earthquakes in Tonga. 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 emergency food, water and equipment stores in many households; and importantly, they have helped avoid panic during an earthquake and promoted cooperation with government officials following such a disaster. Earthquake education programs are effectively combined with other disaster preparedness programs (e.g., hurricanes, 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 the fronts of shelves. Heavy objects that could tip over (such as hot water heaters and gas tanks) can be fastened with anchoring bands. This restraint is especially a concern with gas tanks which could fall over, rupture lines, and result in fire.

Building Codes

Second, adoption of stringent building codes for Tonga is imperative. The experience of the 1977 earthquake (Campbell et al., 1977) demonstrates the severe effects of an earthquake at some distance from Tongatapu. The engineering study following the earthquake concluded that much of the damage resulted from inadequate construction of buildings on Tongatapu and Eua. There is a very real danger of a devastating great earthquake occurring very close to Tongatapu; 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 Tongatapu. Observation of such codes is most crucial for public multistory buildings in the major towns of Tongatapu, Ha'apai, and Vava'u. As important as the design of such buildings is 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.

Emergency Civil Defense Procedures

Third, Civil Defense plans for emergency procedures following an earthquake or tsunami should be developed. Of 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 under the National Disaster Committee. 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 and perhaps most important of these steps for mitigating earthquake risk, long-term seismicity and strong motion observations should be continued or implemented. In the long-term, such information will help to refine estimates of seismic potential along the Tongan plate boundary; they will help to more directly and accurately assess the ground motion parameters of direct concern to engineers for building design in Tonga--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 Tonga's population.

International Cooperation

Fifth, international cooperation among the island countries of the Southwest Pacific may significantly help in Tonga's earthquake preparedness program. All of the countries affected by earthquakes (Tonga, Western Samoa, Fiji, Vanuatu, Solomon Islands, Papua New Guinea, and New Zealand) have to varying degrees developed earthquake preparedness programs. Tonga may take advantage of the previous, current, and any future efforts of the other countries in the region.

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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 liquefaction.

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 300 km depth. **Deep** earthquakes refer to those with depths greater than 300 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 **seismic gaps**. 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 **forecast**. 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 **prediction**.

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.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. 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.

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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.

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. 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.

APPENDIX IV: 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

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 af 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.

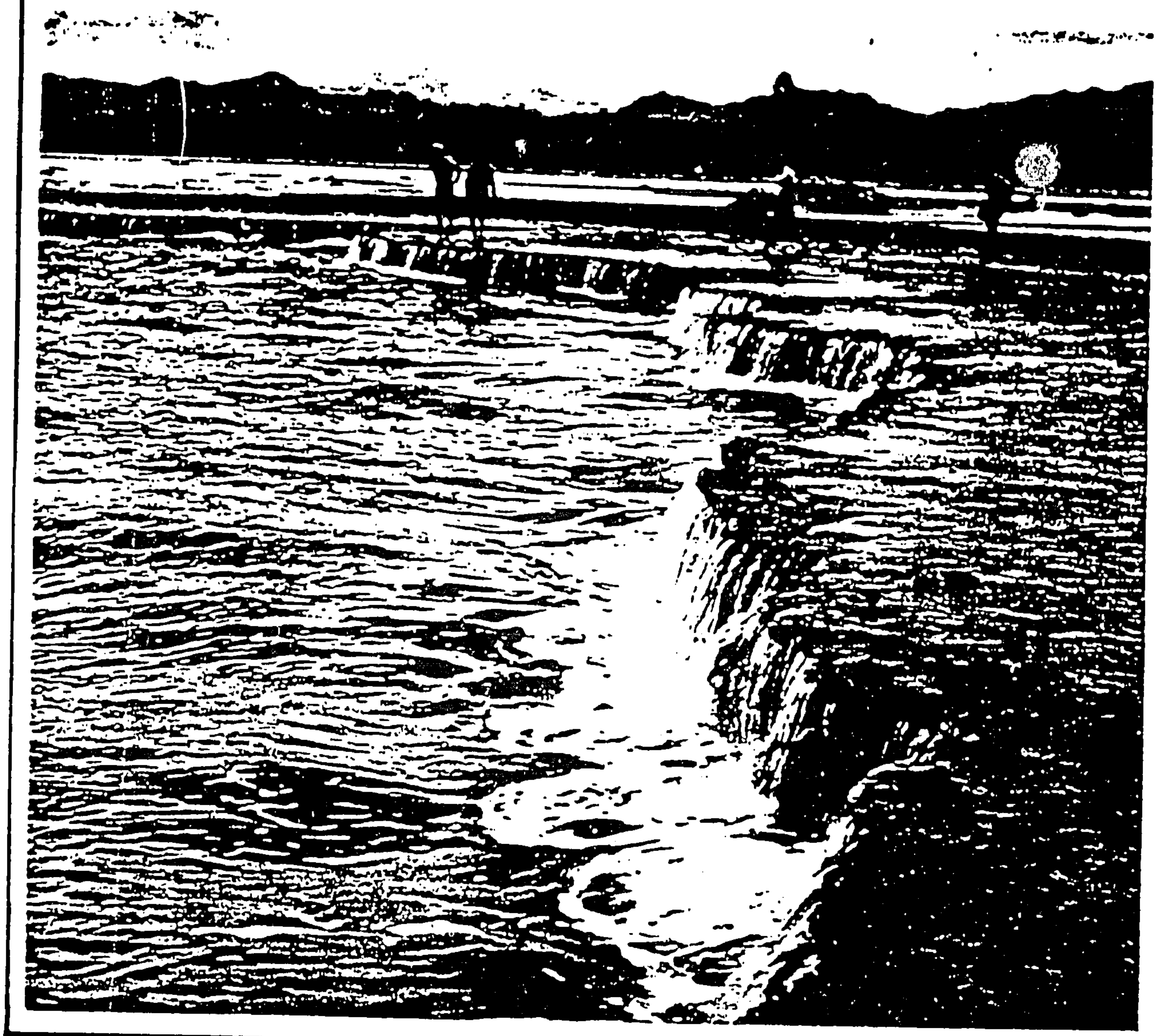
2. A tsunami is not a single wave, but a series of waves. Stay out of danger areas until an "all-clear" is issued by a competent authority.

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 ....

....

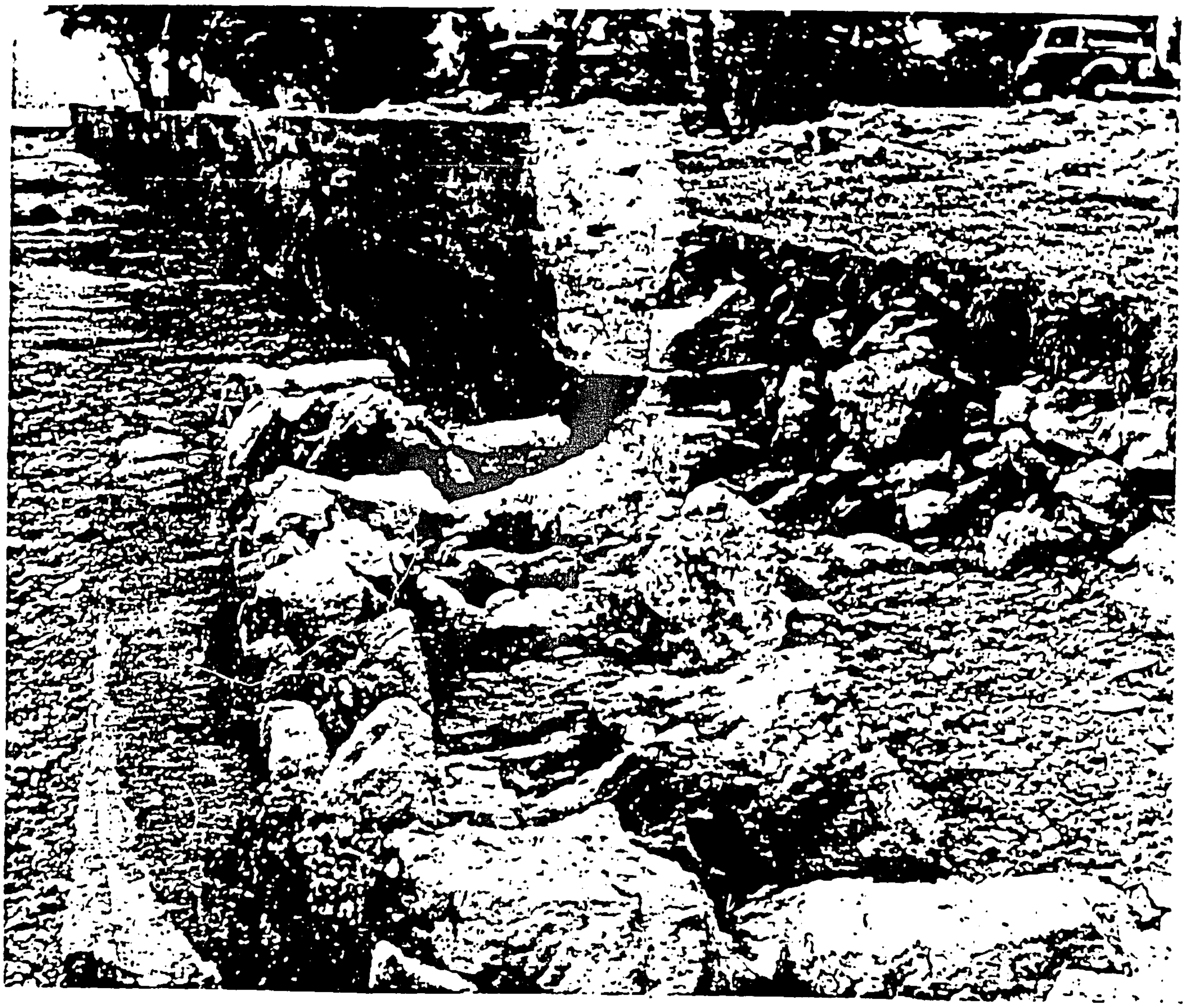
Name: ....Address: ....

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

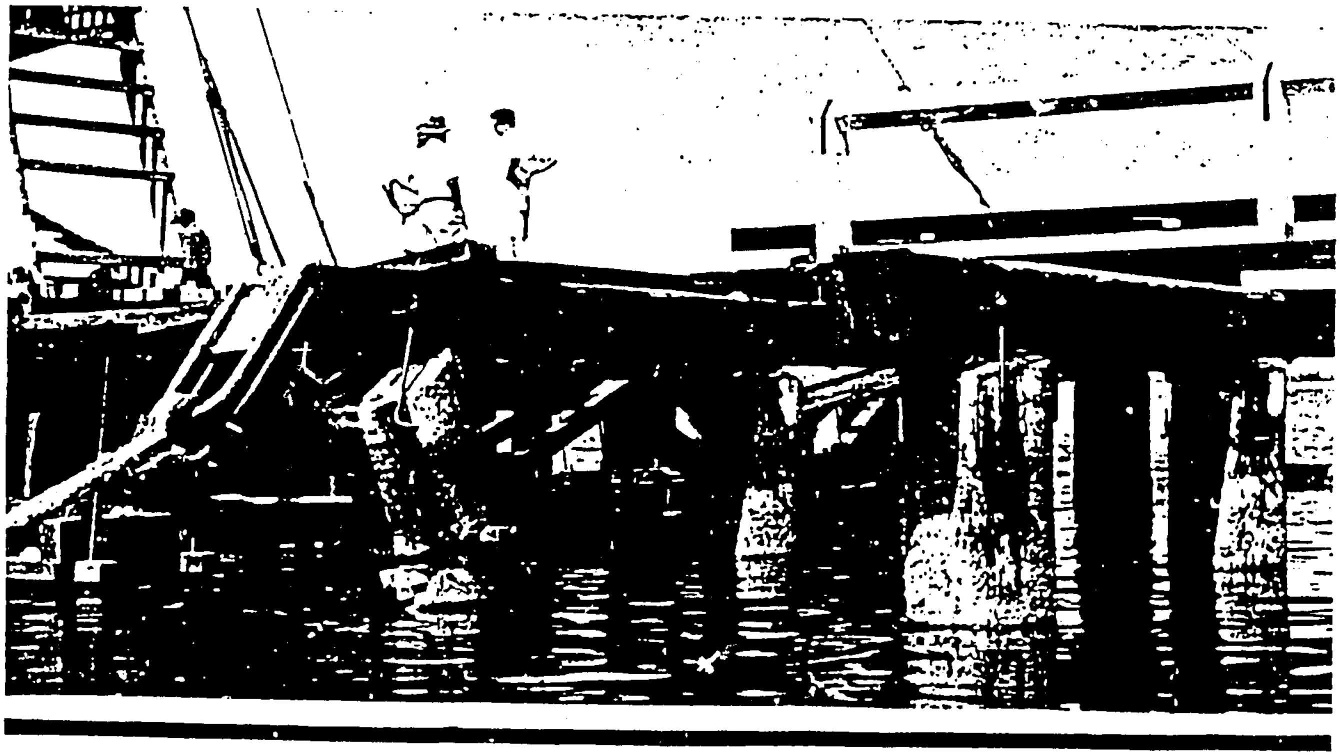
The Director of Mineral Development,
Mineral Resources Division,
Private Bag,
GPO, SUVA

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

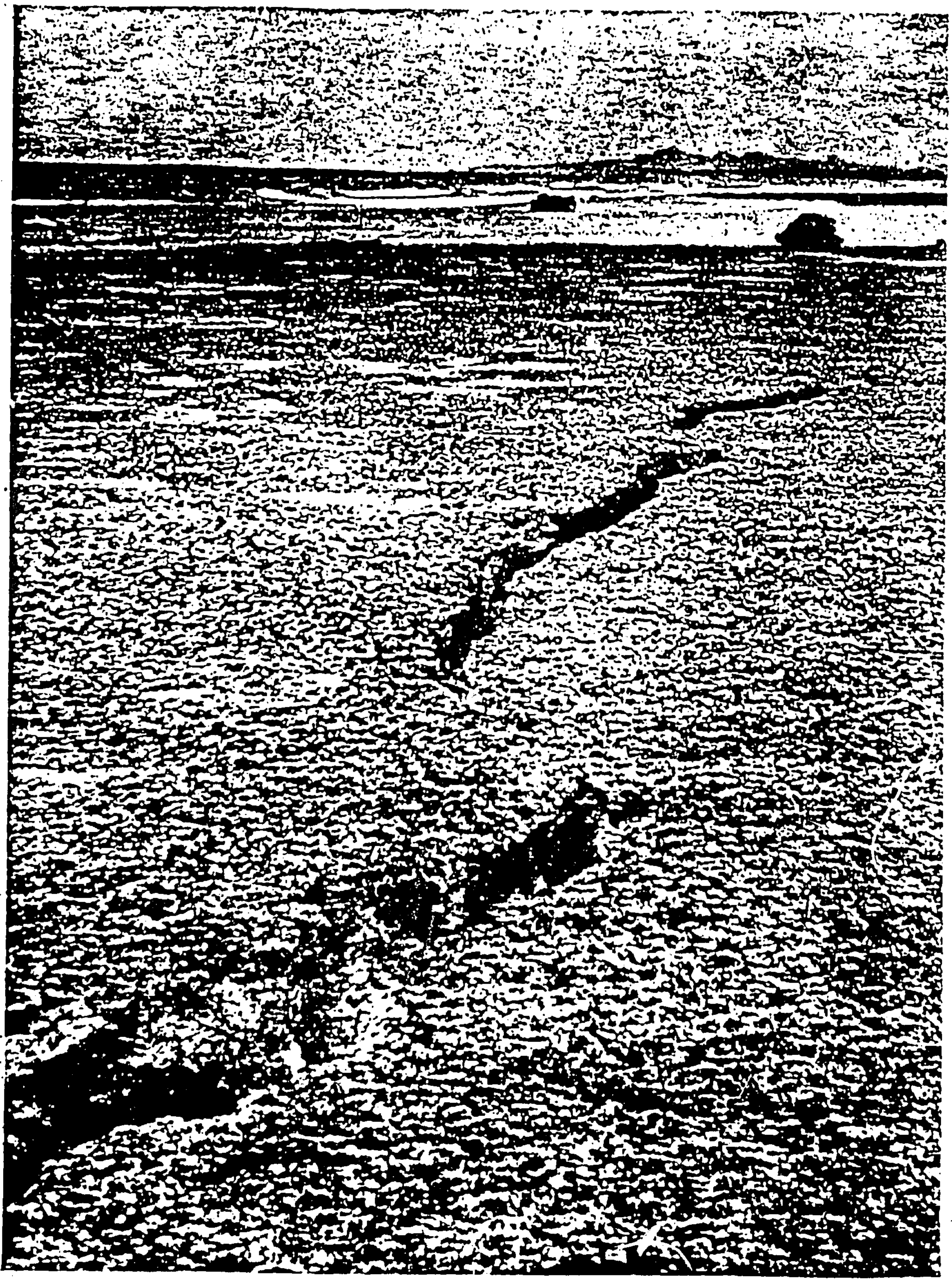
(JANUARY 1976)



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 V: 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 earth quakes, 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. 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 (see Figure A1). 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 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-

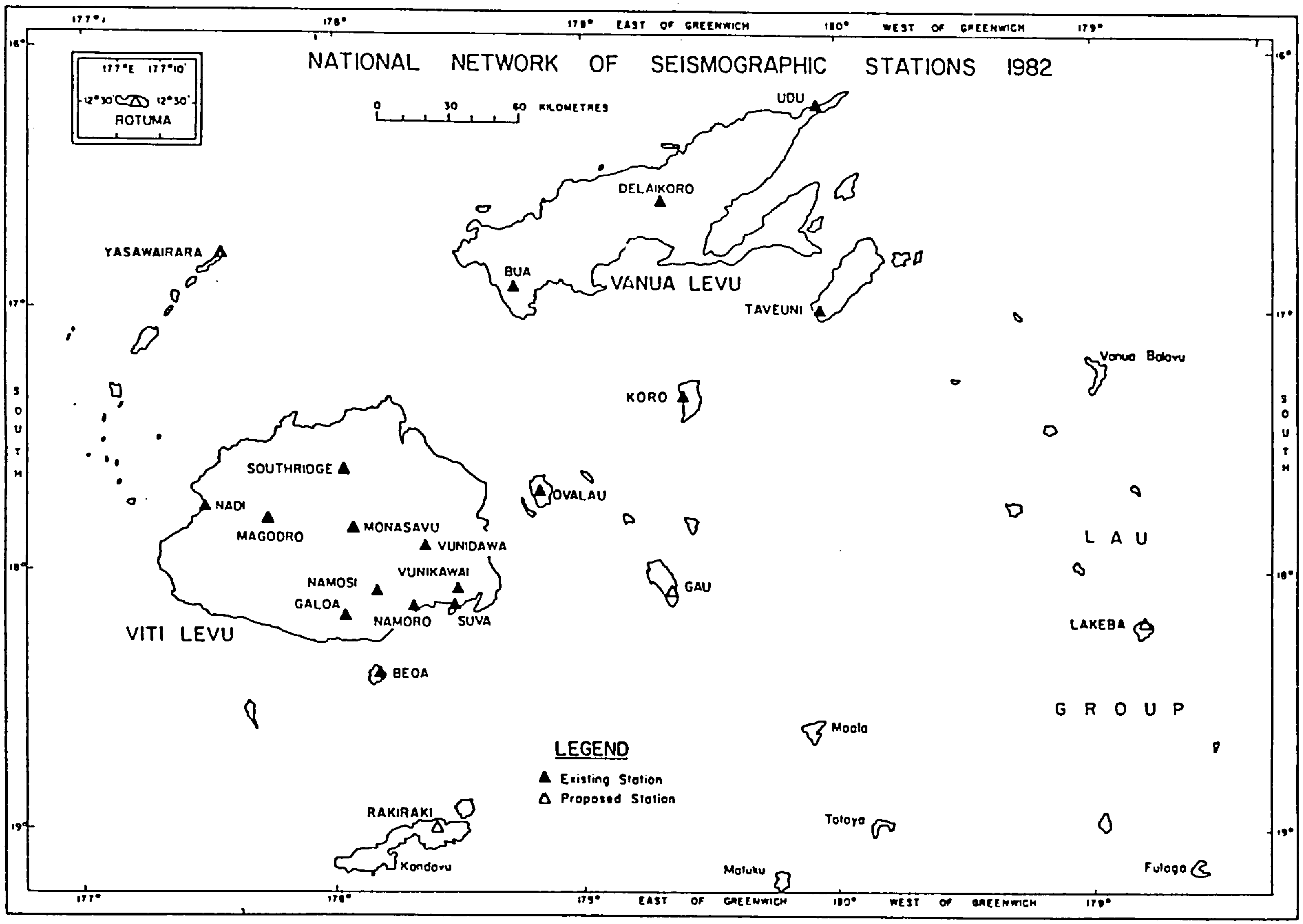


Figure A1. Network of seismic stations in Fiji, established through the assistance of U.S. A.I.D. and Japanese aid programs.

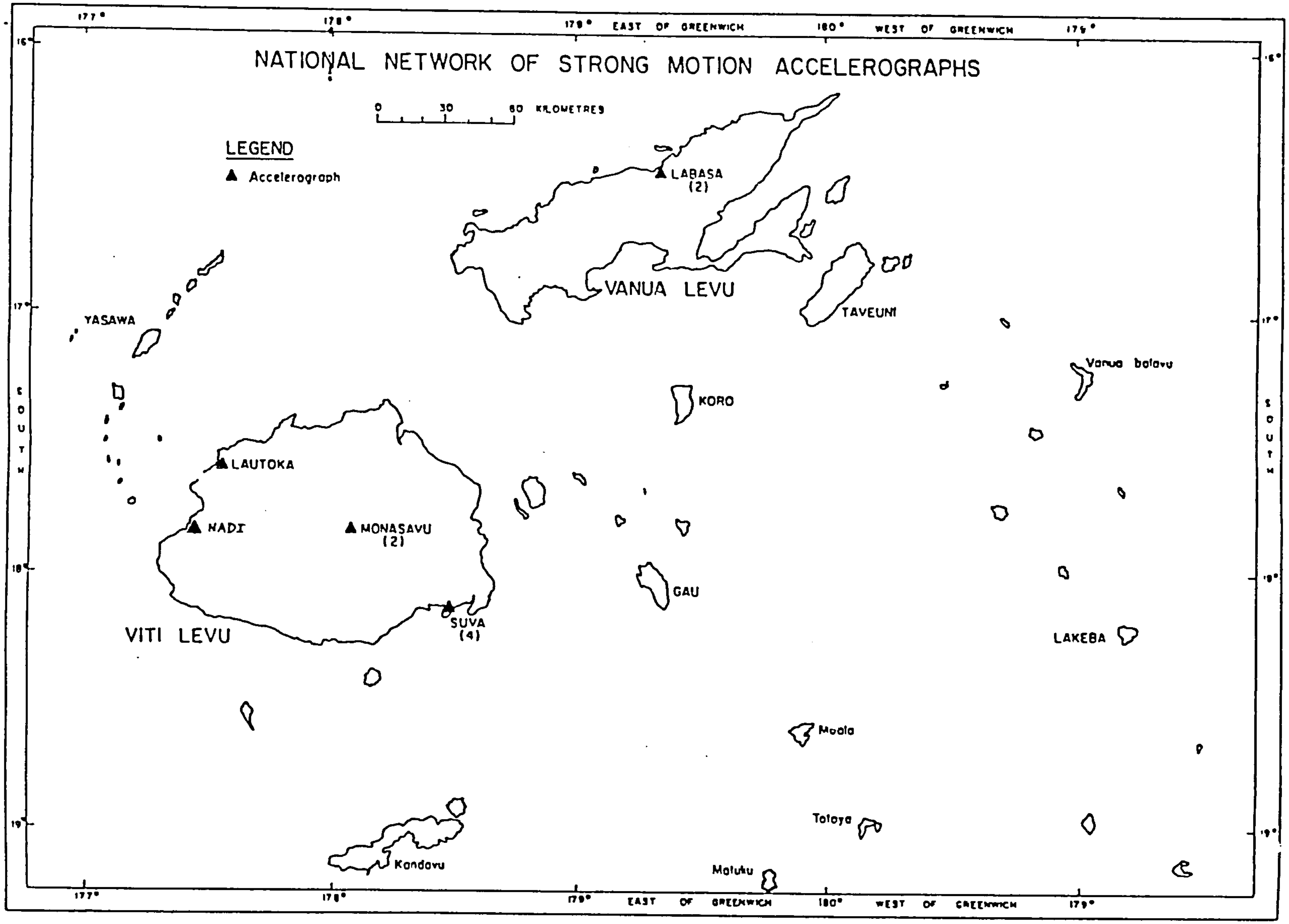


Figure A2. Location of strong-motion accelerographs in Fiji. Some revision of these locations is likely within the next year.

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.

VANUATU

Seismological Facilities

Seismic stations in Vanuatu were first established 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 Luganville, Santo operated through 1980. A third station on Tanna Island (INH) operated through 1978. Cornell's cooperative field programs with ORSTOM began in 1976 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 A3); to date, over 17,000 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. These seismological facilities are complemented by studies of ground deformation using seven bubble-level tiltmeters, a two-component long-baseline water tube tiltmeter, and two levelling arrays.

Strong Motion Accelerographs

As part of the present program of seismic hazard evaluation in Vanuatu, Cornell has installed five strong motion accelerographs on the islands of Efate, Malekula and Santo (Figure A3). These instruments have already been triggered by five moderate-sized shallow events, and will be used to provide a basis for predicting 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. We are hoping that coverage of this network will be expanded in the next year.

Related Scientific 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. Recently 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. A detailed hydrographic survey was carried out in coastal waters by Australian researchers. In addition, proton-precession magnetometers are maintained by Queensland University (Australia) researchers. A tide gauge is maintained by the ORSTOM mission in Port Vila.

Critical Facilities

Port Vila, with a population of under 20,000, is the administrative and commercial center of the country. There are a number of multistory buildings in the capital, and most of Vanuatu's small tourist industry is located 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. 5000). It remains an important economic center for the country, with agricultural

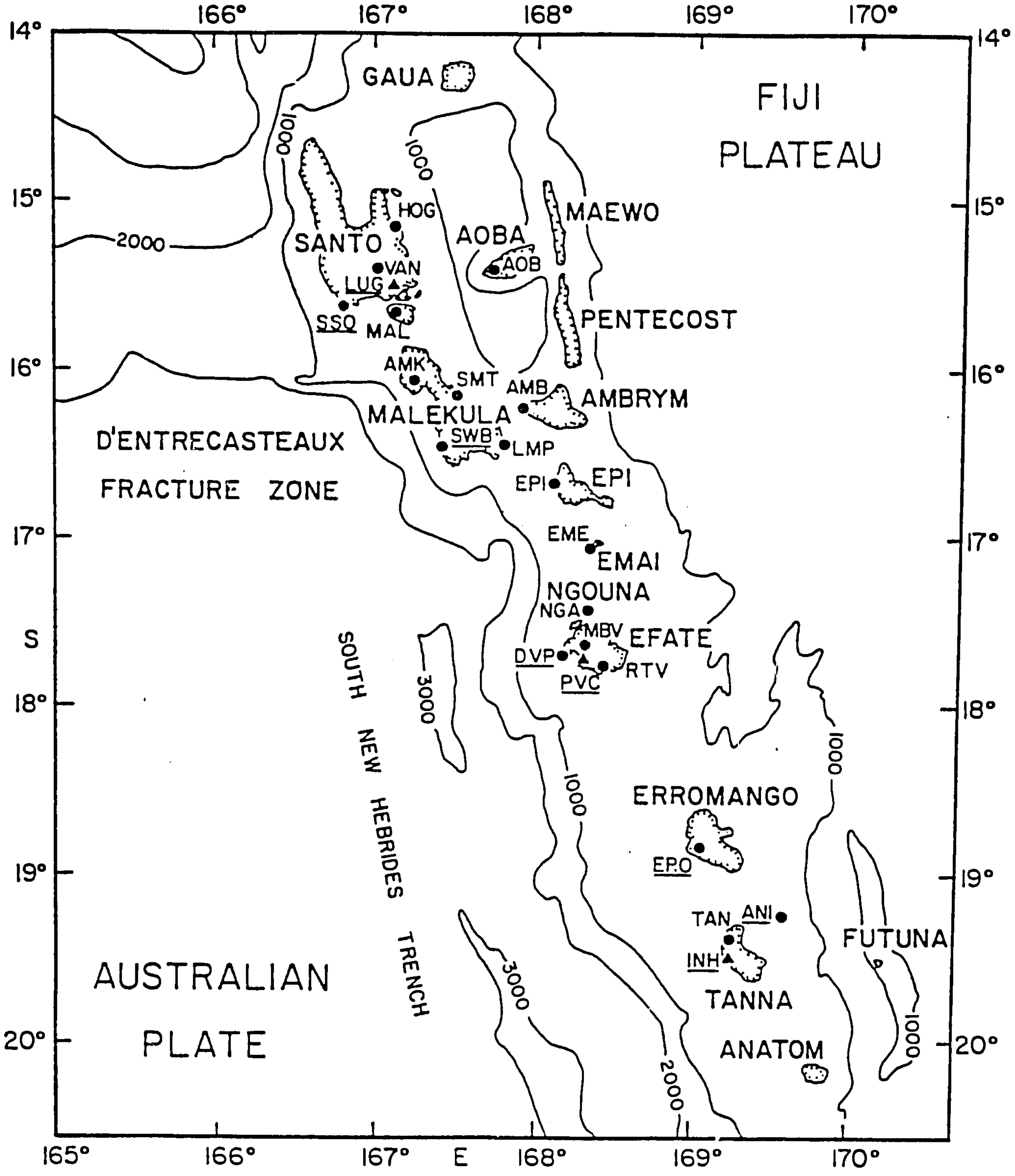


Figure A3. Map showing the seismograph stations in Vanuatu. Circles are stations telemetered to the base station PVC on Efate island, and underlined stations have two components—one horizontal and one vertical. The triangles are older ORSTOM stations. INH and LUG are no longer operational. Strong motion instruments are located at SWB and LMP on Malekula island, DVP and PVC on Efate island, and LUG on Santo island.

processing and shipping facilities located there. There are several three- and four-story buildings in the center of Luganville. There was significant damage to buildings, wharves and bridges in Luganville, following the 1965 Santo earthquake.

Earthquake Preparedness Programs

Disaster preparedness is the responsibility of the Ministry of Home Affairs; a revised Rescue Plan has been adopted since independence. They are responsible for damage assessment and coordination of emergency relief efforts by other ministries and public agencies.

There are presently no building codes enforced in Vanuatu. At present, the government has 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 their 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 project in Vanuatu. Materials have been prepared by ORSTOM seismologists for distribution to teachers, public officials and planners involved in earthquake hazards.

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 assistance 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 A4). 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 operates 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 A4). 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.

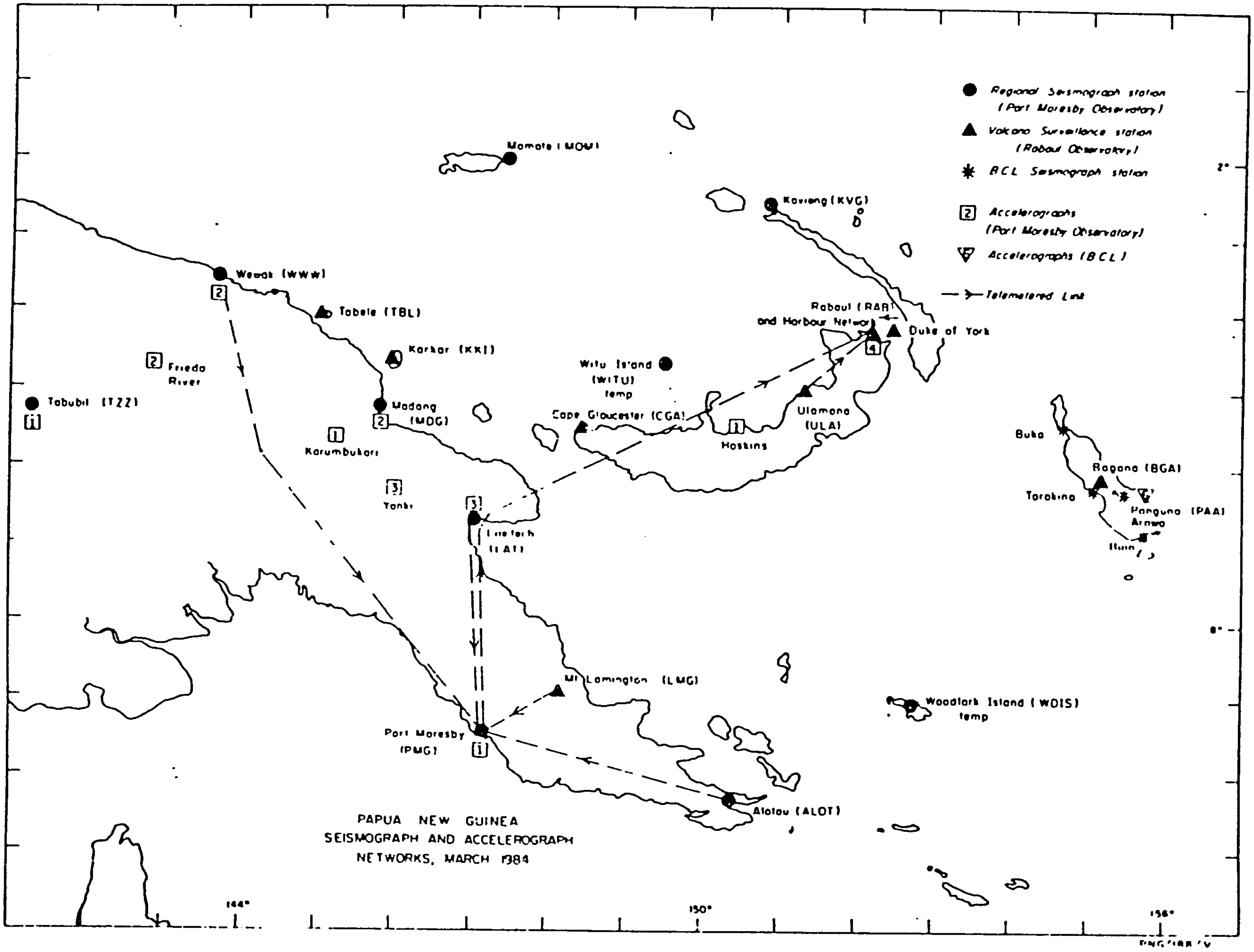


Figure A4. Papua New Guinea seismograph and accelerograph networks.

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 A5). 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 national standard seismograph network, presently consisting of thirty short-period stations, is shown in Figure A6. The network routinely locates all earthquakes of ML > 3.8 within New Zealand, and earthquakes with Ms > 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.

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 Observatory 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.

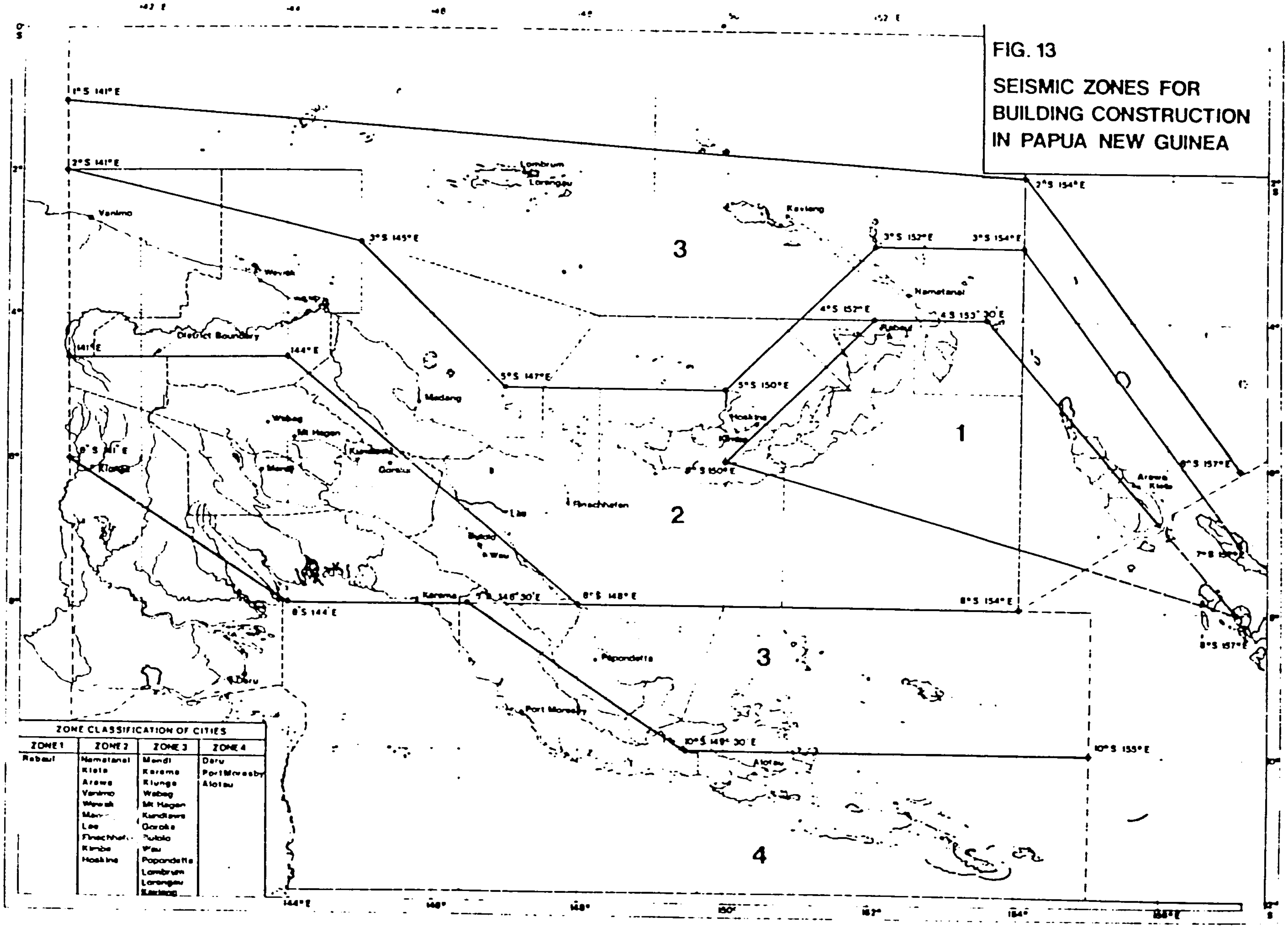


FIG. 13

SEISMIC ZONES FOR BUILDING CONSTRUCTION IN PAPUA NEW GUINEA

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 A5. Seismic zones for building construction in Papua New Guinea. From Jury et al. (1982).

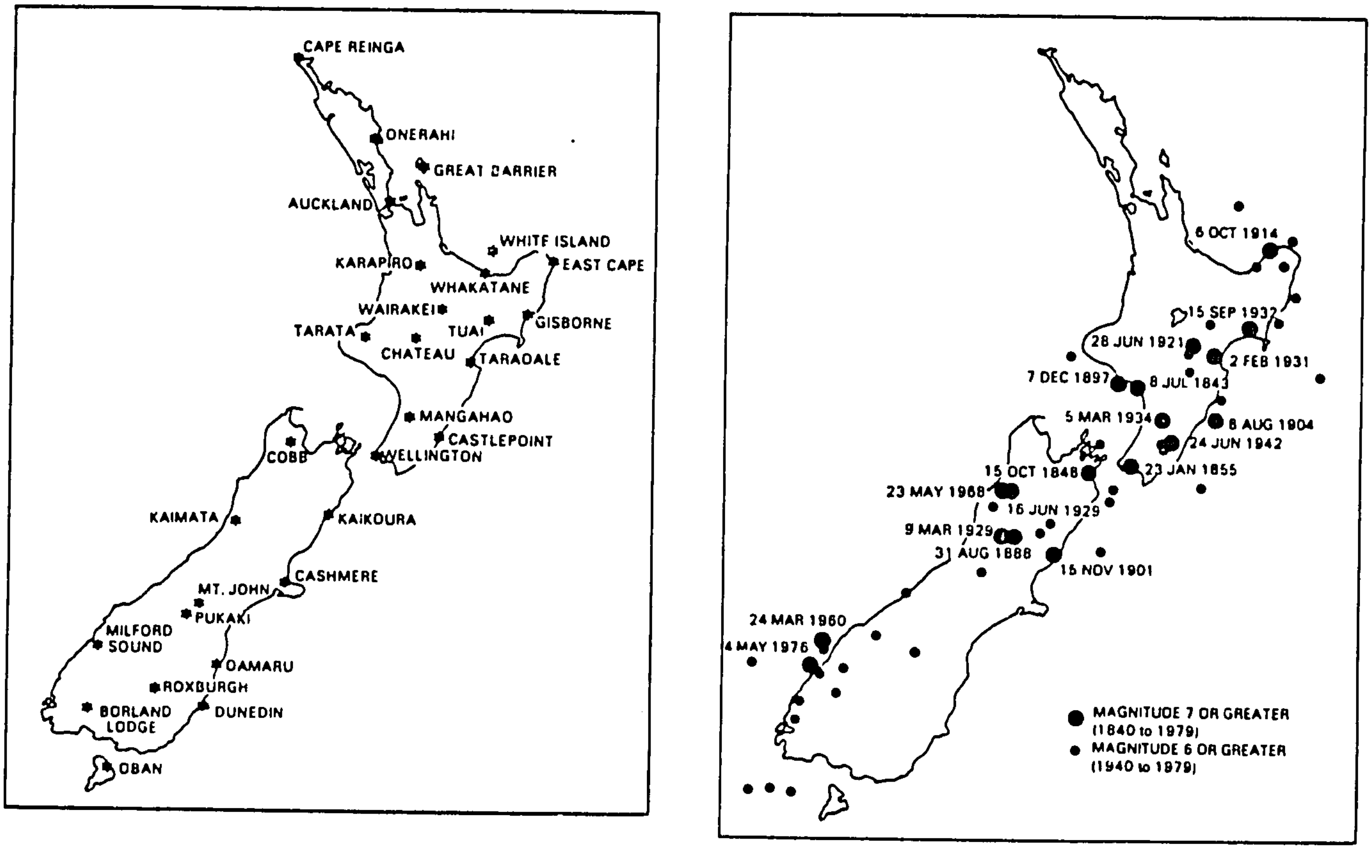


Figure A6. Seismograph stations of the national network (left) and the distribution of large, shallow earthquakes (right) in New Zealand. From Seismological Observatory, Wellington (1980).

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 ML > 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.

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INFORMATION CONTACTS

FIJI

A. Rahamin	Director, Mineral Resources Dept.
A. Simpson	Asst. Director (MRD)
R. Holmes	Princ. Geol. Offshore/Seismol. (MRD)
P. Rodda	Princ. Geol. Inform. Services (MRD)
R. Singh	Principal Geophysicist (MRD)
I. Everingham	Senior Seismologist (MRD)
K. Draunidalo	Seismologist (MRD)
G. Shorten	Senior Engineering Geologist (MRD)
M. Mehrotra	Struc. Engr., Suva City Council
J. Booth	Civil Engineer, Suva
J. Campbell	Engineering Geologist, A. Gibb & Partners (Monasavu)
R. Carter	Marine Geologist (CCOP/SOPAC)
R. Byrne	Marine Geologist (CCOP/SOPAC)
G. Gauss	Marine Geologist (CCOP/SOPAC)
D. Rubin	Marine Geologist (CCOP/SOPAC)

TONGA

S. Tongilava	Superintendent of Lands, Surveys and Natural Resources
D. Tappin	Government Geologist (LSNR)
S. Lemoto	Land Assessor (LSNR)
T. Tukia	Government Planner (LSNR)

VANUATU

C. Clarke	Director, Dept. Mines, Geology and Rural Water Supplies
R. Campillo	Director, ORSTOM Mission
R. Foy	Engineer, ORSTOM
L. Mollard	Engineer, ORSTOM
T. Lee	Civil Engineer, Public Work Dept.
J. Récy	Director, ORSTOM, Dept. Geol. and Geophys. (Nouméa)
J. Chatelain	Seismologist, ORSTOM (Nouméa)
R. Prévot	Seismologist, ORSTOM (Nouméa)

WESTERN SAMOA

L. Ioane	Director, Apia Observatory
S. Iosa	Senior Seismologist (AO)
A. Titimaea	Geologist (AO)

SOLOMON ISLANDS

S. Danitofea	Chief Geologist, Ministry of Lands, Energy and Natural Resources
D. Tuni	Senior Seismologist (MLENR)
R. Walshaw	Senior Geologist (MLENR)
J. Vunagi	Ministry of Home Affairs and National Development
D. Gwynn	Civil Engineer, Public Works Department

PAPUA NEW GUINEA

K. Doble	Chief Geologist, Geological Survey
I. Ripper	Chief Seismologist, Geophysical Observatory
G. Seidel	Information Officer, Volcanological Observatory
G. Anderson	Engineering Geologist, Geological Survey
J. Wilkins	Civil Engineer, Dept. of Works and Supply

NEW ZEALAND

W. Smith	Director, Seismological Observatory, Wellington

UNITED STATES

M. Hamnett	Pacific Islands Development Program
G. Burton	Director, Pacific Tsunami Warning Center
R. Sillcox	Seismologist (PTWC)
G. Pararis-Corayannis	Director, International Tsunami Information Center
G. Greene	Branch of Pacific Marine Geology (USGS)

APPENDIX VI: TONGA EARTHQUAKES ($m_b \geq 5.8$) in SOUTHWEST PACIFIC CATALOG

DATE	TIME	LAT (°S)	LON (°W)	DEPTH	m_b	NO. OF STATIONS	M_s
64/10/ 9	21:34: 9.2	16.20	171.90	33	5.8	40	
64/11/18	22:21: 1.9	20.20	174.10	33	5.8	47	
65/ 1/ 5	18: 5:58.6	20.30	174.10	33	6.0	40	6.8PAS
65/ 3/22	2:44:47.5	15.30	173.40	51	5.9	46	6.5PAS
65/ 8/20	21:21:51.5	22.80	176.20	79	6.1	58	5.8BRK
66/ 6/ 1	11:47:32.7	23.50	174.80	22	5.8	54	
67/ 1/ 1	7: 5:50.2	15.16	173.74	40D	6.0	170	6.6PAS
67/ 1/19	12:40:15.1	14.84	178.74	33N	6.3	70	6.8MSH
67/ 2/17	10:10:51.6	23.74	175.23	19D	6.2	210	6.5PAS
67/ 6/14	5: 6:16.3	15.20	173.60	11	5.9	61	
67/12/27	16:22:48.5	22.30	174.80	33	6.1	78	
69/ 1/29	17:44:31.1	17.20	171.57	33N	6.0	109	5.6MSH
70/ 1/20	7:19:51.2	25.80	177.35	80	6.5	175	7.3PAS
70/ 7/16	21:17:44.2	19.19	173.45	33N	5.8	66	6.0MSH
71/ 3/23	2:15:26.9	22.88	176.36	76D	6.0	112	6.1PAS
71/ 9/10	6:28:51.1	20.43	174.21	33N	5.8	84	5.8MSH
72/ 2/12	18:51:57.0	15.31	173.37	5	5.9	73	5.7MSH
72/ 3/ 1	9: 4:41.7	18.92	173.83	33N	5.8	66	5.3MSH
72/ 4/ 2	9: 1:23.8	16.13	173.08	33N	5.9	96	5.8MSH
72/ 8/ 7	9:24:14.7	16.65	172.10	33D	5.8	74	6.0MSH
72/ 9/ 9	2:44: 3.1	15.37	175.67	35	5.9	52	6.1MSH
72/ 9/27	9: 1:43.8	16.47	172.17	33N	5.9	94	6.0MSH
72/ 9/29	6:37:35.3	21.13	174.63	33N	5.8	55	5.7MSH
73/ 2/16	4:51: 1.4	15.31	173.32	50D	5.8	56	5.2MSH
73/ 8/ 5	15:47:32.9	16.23	173.11	33N	6.1	132	5.7MSH
74/ 3/18	10:56:12.4	14.93	172.83	27D	5.9	101	6.0MSH
74/ 4/27	7:24:54.0	26.25	175.91	45D	6.1	148	5.9MSH
74/ 7/ 2	23:26:26.6	29.08	175.95	33N	6.8	115	7.2MSH
74/ 7/ 3	23:25: 9.3	29.12	176.11	33N	6.2	109	6.6MSH
74/ 7/18	11: 4:43.2	15.22	173.59	33N	5.9	89	5.8MSH
74/11/10	4:25:31.8	15.86	178.51	33	5.8	76	6.1MSH
75/ 9/24	1:47:49.7	20.54	173.99	33N	6.1	79	6.5MSZ
75/10/11	14:35:15.0	24.89	175.12	9	7.0	113	7.8MSZ
75/10/11	14:55: 0.3	24.04	175.37	33N	6.1	34	
75/12/ 9	9:14:40.6	14.79	173.00	33N	6.0	90	6.2MSZ
75/12/26	15:56:38.7	16.26	172.47	33N	6.4	149	7.8MSZ
76/ 1/ 1	1:29:39.6	28.61	177.64	59	6.2	78	6.9PAS
76/ 1/14	15:56:34.9	29.21	177.89	69	6.3	53	7.7PAS
76/ 1/14	16:47:33.5	28.43	177.66	33N	6.5	43	8.0MSZ
76/ 1/24	21:48:25.9	28.63	177.59	78	6.2	97	5.8BRK
76/ 3/24	4:46: 4.4	29.89	177.87	33	6.4	274	6.8MSZ
76/ 5/ 5	4:52:51.0	29.93	177.84	35	6.2	132	6.8MSZ
77/ 4/ 2	7:15:22.7	16.70	172.10	33N	6.8	181	7.6MSZ
77/ 6/22	12: 8:33.4	22.88	175.90	65	6.8	331	7.2BRK
77/ 7/24	6:22:51.3	15.34	173.15	33N	6.0	191	6.2MSZ
77/ 8/11	1:42:47.5	17.56	174.37	57	6.3	170	6.4PAS
77/10/10	11:53:53.6	25.86	175.41	33N	6.6	151	7.2MSZ
77/10/14	4:55:34.8	15.72	173.05	33N	5.9	248	5.7MSZ

DATE	TIME	LAT (°S)	LON (°W)	DEPTH	m_b	NO. OF STATIONS	M_s
78/ 6/17	15:11:33.5	17.10	172.26	33N	6.6	180	7.0MSZ
78/ 7/ 2	4: 1:33.3	15.33	175.49	25	5.9	124	6.4MSZ
79/ 1/25	4: 8:14.2	29.94	177.46	14	6.0	285	6.4MSZ
79/ 6/25	11: 1:12.1	20.02	173.10	42	5.9	254	5.3MSZ
79/11/13	20:43:38.8	23.58	174.86	32D	6.5	153	6.6MSZ
79/11/16	15:21:25.7	16.76	179.98	33N	6.1	117	6.9MSZ
79/11/24	19:19: 4.3	18.94	176.59	33N	5.8	132	6.2MSZ
80/ 2/ 3	11:58:39.8	17.65	171.18	33N	6.2	148	6.4MSZ
80/ 4/13	18: 4:31.9	23.47	177.30	79	6.7	170	7.2PAS
80/ 5/27	13: 1:34.8	18.65	174.75	33N	6.1	223	
80/ 6/18	10:49:10.0	15.27	173.57	43D	5.9	156	6.5MSZ
80/ 6/19	8:31:38.7	29.96	177.99	51D	6.1	126	6.4BRK
80/ 7/14	16:15: 1.7	29.27	177.15	49	5.8	84	6.6MSZ
80/ 8/24	20:10: 4.2	15.22	173.67	39D	6.0	117	6.2MSZ
80/12/15	8:12:45.4	17.59	172.30	33N	6.1	134	6.3MSZ
80/12/19	2:57:57.4	21.34	174.36	33N	5.9	88	6.1MSZ
81/ 8/25	7:16:58.4	22.89	175.85	33N	5.9	167	5.7MS
81/ 9/ 1	7:23: 2.1	15.14	173.29	33N	5.8	130	5.7MS
81/ 9/ 1	9:29:31.5	14.96	173.09	25G	7.0	248	7.7MS
81/ 9/25	14:30:53.4	29.97	178.01	45D	5.9	175	5.9MS
81/11/ 4	14:38:10.7	20.05	174.28	33N	6.3	258	6.0MS
81/12/24	5:33:[illegible]0.7	29.97	177.61	28D	6.0	264	6.8MS
81/12/26	17: 5:32.5	29.93	177.74	33N	6.1	248	7.1MS
82/ 3/ 7	15:41:57.1	25.10	175.57	37D	5.9	157	5.7MS
82/ 3/29	12:20:26.7	15.47	179.61	33N	5.8	136	6.3MS
82/ 4/16	14: 4:51.2	15.79	172.99	33N	6.0	184	6.0MS
82/ 5/ 2	11:19:38.0	29.32	177.15	25	6.0	155	6.5MS
82/ 6/ 2	12:37:34.5	18.08	172.49	33N	6.4	313	6.4MS
82/12/19	17:43:54.8	24.13	175.86	33N	5.9	104	7.7MS
82/12/20	5:54:37.3	24.50	175.87	32D	5.8	125	5.9MS
83/ 1/ 8	11:21:29.5	15.39	173.33	33N	6.1	267	6.3PAS
83/ 2/ 7	18:23:16.6	29.71	177.84	52D	6.0	265	5.9
83/ 2/17	16:10:39.1	21.59	174.18	32D	5.8	101	5.5
83/ 3/21	7:44:17.7	21.47	175.45	68D	6.3	315	0.0
83/ 4/10	2:20:39.9	17.85	174.50	33N	5.8	61	5.4
83/ 4/24	3:29:17.5	23.98	175.96	29	5.9	202	5.5BRK
83/ 4/30	2:51:43.3	21.35	174.25	23D	5.8	217	5.6
83/ 8/30	8:50:17.1	16.71	172.08	39D	6.0	298	5.7
83/ 9/17	12:11:42.7	16.64	177.48	33N	6.1	211	6.5
83/10/17	13:25:21.1	20.79	173.76	30D	6.0	171	6.3
83/12/ 3	1:23:55.3	15.24	172.91	33N	6.0	204	6.0
84/ 9/28	0:03:34.5	25.84	175.91	21	6.4	387	6.8