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

A COUNTRY REPORT: FIJI

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EXECUTIVE SUMMARY

Overall Program

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

Summary of Work Completed

(A) Historical Earthquakes in Fiji. The majority of the large earthquakes reported in the last 130 years occurred along the tectonic boundaries that surround the Fiji Platform. However, a large number of significant earthquakes occurred within the platform, including the damaging 1953 Suva and 1979 Taveuni earthquakes. The magnitudes of these events are all less than 7.1, suggesting that the thin lithosphere of the Fiji region is incapable of storing sufficient stress to result in great earthquakes.

(B) Teleseismically Located Earthquakes. A new compilation of earthquakes located by the global seismic network is used to constrain the activity of the plate boundaries surrounding the Fiji Platform: the Fiji Fracture Zone to the north, the West Viti Levu zone to the west, the Hunter Fracture Zone to the south, and the northwestern edge of the Lau Basin to the northeast.

(C) Tripartite Seismic Network, 1966-1969. The first microearthquake study of Fiji used a three-station network of seismic stations on the main islands of Viti Levu and Vanua Levu. These microearthquakes show the same distribution of seismicity to the northeast, north, and west of the Fiji Platform as the teleseismic data. Scattered seismicity is observed in areas within the platform, previously thought to be aseismic.

(D) Fiji Telemetered Seismic Network, 1979-1985. The nineteen-station national seismic network of Fiji has operated for over six years and provides the bulk of the data for this research program. Over 5000 events were recorded by the network, of which approximately 1800 earthquakes were located. Microearthquakes are located both along the edges of and within the Fiji Platform. The "interplate" zones that surround the platform are continuously active at moderate magnitudes, while the "intraplate" earthquakes within the platform occur more sporadically, separated by long periods of quiescence.
(E) **Earthquake Depths.** The dense seismic network in southern Viti Levu accurately constrains earthquake focal depths. They are uniformly shallow, concentrated in the upper 18 km of Fiji's crust. The distribution is similar to other areas of extension and strike-slip deformation.

(F) **Earthquakes within Viti Levu.** Earthquakes located in the central portion of the island may be related to rapid doming of the island. A group of events near Monasavu Reservoir were induced by rapid filling of a large artificial lake. Earthquakes in southeastern Viti Levu occur in discrete nests that are tightly clustered in space and time. They are related to a series of near-vertical east- to northeast-striking faults that cut the Mio-Pliocene rocks of southeastern Viti Levu.

(G) **Earthquake Focal Mechanisms.** A new focal mechanism for the 1953 Suva earthquake, combined with mechanisms for microearthquakes within and near Viti Levu, suggest the predominance of strike-slip faulting along northwest- or northeast-striking fault planes. The stress direction orientation is similar to that observed throughout the Fiji region, and indicates that the Platform is not isolated, in a tectonic sense, from the remainder of the interarc region of the Southwest Pacific.

**Earthquake Recurrence Intervals**

Two studies of magnitude-frequency relations for the Fiji region suggest similar recurrence intervals for large earthquakes near Fiji: earthquakes of magnitude 7 or greater are expected every 15 - 21 years, while events of magnitude 6.5 or greater are expected every 2 1/2 - 6 years.

**Earthquake Potential**

The earthquake potential is not uniform throughout the Fiji region. We have subdivided the Fiji region into four zones of seismic potential, based on the available seismicity data. **Zone I** includes the Fiji Fracture Zone, Taveuni-northeast Vanua Levu zone, West Viti Levu zone and the western Lau Basin and is conservatively assigned a maximum magnitude of 7.5. **Zone II** includes the Kadavu Island region, the Hunter Fracture Zone, the Baravi and Suva basins, and the Koro Sea. The maximum magnitude assigned to this zone is 7.0; however recurrence intervals may be considerably larger than in Zone I. **Zone III** includes central and eastern Viti Levu, Ovalau Island, and Vatu-Ira Channel, and is assigned a maximum magnitude of 6.5. **Zone IV** includes northern and western Viti Levu, the Bligh Water Basin, northern Vanua Levu, the South Fiji Basin, and the Lau Ridge. These areas have been virtually devoid of seismic activity on all time and magnitude scales. Because of their proximity to the zones of active tectonism, a conservative maximum magnitude of 6.0 has been assigned.

**Macroseismic Effects of Large Earthquakes**

Based on the maximum probable earthquakes assigned to each of the seismic zones, we have predicted maximum intensity of ground shaking at 14 population centers and islands within Fiji. These predictions are based on extrapolations from observed intensity data, and are intended to serve as a
general guideline to identify areas of higher and lower risk. The highest intensities from earthquakes occurring in Zone I are projected for Taveuni Island and the Yasawa Group (MM 9-10); somewhat lower intensity (8) is predicted for Labasa, Savusavu, and Koro. Earthquakes occurring within Zone II are capable of producing high intensities (8-9) at Suva, Sigatoka, Labasa, Savusavu, Koro, Kadavu, and Taveuni. Slightly lower intensities (8) are predicted for Nadi, Monasavu, and Ovalau. Earthquakes within Zone III are capable of producing MM8 shaking in Suva, Monasavu, Sigatoka, and Ovalau; slightly lower values (7-8) are projected for Lautoka, Nadi and Ba. Intensities predicted for Zone IV are all less than MM8.

Tsunami Hazard

The history of earthquake-generated tsunamis in Fiji documents a very real hazard to Fiji’s population. Tsunamis are of particular concern because of the concentration of population in low-lying coastal areas. While tsunamis are not generated by all earthquakes, they must be considered a possible effect of all major earthquakes that occur in submarine areas that surround the Fiji Platform. Real-time monitoring of seismic activity, combined with an active tsunami education program, could significantly aid in tsunami risk mitigation.

Volcanic Hazard

Quaternary volcanic activity is far less prevalent in Fiji than elsewhere in the Southwest Pacific. There is no historical record of volcanic eruptions in Fiji. The evidence for prehistoric volcanism on Taveuni Island warrants continuous seismic monitoring of activity there.

Conclusions and Recommendations

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

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

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

Normally, public attention focuses on emergency and rescue operations once a disaster has taken place. While little can be done to prevent earthquakes or volcanic eruptions from occurring, significant steps may be taken to minimize the destructive effects of such disasters. Scientists are striving to better understand what causes these phenomena and to learn what measures might be taken to mitigate their destructive nature. This report is a summary of the available scientific data that help constrain the potential for destructive earthquakes that may affect the populated areas of Fiji. The report is by no means the final analysis of earthquake hazards to Fiji; it is, however, a well documented synthesis of all available seismic information that provides a basis for judicious engineering, planning, and civil defense decisions in the years to come. Definitions of some of the technical terms that will appear in this report are contained in Appendix I.
The ultimate aim of earthquake risk programs—mitigation of human and economic losses due to earthquakes—involves prediction of the frequency of occurrence and intensity of strong ground motion produced by future earthquakes of specific magnitudes in the vicinity of any given site. These predictions are often summarized in the form of seismic zoning maps and microzonation, which give the spatial distributions of the following parameters: maximum intensity of shaking, engineering design codes, maximum acceleration of ground motion (velocity, displacement) for given return periods of earthquakes of a particular size, or seismic risk (which relates to the expected human and property losses from earthquakes). In this report, we focus on the fundamental seismological observations that will provide the basis for more applied engineering studies of earthquake risk to Fiji.

Evaluation of Seismic Hazard

The seismic hazard in any region is a function of the frequency of occurrence and magnitude of earthquakes, as well as the proximity of the earthquake foci to population and industrial centers. Fiji is located close to the major seismic zones of the Southwest Pacific (Figure 1); the area has an instrumental history of earthquakes with magnitudes greater than 7.0.

Although the country is not heavily populated or industrialized, its proximity to major seismic zones leaves it particularly vulnerable to the risk of earthquake damage. The capital city of Suva 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.
Figure 1A. 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, volcanoes and plate motions are taken from Circum-Pacific Council for Energy and Mineral Resources (1981).
Figure 1B. Moderate to large shallow earthquakes ($M_s \geq 5.0$) in the Southwest Pacific, for the period 1964-1977. Map is at same scale as Figure 1A for comparison. Data are taken from Circum-Pacific Council for Energy and Mineral Resources (1981).
Past disaster associated loss of life in the Fiji has been relatively limited, but the increasing urban concentration and industrial development raises the potential human and economic losses brought on by a large earthquake occurring in the immediate vicinity. These losses are usually the result of the collapse of man-made structures, and can be substantially reduced by adequate engineering precautions.

The 1953 Suva Earthquake

The most significant event in Fiji's seismic history is the large 1953 Suva earthquake. This event, with a magnitude of $M_s = 6.75$, was the most destructive in Fiji's history. The earthquake occurred within 30 km of the capital city of Suva and produced extensive damage throughout southern Viti Levu. Intensities reach MM VII (Modified Mercalli Index; see Appendices I and II) along 40 km of the island's coast; landslides were triggered over an area of approximately 2380 km$^2$ along the southern coast and extending nearly 20 km inland (Houtz, 1962a). A major tsunami was triggered by the earthquake, reaching 4.3 meters height on the island of Kadavu, 100 km south of the epicenter. The earthquake and tsunami resulted in 8 deaths, 12 serious injuries and over £250,000 in property damage. The event also triggered turbidity currents along the shelf south of Viti Levu that damaged communication cables at distances to 100 km from the epicenter (Houtz and Wellman, 1962).

At the time of the earthquake, Suva's population was only 35,000, and development consisted entirely of low-rise structures. Since that time, Suva has grown to over 100,000 population, and has established itself as the major regional center for commerce, shipping, tourism, education, and administration. Multistory building is widespread in the city, and urban development has rapidly extended to outlying areas. Clearly, a repetition
of the Suva earthquake is of major concern to Fiji's Government planners. The seismic risk related to a recurrence of an event of this size (or larger) far outweighs the potential effects of an earthquake along any of the other seismogenic zones near Fiji.

The earthquake has been of considerable interest from a seismotectonic perspective as well: it took place, like a small number of other historical events, directly within the platform on which the Fiji Islands reside. Much of the well-documented seismic activity has occurred along the boundaries of the Fiji block (Hamburger and Everingham, 1986). The cause of the large and infrequent events that take place within the platform has remained a tectonic enigma. A major goal of these seismological investigations has been to comprehend the tectonic causes for such unusual and extremely hazardous earthquakes that occur close to and within the Fiji Islands.

The major new data base that bears on this problem originates from the new telemetered seismic network established in 1979. This network has recorded several thousand earthquakes both within and along the margins of the Fiji Platform. Because the network can locate events as small as magnitude -1.0, small earthquakes in less active seismic zones can be examined. Importantly, the network located over 500 earthquakes within and offshore southeastern Viti Levu, near the source area for the 1953 Suva earthquake. In the following sections, the distribution of earthquakes in the Fiji region is analyzed in order to elucidate the nature of deformation both within and along the boundaries of the Fiji Platform.

A second important observation that bears on the Suva earthquake is the examination of original records collected from over forty observatories operating at the time. Using these records, we have obtained a new focal
mechanism for the 1953 event that places it in a clear tectonic context:
one that proves to be closely linked to the deformation occurring on either
side of the Fiji Platform in the Lau and North Fiji basins.

ACTIVITIES SUMMARY

Seismological Investigations

Reliable seismological observations are necessary for accurate
location, study, and ultimate prediction of earthquakes. 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
a major U.S. 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
telemetry network in 1981 supported by Japanese aid. Additional stations
were installed in 1983 and 1984; the network has now expanded to a
nineteen-station national network with excellent coverage of the Fiji region
(see Figure 2). In addition MRD now has available five MEQ-800 portable
seismographs for occupation of temporary field sites, telemetry station
testing, and special refraction experiments. While the Fiji network has
experienced considerable technical difficulties it has recorded some 5000
earthquakes since its installation, and provides an invaluable basis for
seismological study of the Fiji region.
Figure 2. Locations of seismic stations comprising the national seismic network of Fiji.
The present OFDA-supported program has provided for three years of field and laboratory research on the seismicity and tectonics of the Fiji region, and included approximately fifteen months of field work in Fiji. The field program resulted in substantial improvement of the Fiji seismic network, as well as in detailed studies of seismicity, crustal structure, and tectonics of Fiji. The work has already resulted in a number of publications (Hamburger and Isacks, 1983; Hamburger and Qiolevu, 1983; Draunidalo and Hamburger, 1984; Hamburger, 1986; Hamburger and Isacks, 1986; Hamburger and Everingham, 1986) as well as several others in preparation. The scientific work summarized in this report represents a portion of those studies.

**Strong Motion Accelerographs**

The Mineral Resources Department also operates a network of strong motion accelerographs, now numbering ten Kinematics SMA-1's (Figure 3). The initial six instruments of this network were granted to Fiji by AID; the remainder was purchased by the Fiji government. Since establishment of the SMA network, three accelerogram records have been obtained from moderate-sized earthquakes in Viti Levu. The accelerograms are discussed in detail in the following sections. Records obtained from this network are expected, in the long run, to provide the basis for ground accelerations, and thus for development of building codes specific to Fiji's tectonic setting and seismic regime.

**Related Scientific Programs**

The Mineral Resources Department (MRD) includes an Offshore Geology section, which has an active program of marine geological and geophysical
Figure 3. Location of strong-motion accelerographs in Fiji. Some revision of these locations is likely within the next year.
investigations, in and around Fiji waters. MRD also employs an engineering geologist, whose work includes microzonation of the Suva area, mapping of active faults in southeastern Viti Levu, and investigation of soils subject to earthquake-induced liquefaction. An active program of geological mapping and structural studies is also carried out by MRD. They are supported by personnel assistance from Australia and Great Britain.

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

Critical Facilities

The major development in Fiji has been in and around the capital city of Suva. The population of the metropolitan area now exceeds 145,000, 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 82-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) 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 model 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.

TECTONICS, GEOLOGY, AND PHYSIOGRAPHY

Plate Tectonic Setting

The theory of plate tectonics has provided a fundamental new understanding of the distribution of earthquakes in the Fiji region. This section of the report is intended to briefly review the fundamental concepts of plate tectonics, and to establish the geologic and plate tectonic setting of the Fiji Islands. This information provides a basis for evaluating the seismicity data presented in the following sections.

Fiji is located along a portion of what is commonly called the "Pacific Ring of Fire." The concentration of earthquakes (Figure 4a) and volcanoes (Figure 4b) along this trend were used to establish the boundaries of the lithospheric plates in the modern view of plate tectonic theory (Figure 4c). 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.
Figure 4. World distribution of (A) earthquakes and (B) volcanoes; (C) configuration of the major tectonic plates on the earth's surface (from Turcotte and Schubert, 1982).
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 5 shows schematically the spatial relationship of these different types of boundaries. Convergent plate boundaries are responsible for the majority of the world's large earthquakes and most of the world's tsunamis. Many volcanic arcs form parallel to the deep-sea trenches, above the point where the subducted plate reaches about 100 km depth.

The Fiji Islands are a component of the Melanesian Borderlands that form the boundary between the Pacific and Indo-Australian lithospheric plates (Figure 1a). The entire Southwest Pacific region, extending from the Solomon Islands to New Zealand, is dominated by plate convergence between these two plates. The present loci of convergence are the Solomon, New Hebrides, Tonga, Kermadec and Hikurangi trenches. They are all characterized by large shallow earthquakes, inclined seismic (Benioff) zones, and Quaternary volcanism. The present-day plate convergence vector is oriented east-west over much of the region (Minster and Jordan, 1978).

The Tonga-Fiji-New Hebrides segment of the plate boundary (the Melanesian reentrant) is unusual in several respects: (1) the convergent boundary is discontinuous, jumping from westward subduction at northern Tonga to eastward subduction at the southern New Hebrides; (2) it is one portion of the convergent plate boundary that is not dominated by plate subduction; (3) the broad, geologically complex Fiji Platform sits within the plate boundary; (4) two east-trending bathymetric deeps, the Vitiáz Trench and the Hunter Fracture Zone, mark the sites of former subduction zones.
Figure 5. (A) Sketch of the different types of plate tectonic boundaries and their relationships (Isacks et al., 1968). (B) Diagram of the three types of boundaries in three-dimensional view.
Four bathymetric trenches mark the sites of present or former plate subduction: (1) the Tonga and Kermadec trenches extend in a nearly linear fashion from New Zealand to the northern end of the Tonga arc, over 2000 km in length. Their depth reaches 11 km in southern Tonga; (2) the New Hebrides Trench extends from 11° to 23°S, reaching 8 km depth in the north. The trench is interrupted in the central segment, but plate convergence, is observed along its entire length (Isacks et al., 1981); (3) the Vitiaz Trench appears as a well defined bathymetric deep, locally over 6 km in depth, that separates the Mesozoic Pacific Plate lithosphere from the young, back-arc basin lithosphere of the North Fiji Basin. Its morphology is similar to that of active trenches (Halunen, 1979), but shallow seismicity and Quaternary arc-related volcanism are absent; (4) the Hunter Fracture Zone is a well-defined curvilinear belt of ridge/trough topography extending from Fiji to the southern New Hebrides arc. At its western end, it intersects the southern termination of the New Hebrides Trench. Bathymetric and seismic reflection profiles across the Hunter Fracture Zone show that the subduction margin morphology is preserved well into the Fiji Platform (Brocher and Holmes, 1985). The Koro Sea (between Fiji and the Lau Ridge) represents its eastern termination.

The island arcs stand out as bathymetric highs landward of the trenches: (1) the Tonga and Kermadec arcs form a linear bathymetric high, landward of the trenches. Quaternary volcanic activity has taken place at irregular intervals along its length (Figure 1a); (2) the New Hebrides arc is a bathymetric high extending parallel to the New Hebrides Trench. The geology of the New Hebrides records an irregular history of arc volcanism that has persisted over the last forty million years; (3) the Lau Ridge is a
remnant arc, isolated from the Tonga subduction zone by back-arc spreading in the Lau Basin (Karig, 1970). It previously formed part of the active Tonga arc but is no longer volcanically active (Whelan et al., 1985; Woodhall, 1985a); (4) the Fiji Platform is delineated by a broad area of shallow water depths, separated from the Tonga and New Hebrides arcs by the North Fiji and Lau basins. The rocks exposed on the Fiji Islands record a complex history of arc volcanism and deformation beginning in the Late Eocene and extending into the Quaternary (Rodda, 1967, 1974; Gill et al., 1984; Rodda and Kroenke, 1984).

Active back-arc basin spreading has been identified in the North Fiji Basin and Lau Basin, based on shallow seismicity, seismic wave velocities and attenuation, high heat flow, magnetic anomalies, and the presence of tholeiitic basalts (Karig, 1970; Chase, 1971; Barazangi and Isacks, 1971; Sclater et al., 1972). These basins are marked by relatively uniform areas of shallow water depths (~3 km) surrounding the Fiji Platform. Inactive back-arc basins have been identified in the Loyalty Basin (west of the New Hebrides Trench) and the South Fiji Basin (south of the Hunter Fracture Zone). They are marked by areas of relatively deep water that are separated from the Southwest Pacific Basin by the active arcs and trenches. Finally, a major, regional scale transcurrent boundary in the interarc region is the Fiji Fracture Zone (FFZ). The FFZ is most clearly evident as a continuous belt of seismicity extending westward from the northern termination of the Tonga Trench (Figure 6). Along several segments of the FFZ, the belt of seismicity coincides with rough seafloor morphology; north of Fiji, the FFZ forms the well defined linear boundary of the Fiji Platform. Strike-slip focal mechanisms along its entire length confirm its identification as the
Figure 6. Shallow earthquakes (depth \( \leq 80 \) km) in the interarc region, 1961-1984. Locations are from Preliminary Determination of Epicenters (PDE), constrained by \( \geq 20 \) stations. Light shading indicates areas > 2 km depth; heavy shading shows areas > 5 km depth for New Hebrides and Vitiaz trenches, > 7.5 km depth for Tonga and Kermadec trenches. Bathymetric data from Kroenke et al. (1983).
southern transcurrent boundary of the Pacific Plate in this area (Chase, 1971; Isacks et al., 1969; Green and Cullen, 1973). However, new seismological and bathymetric observations require that the FFZ be a complex plate boundary zone rather than a simple linear fault zone.

Physiography and Submarine Morphology

The Fiji Platform is marked by the broad, apostrophe-shaped shallow platform, at depths shallower than 2 km, of which the islands of Fiji are a small subaerial component (Figure 7). The main islands of Viti Levu and Vanua Levu account for over 85% of the land mass of the country, and are among the largest of the Pacific's volcanic islands. Topographic relief reaches 1400 m in the interior of Viti Levu, 1200 m on Taveuni, and 1000 m on Vanua Levu. The islands of the Lau Group represent volcanic edifices sitting atop the broad remnant arc platform (Karig, 1970), forming the "tail" of the apostrophe.

The volcanic island of Kadavu sits on a separate, elongated ridge, paralleling the deep trough of the Hunter Fracture Zone (HFZ). The fracture zone is defined by an irregular series of deep basins marking the boundary between the relatively deep Oligocene back-arc basin of the South Fiji Basin and the shallow, late Cenozoic North Fiji Basin. A new bathymetric compilation by Smith and Raicebe (1984), shows the HFZ near Fiji to have a double ridge/trough structure, strikingly similar to the trench/structural high/forearc basin/volcanic arc morphology commonly observed in other subduction zone settings. The HFZ continues as a shallower trough into the Koro Sea, east of Viti Levu, and its prominent structural signature is preserved at least as far north as 18.5°S (Brocher and Holmes, 1985).
Figure 7. Physiography of the seafloor in the Fiji region from Rodda and Kroenke (1984). Bathymetric contours, in hundreds of meters, from Kroenke et al. (1983).
The Fiji Fracture Zone (FFZ) represents a complex morphological boundary of the Fiji Platform. It is marked by an en echelon series of ridges and troughs, with over 3 km of relief in the portion of the FFZ north of the Yasawa Group. The FFZ is less evident as a morphological feature east of 178.5°E, north of Vanua Levu, where its expression is masked by sedimentation from rivers draining the northern portion of the island. Sharp changes in strike of the FFZ are observed near 177°E, 178.8°E, and 180°.

A series of basins west of Viti Levu mark another tectonically active boundary of the Fiji Platform. Troughs up to 4 km depth are prominent along the western margin of the platform. Brocher and Holmes (1985) interpreted these basins as the physiographic expression of rifting of the forearc margin of the former Vitiaz arc convergent plate boundary. The rough topography in this area coincides with a belt of shallow seismicity evident on teleseismic maps (Figure 6).

Within the platform, extensive coral reef development is an important morphological element. Fringing reefs and lagoons are evident around most islands, and barrier reefs are developed around the major islands. The reefs are important in limiting the effect of tsunamis originating outside the islands; however, in the case of the 1953 Suva earthquake, tsunamis were apparently generated by slumping off the barrier reefs (Houtz, 1962a).

**Geological Evolution of Fiji**

The rocks exposed on the Fiji Islands are among the oldest observed in the islands of the Southwest Pacific. The geology is dominated by arc-related volcanic and intrusive rocks and thick sequences of volcanoclastic sediments. The size of Fiji's land mass, combined with the presence of felsic intrusives, thick sediment sequences and major orogenic episodes
has led Fiji to be described as continental or "quasi-continental" in character (Green and Cullen, 1973, Eden and Smith, 1984). However, the Fiji Platform differs from continental land masses in several important respects: (1) the average crustal thickness of 15-20 km is far less than normal continental crust; (2) low mantle velocities beneath the platform demonstrate a thermally attenuated lithosphere lacking the thick, rigid "mantle lid" that underlies most continental crust; (3) the presence of ongoing deformation and Neogene volcanism in the Fiji region, observed both around and within the Fiji Platform, indicates a degree of crustal mobility that is not expected of stable continental masses.

Figure 8 presents a simplified geological map of Fiji from Rodda and Kroenke (1984). The oldest known strata in Fiji are the Late Eocene rocks of the Wainimala Group (Rodda, 1976; Gill et al., 1984; Rodda and Kroenke, 1984). These strata were mildly deformed during the Wainimala Orogeny during the middle Oligocene. It is marked by a period of nondeposition throughout Fiji that extends to the latest Oligocene. Arc tholeiitic and calc-alkaline magmatism occurred in Viti Levu throughout the Miocene (Gill et al., 1984; Rodda and Kroenke, 1984).

The major orogenic episode in Fiji was the Colo Orogeny around 10 m.y. B.P. It is marked by: (1) a prolonged gap in the stratigraphic record; (2) widespread folding and faulting, accompanied by greenschist metamorphism; and (3) intrusion of tonalite, gabbro and trondhjemite. The Colo Orogeny also coincides with a significant arc-deforming event in the New Hebrides arc: uplift and erosion of the Western Belt province, at 11-8 m.y. B.P. (Carney and Macfarlane, 1982).
Figure 8. Simplified geology of Fiji, from Rodda and Kroenke (1984). Blank areas within Viti Levu are known or likely Lower Wainimala Group (Late Eocene to Early Miocene rocks).
Following the Colo deformation, a resurgence of volcanism took place throughout Fiji, (Gill et al., 1984; Woodhall, 1985a). An unusual sequence of thick rhyolitic volcanics were extruded at ~7 m.y. B.P. in northeastern Vanua Levu, that may be related to incipient fragmentation of the Fiji arc (Gill et al., 1984).

During the period 5-3 m.y. B.P. magmatism in Fiji changed dramatically, to become dominated by transitional/shoshonitic volcanism in northern Viti Levu and the Lomaiviti Group (Dickenson et al., 1968; Gill, 1976; Gill et al., 1984). After 3 m.y. B.P., volcanic rocks in Fiji were dominated by alkali basalts, generated from a very different, ocean island-like source (Gill, 1976; Gill et al., 1984).

Through the period of arc modification, an unusual remnant of calc-alkaline volcanism persisted on Kadavu Island, at the southern edge of the Fiji Platform. Kadavu is on a major bathymetric ridge paralleling the Hunter Fracture Zone. The trench-like morphology of the fracture zone (Launay, 1982a), combined with the oblique truncation of linear magnetic anomalies in the South Fiji Basin, is indicative of subduction along this boundary, post-dating the Oligocene creation of the South Fiji Basin. Subduction-related andesites and dacites, dated at 3.4 ± 0.5 m.y. B.P. (Whelan et al., 1985) document convergence along the Hunter Fracture Zone extending into the Quaternary.

Other documented Quaternary volcanism in Fiji is found in the alkali basalts of the Lomaiviti and southern Lau Groups (Whelan et al., 1985; Woodhall, 1985a), and on Taveuni Island (Frost, 1974). The Taveuni ash eruption, dated at 2050 years B.P., based on archaeological investigations, is the only documented Holocene activity in Fiji.
Post-Colo structural deformation is evidenced by faulting of rocks deposited above the Colo unconformity. Many of these faults observed in Viti Levu are near-vertical with significant stratigraphic throws (Band, 1968; Rodda, 1974). In many cases, the post-Colo rocks are unaffected by the faults in the underlying basement (Rodda, 1974). From the Late Pliocene, the island of Viti Levu has been affected by rapid domal uplift that has resulted in the abandonment and deformation of late Cenozoic erosion surfaces in western Viti Levu (Dickenson, 1972). Basaltic rocks of the Ba Volcanic Group, erupted as pillow lavas below sea level during the Pliocene, have subsequently been uplifted to over 1000 m elevation in central Viti Levu (Rodda, 1976). This uplift within the Fiji Platform clearly post-dates the fragmentation of the Vitiaz arc and the establishment of the present tectonic configuration. The observation of anomalous (low-velocity) mantle beneath the Fiji Platform (Hamburger, 1986) reflects thermal thinning of the Fiji lithosphere associated with the processes of back-arc magmatism in the neighboring Lau and North Fiji basins. The rapid doming of Viti Levu, then, may be an isostatic response to the introduction of low-density mantle material beneath the Fiji Platform.

On a historical time scale, geodetic observations in southeastern Viti Levu by Berryman (1981) indicate rates of shear strain on the order of 0.6 \( \mu \text{rad/yr} \), accumulated over the period 1909-1980. The crustal seismicity that is documented in the following section is the product of ongoing deformation of the Fiji lithosphere.

**SPATIAL DISTRIBUTION OF EARTHQUAKES IN FIJI**

A prodigious amount of seismicity data has been gathered for the Fiji region, including: (1) the historical record of large earthquakes, based on
macroseismic and instrumental observations, (2) teleseismic earthquake locations from the global seismic network, (3) results from an early three-station network operated in Fiji during 1965-1969, and (4) local and regional earthquake locations from the telemetered network operated in Fiji since 1979.

The combination of all these data sources provides a composite picture of the seismicity of Fiji over a wide range of spatial, temporal and magnitude scales; each data source is limited by its magnitude threshold, duration of observation, and degree of spatial resolution. Together, they provide the state-of-the-art in our understanding of where and how earthquakes occur within and around the Fiji Islands. The important application of this understanding is a more realistic assessment of seismic potential along Fiji's seismogenic zones and the seismic risk to major development within the country.

**Historical Earthquakes**

Fiji's short written history prevents a complete reconstruction of the recurrence cycles of major earthquakes throughout the Fiji region. Nonetheless, the earthquake history for the past 137 years, however incomplete, demonstrates aspects of Fiji seismicity not evident from an examination of more uniform, but shorter-term seismicity catalogs.

Figure 9 shows the major historical earthquakes in the Fiji region, from Everingham (1983a, 1984). Seventeen major earthquakes, with magnitudes greater than 6.5, have occurred close to the islands. An additional fifteen events, with magnitudes greater than 6.0, are located in the same vicinity. The locations for these events are based on both macroseismic (intensity) and teleseismic (instrumental) observations. Those occurring before the
Figure 9. Historical seismicity in the Fiji region. Data are from Everingham (1983a, 1984).
middle of this century must be regarded as approximate. Errors of up to one
degree in instrumental locations result from inaccuracies in reporting of
arrival times, uneven station distribution, manual earthquake locations,
etc. Reporting of earthquake intensities is not altogether reliable,
particularly before the beginning of the century. Nonetheless, the level of
development in Fiji since 1900 provides assurance that major events have not
been omitted from the catalogs.

A large proportion of the major events around Fiji took place along the
microplate boundaries surrounding the platform. As with the teleseismic and
microseismic events discussed below, these earthquakes concentrate in the
northwestern Lau Basin (large events northeast of Vanua Levu), along the
Fiji Fracture Zone (seven events located north and west of Vanua Levu) and
along a zone of seismicity west of Viti Levu (five events near 176°E).

In contrast to the overall distribution of teleseismically located
earthquakes, however, several major events occurred within the Fiji
Platform. These include the 1953 Suva earthquake ($M_S = 6.75$), the 1932 Koro
earthquake ($M_S = 6.5$), and the 1979 Taveuni earthquake ($M_S = 6.9$) discussed
in the following sections. In addition, Everingham (1983a, 1984) reported
four significant events near Kadavu Island (1850, 1935 and 1950), and one
within Viti Levu (1869). Two smaller, but damaging earthquakes took place
near Kadavu (1918) and near Ovalau Island (1906). None of these events
exceeded magnitude ($M_S$) 7.1; however, several had significant macroseismic
effects and are thus important for seismic hazard evaluation. The occurrence of large earthquakes within the platform confirms a conclusion that emerges from the microearthquake observations: intraplate deformation
within the Fiji Platform is a significant component of the regional deforma-
tion field, but it occurs more infrequently, and is separated by longer periods of quiescence than that occurring along the interplate seismic zones that bound the platform. The observation that earthquakes larger than $M_S = 7.1$ are not recorded in a region characterized by high rates of relative plate motion suggests that the Fiji lithosphere is incapable of storing sufficient stress to result in larger earthquakes. Because of the brevity of the seismological history of the Fiji region, the occurrence of larger prehistoric earthquakes cannot be ruled out.

**Teleseismically Located Earthquakes**

Figure 10 shows in detail the teleseismically determined distribution of shallow earthquakes around Fiji (depth $\leq 80$ km). This map includes all the events located by more than 15 stations of the global seismograph network from 1961-1983, plus the better located of the earlier events (1928-1960) that were relocated by Sykes (1966) and Sykes et al. (1969). The criteria used in compiling this catalog are described in detail by Hamburger (1986). This data set provides generally higher precision, records lower magnitude activity (to $m_b > 4.5$), and a larger number of events than the historical catalog. The higher sensitivity improves the resolution of finer scale spatial patterns. Generally, the events in this data set are expected to have absolute errors under 20-25 km. The overall distribution of epicenters presented in this figure shows that on this limited time and magnitude scale, seismic deformation is largely confined to active interplate zones surrounding the Fiji Platform.

The detailed bathymetry in this area shows that the seismic zone north of the Fiji Islands coincides with the rough topography of the Fiji Fracture Zone. The structural trends inferred from the elongation of the steep-sided
ridges and basins are close to the regional strike of the earthquake belt. Over 3 km of relief is observed in these en echelon ridges and troughs. The nearby island of Cikobia, situated northeast of Vanua Levu and directly adjacent to the fracture zone (location shown in Figure 7), shows marked Quaternary uplift (Berryman, 1979), as additional support of active tectonism of the area.

The seismic zone west of Viti Levu has been proposed as the location of a North Fiji Basin spreading center (Sclater and Menard, 1967; Chase, 1971; Brocher and Holmes, 1985). The earthquake belt coincides with a series of irregular basins with a marked north-northeast trend. The basins coincide with a north-trending free-air gravity low and high-amplitude magnetic anomalies. Seismic reflection profiles show little sediment cover in the basins and document extensional deformation of the "rifted arc margin" at the shelf edge of western Viti Levu (Brocher and Holmes, 1985).

A few isolated epicenters are located within the Fiji Platform, particularly in the area east of Vanua Levu. A second group of events is located south of Viti Levu within and surrounding the Kadavu Island ridge. A single isolated event that appears within the island of Viti Levu is actually a mislocated aftershock of the 1953 Suva earthquake, which is located immediately south of the main island.

Tripartite Seismic Network, 1966-1969

Sykes et al. (1969) first examined seismicity of the Fiji region using a network of local seismic stations installed by B. L. Isacks in 1965. The three-station network operated for nearly four years and included several temporary sites throughout the Fiji Islands. Locations from the first six months of network operation were presented in their paper; those from the
subsequent period were examined by Draunidalo and Hamburger (1984); HYPOELLIPSE (Lahr, 1984) relocations of these events were obtained using the same velocity model used for telemetered network locations. Hypocentral parameters are given in Hamburger (1986), and the two sets of earthquake locations are shown in Figure 11. These earthquake locations show the same prominent seismic zones north and west of Viti Levu as the teleseismic data shown in Figure 10, with a small number of shocks occurring south of that island. The large aperture of that network did not permit location of very small events. However, Sykes et al. did observe scattered seismicity in areas previously thought to be aseismic: east and northeast of Viti Levu, southwest of Viti Levu (near Kadavu Island), and in the seismic zone just offshore southeastern Viti Levu. In histograms of S-P intervals of earthquakes recorded at the Fiji stations, Sykes et al. noted a continuum of earthquakes with S-P intervals less than 10 sec at the southeastern Viti Levu station Vunikawai. These earthquakes, few of which were located, must have occurred within the Fiji Platform, rather than along its edges. Furthermore, a prominent peak in activity was observed at VUN for S-P intervals of 1-4 sec, reflecting the high activity in the southeastern Viti Levu seismic zone, discussed in the following section.

Fiji Telemetered Seismic Network, 1979-1985

The seventeen-station national seismic network of Fiji is shown in Figure 2. The network began operation with the establishment of the eight-station U.S. AID network in 1979 on the islands of Viti Levu, Ovalau and Beqa, supplementing the three stations already operating at Vunikawai, Suva and Nadi.
Figure 11. Microearthquakes in the Fiji region, 1965-1969. Locations from 3-station seismic network operated by Sykes et al. (1969). Triangles show locations of seismic stations. Squares indicate locations obtained by Sykes et al. for first 6 months of network operation. Circles indicate relocations of events reported in subsequent 2 1/2 years by Draunidalo and Hamburger (1984). Depths constrained at 10 km. Bathymetry as in Figure 10.
In December, 1981, a five-station telemetered network was established on the islands of Vanua Levu, Koro, and Taveuni, through the Japanese aid program. From that time, all the telemetered stations have been recorded on a Japanese, event-triggered 25-channel hot stylus pen recorder. In early 1983, the Fiji Mineral Resources Department expanded the network by the establishment of a three-station telemetry network around Monasavu Dam in central Viti Levu. Considerable technical difficulties have been encountered at many of the telemetered stations due to unreliable power supplies, degradation of electronic equipment, weather-related interference, and wind and lightning damage. Such problems have limited the operation of network stations to some 50-75% of total operating time.

The history of network operation is reflected in the histogram of earthquakes located by the network (Figure 12). The system began recording in November, 1979, and was immediately inaugurated by the occurrence of two major earthquake sequences: the November 16 Taveuni earthquake (Ms = 6.9) and its aftershocks, and a prolonged swarm of moderate-sized events in April-May 1980, including three events with $M_L \geq 5.0$, northeast of Vanua Levu. Two additional peaks in the histogram are associated with sequences west of Viti Levu and along the Fiji Fracture Zone, in September and December 1980, respectively. Through 1981, the network operated less reliably, debilitated by technical problems with field stations, telemetry, and the recording system.

The increase in activity in December 1981 reflected a period of maintenance and repair of existing instruments and the establishment of the Japanese aid network. Through June 1983, the level of recorded seismicity was to some degree limited by the operation of an event-triggered recording
Figure 12. Histogram of earthquakes recorded by the Fiji seismic network, 1979-1985. Major earthquake sequences are noted, with mainshock magnitudes ($M_L$) given in parentheses. See text for discussion.
system. The sudden increase in mid-1983 followed the reinstallation of a continuous recording system and a second period of instrument maintenance. Subsequent peaks in the histogram are associated with major earthquake sequences near Kadavu Island (July-August 1983), along the Baravi Basin (June 1984), and along the western Fiji Fracture Zone (October 1984). The major gap in recording at the beginning of 1985 follows the devastation of network telemetry by Hurricanes Nigel and Eric. The data available at the time of this writing end in August 1985.

Earthquake Locations

During the nearly six years of network operation over 5000 local earthquakes were recorded by the Fiji seismic network. Of these events, approximately 1800 were recorded with sufficient redundancy to provide reliable earthquake locations. Details of the earthquake location procedure can be found in Hamburger (1986).

A grading scheme was designed to cull out the best locations within each earthquake source region. The earthquakes were first classified into eight source regions, based on the distribution of earthquake foci and their relation to the seismic network (Figure 13). Grading criteria were applied consistently within each seismic region, but varied from region to region. The criteria used are based on the output parameters from the location program HYPOELLIPSE: number of recorded P- and S-arrivals, RMS residuals, minimum epicenter-station distance, azimuthal gap, and the size of the error ellipse for each event. The grading criteria are summarized by Hamburger (1986). These grading criteria provide a systematic means to compare earthquake locations within each area.
Figure 13. Earthquake source regions near Fiji. Regions are defined based on distribution of earthquakes and relation to network geometry, and are used in defining grading criteria. See text for discussion.
Depth Determinations

Determination of reliable earthquake depths is a function of the number and accuracy of arrival time readings, and of the geometry of the network used for locating each event. For earthquakes located within the dense network of southeastern Viti Levu, the pattern of arrival times (or source-to-station distances) uniquely determines a particular depth at which the RMS of the traveltime residuals is minimized. On the other hand, for an earthquake in the Taveuni region, far outside the seismic network, the arrival-time data can be matched by virtually any crustal depth.

Because there is very little constraint on hypocentral depths outside the seismic network, the hypocenters of these earthquakes were simply fixed at a midcrustal depth of 10 km, consistent with the observed focal depths in Viti Levu (see below). Depths were allowed to vary only for earthquakes within and near Viti Levu and for the small number of events outside this region, recording both P- and S-arrivals at a station within 50 km.

The distribution of earthquake depths in Fiji is given in Figure 14. Virtually all the well constrained depths fall within 20 km of the earth's surface and a substantial majority at depths < 13 km. A very small number of earthquakes were located at depths exceeding 30 km, but all of these events are considered poorly constrained (grade D). From the network locations, there is no evidence of any intermediate-depth activity that might be expected from the recent northward subduction of South Fiji Basin lithosphere beneath the Fiji Platform (Malahoff et al., 1982a; Gill et al., 1984). A single teleseismic event located south of the Platform at 73 km depth was found to be a mislocated shallow event. The best-constrained hypocentral depths, those located within the small-aperture network in
Figure 14. Histogram of hypocentral depths for all earthquakes located by the Fiji seismic network, classified by grade: D - unfilled, C - light shading, B - dark shading, A - black.
southeastern Viti Levu cluster at midcrustal depths of 7-13 km. The deepest A-grade event is near the base of the crust, at 18 km. The B-grade events extend to 20 km depth.

In general, the depth distribution is quite similar to that observed in areas of continental extension and strike-slip deformation (Chen and Molnar, 1983; Smith and Bruhn, 1984). Corbett (1984) found earthquakes located by the southern California seismic network to be limited to the upper 22 km of crust. A similar double-peaked histogram was observed, with concentrations of activity in the upper 4 km and between 10 and 16 km depth. Chen and Molnar ascribe the overall concentration of activity in the upper crust to high geothermal gradients limiting the material strength in the mantle and lower crust. The observed concentration of seismic activity within the Fiji crust, and the sharp drop-off in activity near its base is consistent with the observation of anomalous (low-velocity) upper mantle beneath Fiji: stresses sufficient to generate earthquakes can accumulate only in the thin crust that forms a rigid cap on the relatively hot, ductile mantle of the Fiji Platform.

Earthquake Magnitudes

When possible, earthquake magnitudes have been assigned to all of the newly located events in Fiji. The magnitudes were computed from trace amplitudes and coda durations recorded on instruments of the telemetered network. The development of a magnitude scale for the Fiji network is described in detail by Hamburger (1986).

The distribution of magnitudes reported for all events during the operation of the seismic network is shown in Figure 15. Magnitudes range from local magnitude $M_L = -1.0$ (microearthquakes in southeastern Viti Levu),
Figure 15. Histogram of magnitudes for all earthquakes located by the Fiji seismic network.
to $M_L = 6.5$ (the large November 1979, Taveuni earthquake). From the largest
events, the number of earthquakes in each magnitude range steadily grows, to
a maximum of 130 earthquakes in the range $M_L = 2.8 - 3.0$. At smaller
magnitudes, the number drops due to the network's loss of sensitivity to
small earthquakes outside the network. In fact, the magnitude threshold may
be somewhat lower, due to systematic underreporting of magnitudes of small
events during the latter period of network operation. The magnitude
threshold is also evident in the magnitude-frequency relation of Figure 16.
This figure shows the log of the cumulative number of events as a function
of magnitude. Again, a change in character is evident near the threshold
magnitude of $M_L = 3.0$. At larger magnitudes, the curve may be approximated
by a linear slope, given by the line

$$\log N = 5.17 - 0.80 M_L,$$

following Richter's formula $\log N = A - bM$, where the "$A$" value describes
the level of seismic activity in a region and the "$b$" value describes the
recurrence relations for that region. The $b$-value of 0.80 is in the range
of tectonically active regions throughout the world (see Lee and Stewart,
1981). It contrasts with the $b$-value of 0.49 obtained for the instrumental
catalog, based on magnitudes less than 6.0 by Everingham (1983c). His low
$b$-value is based on compilation of surface-wave magnitudes ($M_S$), and results
in part from underreporting of smaller magnitude events during the early
part of this century.

Seismicity Maps

In the following section we present maps of earthquakes in the Fiji
region recorded by the telemetered seismic network. As a result of the
improved spatial resolution provided by the telemetered network, the maps
Figure 16. Magnitude-frequency plot for all events located by the Fiji seismic network. The portion of the curve above $M_L = 3.0$ is approximated by the straight line $\log N = 5.17 - 0.80 M_L$. The maximum network threshold near $M_L = 3.0$ is indicated by the falloff in the curve at smaller magnitude levels.
can be used to characterize the seismic regime along each of the seismic zones in the Fiji region. Space-time diagrams of the network seismicity are used to elucidate temporal patterns of earthquake occurrence along the seismic zones. Cross sections are presented for the earthquakes located within and around the island of Viti Levu, where depth resolution is greatest.

The 1800 earthquakes located by the telemetered network are presented in Figure 17. Hypocentral parameters for each event are given in Hamburger (1986). Figure 18 shows all earthquakes classified by magnitude. Detailed maps of several major earthquake sequences are displayed in Figure 20. Figures 24 and 29 present larger-scale maps of the seismicity within the island of Viti Levu.

Compared to the historical and teleseismic data shown in Figures 9 and 10, these new seismicity maps provide a new, detailed picture of the pattern of deformation within and around the Fiji Platform. Several initial observations stand out. First, the pattern of activity is far from uniform. Earthquakes occur in concentrated zones both within and along the boundaries of the platform; large areas exist which are virtually aseismic.

Second, the major zones of activity along the platform's margins coincide with those defined by the historical, teleseismic, and the tripartite network data: the northeastern edge of the platform, the Fiji Fracture Zone, the basins west of Viti Levu, and to a lesser extent, the Hunter Fracture Zone/Kadavu region. That is, these zones are also active at higher magnitude ranges within a time scale observable by instrumental observations. The areas of high activity within the Fiji Platform are not well populated in the teleseismic data. This contrast between network and
Figure 17. Map showing all earthquakes located by the Fiji seismic network. Bathymetry as in Figure 10.
Figure 18. Map showing all earthquakes located by the Fiji seismic network, classified by magnitude. Crosses: $M_L < 2$; small open circles: $2 \leq M_L < 3$; large open circles: $3 \leq M_L < 4$; shaded circles: $4 \leq M_L < 5$; filled circles: $M_L \geq 5$. 2-km contour as in Figure 10.
Figure 19. Location map for major earthquake sequences presented in Figure 20. Bathymetry as in Figure 10.
Figure 20. Maps of major earthquake sequences since establishment of the seismic network: (A) November 1979 Taveuni earthquake ($M_L = 6.5$); (B) December 1980 Fiji Fracture Zone earthquake ($M_L = 5.8$); (C) October 1984 Fiji Fracture Zone swarm ($M_L = 5.7, 5.4, 5.9$); (D) September 1980 West Viti Levu swarm ($M_L = 5.7$); (E) July, 1983 Kadavu swarm ($M_L = 5.1, 5.1, 4.8$). Mainshock locations shown by filled squares. Focal mechanism(s) and isoseismal data (Roman numerals) shown where available. Unshaded bathymetric contours are identical those shown in Figure 10. Earthquake grades: D - small open circles; C - large open circles; B - shaded circles; A - filled circles. Large historical earthquakes in the Taveuni area (A) are shown by filled triangles.
teleseismic observations is fundamentally a sampling problem. The intra-
plate zones of activity are observed by the network because: (1) the
intraplate seismic zones are very active at lower magnitude ranges, and
(2) the network "happened to catch" several unusual major earthquake
sequences in areas of relatively low activity. The distribution of earth-
quake magnitudes (Figure 18) bears out both causes: (1) the concentra-
tion of activity in southeastern Viti Levu is almost entirely composed of small
events ($M_L \leq 3$). Of the 500 earthquakes located within Viti Levu, none have
been large enough ($m_b \geq 4.5$) to have been located teleseismically; (2) the
concentration of activity near Taveuni Island is the result of a fortuitous
earthquake sequence two weeks after the network began operation. In the
following section each of the major earthquake source areas in the Fiji
region are considered in detail (shown in Figure 13).

1. Taveuni (TAV): This area is dominated by two major earthquake
sequences that occurred early in the network's operation. The 16 November
1979 Taveuni earthquake ($M_s = 6.9$) is the largest event to occur in the
region in over 30 years and the most destructive in Fiji since the 1953 Suva
earthquake. The earthquake was strongly felt (MM VII in the closest
islands) throughout the islands of Taveuni, Vanua Levu, Rabi, and Kioa
(Figure 20A). An intense aftershock sequence continued for several weeks
following the mainshock, and isolated events continued for over a year
thereafter. The probable mainshock location was constrained by the pattern
of macroseismic data, as well as by S-P intervals at temporary seismic
stations occupying nearby sites in the days following the mainshock
(Everingham, 1982a). The teleseismic solutions (PDE, ISC locations) did not
utilize the local network observations, and are positioned 20 km to the
southwest of the probable location. In any case, the mainshock and after-shock locations indicate that the rupture occurred well within the thickened crust of the Fiji Platform.

The earthquake focal mechanism (Figure 21) was pure strike-slip with fault planes oriented nearly north-south and east-west. These orientations coincide with neither the northeast-trending bathymetric fabric nor major faults mapped onshore Vanua Levu or Taveuni. But the NW-SE orientation of the mechanism's T-axis is consistent with the sense of extension inferred from the axial fissure zone, and parallel normal faults that strike along the axis of Taveuni (Woodhall, 1985b), as well as the normal faults that delimit the Natewa Bay graben, separating the twin peninsulas of Vanua Levu (Green and Cullen, 1973). Taveuni is the one locality in Fiji where Holocene volcanic activity has been documented (Frost, 1974) and the alkalic trend of Taveuni's Quaternary lavas reflects this extensional character. In addition, the elongation of the volcanic axis of the island reflects the NE-SW direction of maximum compression, as described in the Japanese (Nakamura, 1977), Alaska (Nakamura et al., 1977), and the New Hebrides arcs (Roca, 1978). The axis of principal compression observed in the Taveuni earthquake shows the same dominant stress field. The historical record for this region (Figure 9) indicates that major intraplate activity has occurred near Taveuni throughout this century.

A second major sequence of earthquakes occurred northeast of the island of Vanua Levu (Figure 17) and constitutes a major swarm of activity in April-May, 1980. The sequence included three events with $M_L \geq 5$ and nine events with $4 \leq M_L < 5$. Recordings from the earthquakes are characterized by highly attenuated, low-frequency P- and S-arrivals, and contrast sharply
Figure 21. Focal mechanism for the 1979 Taveuni earthquake. Equal-area projection of the lower hemisphere of the focal sphere. Large open and filled circles represent clear dilatational and compressional first motions, respectively. Less reliable first motions are shown as small open and filled circles. Large and small X-marks indicate clear and uncertain P-wave arrivals respectively, that are judged to be near a nodal plane. Arrows show directions of S-wave polarization. The P (pressure) and T (tension) axes are located at the base of the letters P and T.
with those associated with the nearby Taveuni aftershock sequence. Because
the propagation path from the Vanua Levu swarm to the seismic network is
nearly identical to that followed by the Taveuni sequence, the zone of
attenuation must be located close to the swarm’s source area. In any event,
the quality of the arrivals resulted in a generally poor location accuracy,
which implies that the strong apparent northwesterly trend to the sequence
is simply an artifact of the poor constraint on station arrival times. The
best constrained locations cluster near the northeastern tip of Vanua Levu
island, the probable source area for the sequence. Like the Taveuni earth­
quakes, this sequence is located within the margins of the Fiji Platform.
The area is adjacent to a particularly complex confluence of tectonic
elements, where the Fiji Fracture Zone intersects the margin of the Fiji
Platform and Lau Basin. The influence of magmatic processes is suggested by
the swarmlike character of the sequence (e.g., Hill, 1977) and the highly
attenuated waveforms (e.g., Sanford and Einarsson, 1982; Iyer, 1984). Other
than these two major earthquake sequences, the Taveuni region appears to be
quiescent.

The temporal distribution of earthquakes in the Taveuni area is shown
graphically in Figure 23E. This figure demonstrates the dense clustering of
activity in the 1979 Taveuni mainshock-aftershock sequence and the 1980
swarm offshore Vanua Levu, as well as the subsequent quiescence of the
region. This pattern is characteristic of intraplate activity within the
platform, and contrasts with the more continuous activity along the Fiji
Fracture Zone (Figure 23A) and the West Viti Levu seismic zone (Figure 23B).
Long-term aftershocks of the Taveuni event are recorded up to a year after
the mainshock; subsequently, the zone is entirely aseismic (at the magnitude
Figure 22. Map showing locations of space-time diagrams presented in Figure 23. Brackets denote area included in diagrams.
Figure 23. Space-time diagrams for main earthquake zones in Fiji. Small open circles: $M_L < 3$; large open circles: $3 \leq M_L < 4$; shaded circles: $4 \leq M_L < 5$; filled circles: $M_L \geq 5$. Locations shown in Figure 22.
range to which the network is sensitive). Activity at very small magnitudes, like that observed in southeastern Viti Levu, is probably characteristic of the Taveuni area as well; small events with S-P times less than 10 seconds are recorded on seismographs on Taveuni and Udu Point, but are seldom of sufficient size to be recorded by the remainder of the network. This sporadic nature of intraplate activity underscores the importance of the network data (low magnitude threshold) and historical data (long time scale) in evaluating intraplate activity within the Fiji Platform.

2. Fiji Fracture Zone (FFZ): Through each period of observation the area of rough topography north of the platform has been the most seismically active area of the Fiji region. This belt of earthquakes is part of a larger seismogenic feature and continues to the east as a complex but continuous zone of seismic activity which extends to the northern end of the Tonga Trench. Further west, it continues as a linear belt of seismicity into the center of the North Fiji Basin. As such, it represents the present southern transform boundary of the Pacific Plate in this area, and has been termed the Fiji Fracture Zone (Green and Cullen, 1973; Hamburger and Everingham, 1985). The concentration of large earthquakes along this belt (Hamburger and Everingham, 1985; Hamburger and Isacks, 1985; see Figures 9 and 18) confirms the contention that a major portion of the interplate deformation is taken up there. The westward extent of the fracture zone is more ambiguous, as its topographic expression is not well preserved west of Fiji. Seismicity extends into the central portion of the North Fiji Basin, but rapidly drops off west of about 174°E.

Within the FFZ, the seismic activity is non-uniform. At all time and magnitude scales (Figures 9, 10, 11, 17) the portion of the FFZ directly
north of Viti Levu (176.5°-178.5°E) has been continuously active. The portions of the FFZ further west and that located north of Vanua Levu (east of 178.5°E) are far less active. However, the historical record of seismicity (Figure 9) shows that significant earthquakes have occurred in the quiet zone north of Vanua Levu during the last century, indicating that the present quiescence reflects a temporary locking of the plate boundary during the interseismic period.

The difference in seismic regime along the adjacent segments of the FFZ reflects differences in the dynamics of plate interaction along this boundary. The eastern zone is oriented close to the Pacific/Indo-Australian plate motion vector in this area, implying predominant strike-slip motion along the FFZ. A sharp kink in the strike of the fracture zone occurs at 178.8°E, where the seismic activity picks up. It is in the portion of the FFZ west of 178.8°E, where active rifting has been observed: Von Stackelberg et al. (1985) reported minor north-trending bathymetric ridges offsetting the FFZ, bearing fresh, hydrothermally altered pillow basalts. These observations indicate that plate motion in this area is accommodated by extensional as well as strike-slip deformation. The continuous swarm-like activity of the western FFZ is typical of localized areas of extension within strike-slip tectonic environments (Hill, 1977).

The space-time diagram for the FFZ (Figure 23A) clearly demonstrates this contrast in activity. The portion of the FFZ west of 178.8°E (< 225 km distance) is characterized by virtually continuous activity, with larger events occurring in swarm-like sequences. The eastern FFZ is characterized by more isolated, individual small to moderate-sized events. Despite the lower level of activity, this quiescent portion of the FFZ has the evenly
distributed occurrence of events that is characteristic of the interplate seismic zones. The two major sequences along the FFZ (December, 1980 and October, 1984) occurred near the edges of the active zone.

These two important sequences are shown in detail in Figure 20B,C. The December 1980 cluster was a mainshock-aftershock sequence, following a $M_L = 5.8$ mainshock. The sequence occurred close to the eastern edge of the fracture zone's active belt, and close to a pronounced change in strike of the zone. The aftershocks are generally not very well located, due to the limited number of stations operating at the time; their distribution suggests a very small rupture area near 16.2°S, 178.5°E.

The October 1984 sequence is somewhat more complex, and involved three major events with magnitudes of 5.7, 5.4, and 5.9. Centroid moment-tensor focal mechanism solutions for these three events were available from the U.S. Geological Survey's Preliminary Determination of Epicenters. This sequence took place on the western end of the active zone, near a second change in strike of the FFZ. The mainshocks are all characterized by strike-slip faulting, with east-west nodal planes paralleling the western segment of the fracture zone. The third major event of the sequence occurred 125 km north of the fracture zone, in a normally quiet portion of the North Fiji Basin. While this event may be considered a coincidental occurrence, its proximity in time and the similarity of mechanism suggest that the earthquake was triggered by the rupture along the fracture zone. The east-west trend of the mechanisms' nodal planes implies that it was the portion of the FFZ west of 177.5°E that ruptured during the sequence, rather than the active ENE-trending segment.
At moderate magnitudes ($3 < M_L < 4$) the portion of the FFZ between 176.8° and 178.8°E is continuously active. In contrast, the same area is devoid of major historical events (Figure 9). During the six years of operation of the telemetered network the two major earthquake sequences along the FFZ nucleated at the edges of the active zone. These phenomena indicate that slip occurs relatively freely along the ENE-trending active segment, accommodated by continuous occurrence of small earthquakes and by possible aseismic slip. The occurrence of back-arc extension within the seismically active portion of the FFZ also indicates that normal stresses acting along this portion of the FFZ are at a minimum. Slip along the east-trending, relatively quiescent portion of the FFZ occurs in major earthquake sequences; such sequences may nucleate at the edges of the active zone.

3. West Viti Levu Zone (WVL): Some 200 earthquakes are located in the seismic zone forming the western edge of the Fiji Platform. Like the events northeast of Vanua Levu, many of the WVL earthquakes produce poorly recorded, low-frequency shear arrivals that degrade the location accuracy in this area. In general, the epicenters coincide with a series of bathymetric troughs that mark the extensionally deformed margin of a former forearc terrane (Larue et al., 1980; Brocher and Holmes, 1985). While the activity in this zone is considerably lower than that along the Fiji Fracture Zone, the character of earthquake occurrence (Figure 23B) is similar—earthquakes occur irregularly throughout the network operation. The WVL zone is marked by relatively high activity on all time and magnitude scales (Figures 9, 10, 11).
The bathymetric troughs west of Viti Levu are part of an area of rough seafloor morphology, where the 4 km-deep troughs approach the shelf slope of the Fiji Platform. Parallel to and inland of the troughs, an elongate bathymetric ridge forms the outer edge of the Baravi Basin. This basin is a sediment-filled trough located west and south of Viti Levu, interpreted by Brocher and Holmes (1985) to represent the forearc basin of the active pre-Late Miocene Fiji volcanic arc. The bathymetric ridge was interpreted to represent a structural high analogous to the trench slope break of active convergent margins in the terminology of Karig and Sharman (1975). Single-channel seismic reflection profiles are suggestive of extensional deformation of basin sediments near this former arc margin (Figure 4 in Brocher and Holmes, 1985). This sediment deformation combined with high heat flow (Sclater and Menard, 1967) and high-amplitude magnetic anomalies (Brocher and Holmes, 1985) provides evidence for recent North Fiji Basin extension, that Brocher and Holmes attributed to the Neogene rotation of Viti Levu. If this process is continuing, the associated deformation should be reflected in the present-day seismicity.

The most important sequence within the WVL zone took place in September 1980, and constituted a mainshock-aftershock sequence, which followed a magnitude 5.7 earthquake in the southern portion of the seismic zone (Figure 20D). The mainshock, located at 19.2°S 176.5°E, appears to have been mislocated, as the aftershock zone is positioned some 40 km or more to the north, extending no further than the area 18.4°-18.9°S.

The focal mechanism solution for the mainshock of this sequence indicates strike-slip faulting with a significant normal component (from Everingham, 1985). The NNE strike of the sinistral plane of this mechanism
coincides with the strike of the seismic zone, and also parallels the deep basins west of Viti Levu. This observation suggests that the basins forming the western margin of the Fiji Platform are presently accommodating a dominant component of left-lateral strike-slip faulting parallel to the basins' strike. The sense of motion along this fault is close to that observed throughout the eastern North Fiji Basin and within the Fiji Platform.

Thus the hypothesis of simple extensional deformation of the WVL zone is not supported by the seismicity patterns associated with the 1980 sequence. Rather, they suggest that in its present configuration, the western margin of Fiji is accommodating a significant degree of strike-slip motion. Nonetheless, the attenuation of seismic waves that originate in this zone, the high heat flow, the recent extensional deformation of the margin, and the high-amplitude, short wavelength magnetic anomalies suggest that backarc rifting is a significant component of deformation in this area. However, contrary to Brocher and Holmes' simple model of mid-ocean ridge-type extension, this area, like the Fiji Fracture Zone, appears to be characterized by a leaky transform-type extension, dominated by strike-slip deformation. In this case, the proposed transform faults offsetting the west Viti Levu basins would become a series of left steps of a longer, sinistral strike-slip feature. According to this model, rifting is concentrated along the shallower ridges separating the basins, rather than within the basins themselves.

4. Kadavu/Hunter Fracture Zone Region (KAD): This zone stands at the intersection of a former convergent plate margin with the Fiji Platform. The Hunter Fracture Zone is a well-defined curvilinear belt of ridge/trough
topography extending from Fiji to the southern New Hebrides arc. At its western end, it intersects the southern termination of the New Hebrides Trench. The transition between these two features is a morphologically complex zone, characterized by subduction-related volcanism on Matthew and Hunter Islands, irregular bathymetric features on the upper plate, and intense shallow seismic activity (Louat, 1982; Maillet and Monzier, 1982; Monzier et al., 1984). In fact, bathymetric and seismic reflection profiles across the Hunter Fracture Zone show that the subduction margin morphology is preserved well into the Fiji Platform. The Koro Sea (east of Viti Levu; see Figure 7) represents its eastern termination. Hinge-faulting focal mechanism solutions at the western end of the HFZ document tearing of the Indo-Australian Plate (Hamburger and Isacks, 1985). Chase (1971) pointed out that shallow seismicity along the Hunter Fracture Zone rapidly drops off east of 174°E, where it was hypothesized to intersect a major North Fiji Basin spreading center. East of this intersection, the fracture zone may simply mark a relict lithospheric scar tracing the westward migration of the southern New Hebrides arc. Malahoff et al. (1982a) and Gill et al. (1984), however, proposed that the fracture zone has accommodated oblique subduction of South Fiji Basin lithosphere as recently as the early Quaternary. In fact, Kadavu Island is the one area of Fiji where calc-alkaline volcanism persisted beyond the Pliocene (Gill et al., 1984; Whelan et al., 1985). Nonetheless, the absence of an inclined seismic (Benioff) zone and shallow thrust-type mechanisms suggests that the Hunter Fracture Zone is not accommodating plate convergence at present; however, isolated earthquakes do occur along the entire length of the Hunter Fracture Zone, and major events
have occurred near its intersection with the Fiji Platform (Figures 9 and 10).

A significant number of earthquakes recorded by the seismic network are located in this region. Virtually all of them are positioned landward of the Fracture Zone and its continuation into the Koro Sea. The depths of these events are not well constrained, but there is no evidence of any intermediate-depth subduction-related seismicity in this zone.

The major earthquake sequence in this zone is the Kadavu earthquake swarm of July-August, 1983 (Hamburger and Qiolevu, 1983). The swarm included over 100 earthquakes and culminated in mainshocks of magnitude 5.1, 5.1, and 4.8. The maximum intensities were reported in westernmost Kadavu (MM V-VI), and several landslides were triggered by the largest of the mainshocks. The earthquakes occurred approximately 20 km offshore western Kadavu (Figure 20E), along a submarine extension of the Kadavu ridge.

The concentration of activity at shallow depths of the HFZ demonstrates active deformation of the upper plate of this former subduction zone; plate kinematic arguments suggest that the HFZ is presently accommodating extension between the South Fiji Basin (Indo-Australian Plate) and the Fiji Platform. The shallow activity is the manifestation of that deformation.

5. Lau Ridge (LAU): This is the least active portion of the Fiji region; most of the earthquakes within this seismic region are in fact located along the western edge of the ridge or within the eastern Koro Sea. One reliably located event, however, is positioned within the central portion of the ridge; it was recorded by the temporary station operating on Lakeba Island (Figure 2). Tectonically, the Lau Ridge is now part of the stable Indo-Australian Plate, and the major deformational areas are the
extensional centers of the Lau Basin to the East, the Fiji Fracture Zone to
the North, and the Hunter Fracture Zone to the west. No major historical
earthquakes (Figure 9) are reported in this region. Quaternary volcanism
has been reported at several localities in the Lau Group (Whelan et al.,
1985; Woodhall, 1985a), and recent tilting of the islands was observed by
Taylor (1978). Teleseismically located earthquakes are reported from the
southern Lau Ridge. This evidence of recent tectonism indicates that the
stability of the Lau Ridge is only relative, and that there is potential for
moderate-sized earthquakes, even within this relatively quiescent block of
the Fiji region.

6. Offshore Viti Levu (OF': This seismic region is characterized by
low activity, relative to the active belts of seismicity surrounding this
region. The low activity is reflected in a minimum in S-P intervals at
times of 6-20 seconds at seismic station Vunikawai in southeastern Viti Levu
(Sykes et al., 1969). It is striking that the broad shallow shelf north of
Viti Levu (Bligh Water Basin) is virtually devoid of seismicity (for ML
> 3) through the entire period of network observation. Activity is observed only
near the 1 km-deep trough (Vatu-Ira Channel) separating the basin from the
western shelf of Vanua Levu. This trough follows a major structural trend
controlling Pliocene volcanism in the Lomaiviti Group (Green and Cullen,
1973), and has been proposed as an active transform fault terminating the
Hunter Fracture Zone (Rodda and Kroenke, 1984). This conclusion is
certainly not warranted by the seismological data; however, the bathymetric
and structural trends, combined with the concentration of activity here,
indicate fault control.
A second area of seismic activity is the area surrounding the island of Koro, near the termination of the Hunter Fracture Zone. This zone has been active at low magnitude levels during several brief periods of activity (Figure 23E). It is clearly a zone of significant seismic potential, evidenced by the occurrence of a major historical event, the Ms = 6.5 Koro earthquake of 1932 (Everingham, 1982b). The area is an important confluence of major structures: the western end of the Hunter Fracture Zone terminates against the strong northeast-striking structural fabric of eastern Vanua Levu and Taveuni (Green and Cullen, 1973). There is evidence that convergence along the HFZ has terminated (Hamburger, 1986), but the Late Pliocene and Quaternary volcanic activity landward of the fracture zone attests to its recent activity. Throughout the area south and east of Viti Levu, seismic activity is concentrated on the landward (north and west) side of the bathymetric trough. The extensional stresses deforming the Fiji Platform do not appear to significantly deform the lithosphere of the neighboring South Fiji Basin or its continuation into the arc complex, the Koro Sea. However, where the South Fiji Basin lithosphere meets the deformed arc lithosphere south of Vanua Levu, it becomes a zone of high seismic activity, and is capable of a damaging earthquake of the size of the 1953 Suva or 1979 Taveuni events.

A third area of high activity is observed in the opposite corner of the offshore region: the Baravi Basin. Here, like other intra-platform seismic zones, activity is concentrated in several discrete periods of activity, separated by long periods of quiescence (Figure 23C). Activity is focussed along the 2 km depth contour marking the edge of the Fiji shelf. The contour also marks the edge of a major sedimentary basin fed by the rivers
of southern and western Viti Levu (Larue et al., 1980). It is characterized by free-air gravity lows to -70 mgal that result from up to 3 km of sediment fill in the basin. Seismic reflection profiles across the basin (Brocher and Holmes, 1985) demonstrate significant post-Pliocene extensional deformation along the its seaward margin. The high-angle faults show a significant normal displacement, but a strike-slip component is also suggested by Brocher and Holmes, based on the coincidence with structural trends in the West Viti Levu zone. In any case, the major earthquake sequences in 1979-1980 and 1984 demonstrate ongoing deformation of the Baravi Basin margin. Like other actively deforming zones close to the Fiji Platform, the apparent quiescence of the Baravi Basin at larger magnitudes (Figures 9 and 10) is likely to be a temporary one, reflecting a period of interseismic strain accumulation.

7. Central Viti Levu (CVL): Within the island of Viti Levu, the telemetered seismic network offers the best opportunity for evaluating the detailed characteristics of crustal seismicity associated with deformation within the Fiji Platform. The island of Viti Levu is also the source area for the most destructive earthquake in Fiji's history, the 1953 Suva earthquake, \((M_s = 6.75)\), making it the critical focal point of seismic hazard analysis for the country.

The earthquakes within the island of Viti Levu (Figure 24) are concentrated in two zones: one, a broad swath extending from central Viti Levu across the island to Ovalau, the second, a dense concentration of earthquakes within and offshore the southeastern portion of the main island. Cross sections AA' and BB' (Figure 2c), taken across the entire island, demonstrate the relative quiescence of northern and western Viti Levu and
Figure 24. Map of earthquakes within and around the island of Viti Levu. Earthquake grades: D - crosses; C - open circles; B - shaded circles; A - filled circles. Light shading shows areas of relief > 75 m; dark shading emphasizes high inland Nadrau Plateau, at elevation > 750 m. Topography from Dickenson, 1972. Faults, from Rodda and Band (1966), are shown by heavy lines. 100, 500, and 1000 m bathymetric contours are from Smith and Raicebe (1984). Seismic stations are shown as filled triangles.
Figure 25. Map showing locations of cross sections A-D within the island of Viti Levu. Brackets denote area included in sections.
Figure 26. Cross sections within the island of Viti Levu. Symbols denote earthquake grades, as in Figure 18. Locations shown in Figure 25. Triangles at top of sections denote positions of seismic stations along strike of the projections. No vertical exaggeration. Note that scales vary from section to section.
the dense concentrations of microearthquakes in the central and southeastern portions of the island. The sections also demonstrate graphically the confinement of seismicity to the upper 20 km of Fiji's lithosphere. The two subcrustal events at 42 and 45 km depth are poorly constrained (grade D), and are considered to be mislocations. The limiting depth is close to the average crustal thickness of ~19 km; this coincidence of focal and crustal depths is unique: in all other areas of extensional and strike-slip tectonism, the seismicity does not extend deeper than midcrustal depth (Chen and Molnar, 1983). Little information, however, is available from tectonic settings comparable to Fiji. The errors in hypocentral depth determinations and in crustal thickness estimates permit the existence of a relatively thin, aseismic lower crust. In any case, the crustal activity begins to taper off from 13 km depth; the majority of the earthquakes take place in the upper two-thirds of the crust.

The cross sections CC' and DD' examine the earthquake clusters in central Viti Levu. Two notable groupings stand out: one near 17.8°S, 177.8°E, which will be referred to as the Nadrau swarm, and a second near 17.8°S, 178°E, which will be referred to as the Monasavu swarm. Approximately fifty earthquakes occurred, in clusters of activity from early 1980 to mid-1981, in the western, or Nadrau, swarm. Because only the southwestern Viti Levu stations were operating at the time, the swarm earthquake depths in this area are poorly constrained; they appear to correspond to those observed within the seismic network; that is, generally limited to the upper 20 km of crust (cross section CC', Figure 26). A small number of deeper events are located in this area, but these, too, probably remain within the thickened crust beneath the axis of Viti Levu. The swarm
included three events with magnitudes $M_L > 3$. The cause of the swarm is unclear, but it is located on the western flank of the large central uplift at the core of Viti Levu. Adjacent to the Nadrau Plateau is a broad upland basin, the Mbuuku-Nandrungu basin. According to Dickenson (1972), this heavily dissected inland valley of Pliocene age was rapidly deformed from a gently graded concave stream valley to a convex plateau surface at 300-500 m above sea level; this uplifted valley surface has been deeply incised by modern streams whose floors are 50-150 m below the plateau surface.

Because of their position outside the seismic network, focal mechanism solutions for individual events are not available; however a composite focal mechanism for the Nadrau swarm indicates east-west extension, but is compatible with either a dip-slip (pure normal faulting), or strike-slip solution. In either case, the direction of extension is compatible with the regional direction of extension inferred from strike-slip focal mechanisms in the North Fiji and Lau basins (Hamburger, 1986). The crustal flexure induced by the rapid domal uplift that is peculiar to central Viti Levu is also likely to result in localized extensional stresses.

The second concentration of activity in central Viti Levu is the Monasavu swarm, positioned atop the central uplift of Viti Levu (Figure 24). This earthquake sequence presents a strong case for reservoir-induced seismic activity. The earthquakes also occur at crustal depths; those well constrained by the nearby Monasavu seismic station are shown to occur in the upper 4 km of crust (cross section DD', Figure 26), adjacent to the Monasavu Reservoir. The Monasavu Dam is an 82-meter high earthfill dam on the Nanuku Creek which impounds $133 \times 10^6$ metric tons of water; it is designed to provide hydroelectric power for the island of Viti Levu. The dam is the
largest public works project in the country's history and represents the major critical structure from the standpoint of seismic risk. Earthquakes within Viti Levu were unknown during the planning for the project, but a subsequent historical study (Everingham, 1983a) has uncovered at least one major event during the last century, of a size that could affect the dam's structure. The dam was completed in April 1982 and rapidly filled to its operating volume by February 1983. Three felt earthquakes shook the damsite as the water first approached its spill level, when the water weight in the reservoir increased most rapidly (J. Campbell, pers. comm., 1984). The three shocks, of magnitude 3.3, 2.7, and 2.8, were part of a sequence including 14 recorded events; several of the events were strongly felt in the surrounding villages (Everingham, 1983d). Each of the swarm "mainshocks" triggered a strong-motion accelerograph atop the dam, producing peak accelerations of 0.13 g, 0.07 g and 0.04 g, all on the north-south component of the accelerograph (Figure 27). A nearby accelerograph, positioned on bedrock adjacent to the dam, went untriggered, demonstrating considerable amplification of ground acceleration by the dam structure. The accelerograms are all extremely similar in character, with large mono-frequency oscillations on the north-south component, clearly shown by a sharp peak in the Fourier amplitude spectra at a period of 0.2 sec (Figure 28). This component is oriented transverse to the dam's structure and indicates probable resonant oscillation of the dam as a whole.

The limited number of stations operating at the time of the swarm did not permit very accurate locations of the mainshocks. However, the mainshocks are shallow and positioned within 5 km of the dam and the deepest part of the reservoir.
Figure 27. Accelerograms from strong-motion accelerograph operating on Monasavu Dam, Viti Levu, from earthquakes of 13, 14, and 23 February 1983 (ML = 3.3, 2.7, and 2.9, respectively). North-south component is transverse to the dam's structure. Figure is from Silverstein, 1985.
Figure 28. Fourier amplitude spectrum of acceleration from Monasavu Dam accelerograph, earthquake of 13 February, 1983. North-south component, transverse to dam's structure. Note resonance at approximately 5 Hz.
The area is one of significant background activity, evidenced by nine events located in the reservoir's vicinity prior to impoundment and numerous reports of felt earthquakes in the area (Everingham, 1983d). Nonetheless, a case for reservoir-induced activity can be made on several grounds: (1) The coincidence of the February, 1983 swarm with the peak in reservoir water level; (2) the proximity of these and subsequent events to the deepest portion of the reservoir; (3) the recording of 270 events at the Monasavu seismic station with S-P intervals less than about 1 second during a 17-month recording period (Stuart, 1985).

The third group of earthquakes in east-central Viti Levu follows the trend of a belt of sediments of the Upper Wainimala Group (Early-Middle Miocene) that separates the Pliocene Ba Volcanic Group in northern Viti Levu from the Late Miocene to Recent deposits of the Rewa Basin in southeastern Viti Levu (Verata Sedimentary Group; see Figure 8). The basin is fault-bounded on its western edge (Rodda, 1967); the lineation of epicenters along its northern edge suggests fault control along this margin as well.

8. Southeastern Viti Levu (SVL): This seismic region is densely populated by small-magnitude events (Figures 18 and 29) within the tightly spaced U.S. AID seismic network (see Figure 2). Many of the events in this zone are very small (to $M_L = -1.0$) and recorded only by 3 or 4 nearest stations. The apparent concentration of activity in this area is thus to a large degree a product of the station distribution. Nonetheless, a real concentration of activity does exist in the southeastern Viti Levu area, based on several observations: (1) there is a concentration of earthquakes of $M_L > 2$, for which uniform coverage is available for the entirety of Viti Levu (Figure 15); (2) several earthquakes were located in this area by the
Figure 29. Map of earthquakes in southeastern Viti Levu. Topography, bathymetry, faults, and symbols as in Figure 24.
tripartite network during 1965-1969, whereas the remainder of Viti Levu appears to be altogether aseismic (Figure 11); (3) a peak in S-P intervals was observed at times of 1-4 seconds at station Vunikawai, corresponding to earthquakes in the SVL zone (Sykes et al., 1969); (4) several felt earthquakes have originated in this portion of Viti Levu, including the destructive 1953 Suva earthquake (Houtz, 1962a,b; Everingham, 1983a, 1984). Earthquakes occur both on- and offshore southeastern Viti Levu. They are concentrated near the coast, in the area extending from Suva to Navua that was most severely affected by the 1953 Suva earthquake (Houtz, 1962a). The Houtz (1962a) "H" location of the 1953 mainshock, based on macroseismic data, submarine cable breakage and tsunami travel times, is directly within the dense nest of activity offshore Viti Levu (Figure 29). The teleseismic location by Sykes et al. (1969) "S" is significantly offset from the main zone of activity. Based on Houtz's field observations and the microearthquake activity recorded by the telemetered network, the Houtz location is accepted as the best estimate of the earthquake epicenter. Houtz proposed a normal (33 km) focal depth for the Suva earthquake, while Sykes et al. found a 21 km depth. The shallower depth is supported by the distribution of earthquakes offshore Viti Levu and by the character of the P-waveform recorded on long-period instruments at teleseismic distances. Cross section HH' (Figure 31) shows that earthquake depths in the area, like those within Viti Levu, are limited to the upper 22 km; the best constrained events are limited to the upper 15 km of crust. The Suva earthquake is likely to have occurred at a similar midcrustal depth; this is also suggested by the limited area from which maximum intensities were reported.
Figure 30. Map showing locations of cross sections E-J within southeastern Viti Levu. Brackets, dashed lines, and shading denote area included in cross sections.
Figure 31. Cross sections E-J within southeastern Viti Levu. Locations shown in Figure 30. Symbols as in Figure 24. No vertical exaggeration. Note that scales vary from section to section.
The well located events offshore Viti Levu fall into three groups: two north-trending belts of activity (near 178.25°E and 178.35°E), offset by an east-trending segment near 18.3°S. The epicentral pattern is suggestive of small fault segments within a broad, complex zone of deformation offshore Viti Levu. The north-south trends are close to the strike of a series of submarine canyons that cut the shelf of Viti Levu, as well as to important structural trends in south-central Viti Levu (Houtz, 1959). A subtle change in activity occurs near the coast (cross section JJ'; Figure 31), where activity widely distributed throughout the crust gives way to discrete nests of fault-related activity within Viti Levu.

On land the southeastern Viti Levu seismicity is located within an area of faulting, which disrupts the Oligocene to Pliocene strata exposed in the southeastern portion of the island. In only one case has an upper age limit been placed on faulting in this area, by the presence of a Miocene intrusion post-dating the tectonism. In all other cases, faulting may have continued into the Quaternary (P. Rodda, personal communication, 1984). While Tertiary faulting is documented elsewhere in Viti Levu, faulting is particularly evident in this portion of the island (Rodda and Band, 1966). The association with active shallow seismicity suggests that renewed (or continuing) movement along these faults in southeastern Viti Levu is accommodating the present stress system of the Fiji region. That this portion of Fiji is presently deforming is also corroborated by geodetic observations in southeastern Viti Levu. Berryman (1981) used retriangulation of six benchmarks in southeastern Viti Levu and one on Beqa Island to analyze shear strain within the southeastern Viti Levu seismic zone. Only by omitting the Beqa benchmark and one of the Viti Levu benchmarks could a consistent strain
pattern be resolved. With this correction Berryman determined a shear strain rate of 0.6 μrad/yr accumulated over the period 1909-1980. The direction of maximum compression determined was nearly east-west, in contrast with the east-west extension determined from focal mechanism solutions. However, the area from which the data are taken (within southeastern Viti Levu) is within the area strongly affected by the 1953 earthquake. Thus, the deformation may be dominated by the coseismic movement, rather than continuously accumulating coseismic strain. In any case, the data do suggest that significant horizontal deformation is taking place in an area coinciding with the southeastern Viti Levu seismic zone.

The earthquakes occur in discrete clusters within the seismic zone. Two densely populated centers of activity are located in southern Viti Levu; they are tightly clustered in space and time. The Waidina swarm, near 18.0°S, 178.25°E, is characterized by low magnitude activity (-0.9 ≤ M_L ≤ 2.9) occurring within a six-month period from late 1979 to early 1980. In cross section (EE' and FF', Figure 31) the well located earthquakes define a narrow cylindrical zone, less than 1.5 km in width, extending from 3 to 14 km depth. The swarm coincides with the eastern termination of a major east-striking fault, the Nakasu Fault (Colley, 1976), which parallels the southern boundary of the large Middle Miocene Wainivalu stock (Whelan et al., 1985). At its eastern end, the fault terminates at a small intrusive body, located along the western flank of the Medrausucu Range. Based on field observations, this Miocene intrusion is thought to post-date activity along the fault (P. Rodda, personal communication, 1984); in fact, the high activity along its margin suggests a concen-
tration of stress where movement along an active fault is limited by the presence of this intrusion.

The second major swarm in southeastern Viti Levu is the Waimanu swarm, located near 18.15°S, 178.25°E. The swarm had a magnitude range similar to the Waidina swarm and was also clustered in time. In cross section (GG', JJ', Figure 31) the well located events originate from a small volume, located at depths of 10-12 km. The swarm is located along a 10 km-long near-vertical normal fault that offsets a gabbro stock of probable Colo (Middle Miocene) age (Band, 1968). The northeast trend of the fault coincides with that of a series of important post-Colo normal faults. The trend is also close to that defined by the new mechanism for the Suva earthquake, and indicates probable reactivation in a strike-slip sense.

A secondary concentration of activity is observed along the Wainivakidau Fault, another of the northeast-striking faults that deform the late Tertiary rocks of southeastern Viti Levu. The sense of throw on this fault is similar to that observed near the Waimanu swarm. Earthquakes along the fault are concentrated at midcrustal depths (cross section EE', Figure 31).

Earthquake Focal Mechanisms

Only a limited amount of information is available on the state of stress and the nature of faulting within the Fiji Platform. As described by Hamburger and Isacks (1985) and Hamburger (1986), earthquakes in the inter-arc region describe two basic fields of stress: one associated with the Fiji Fracture Zone, characterized by strike-slip faulting along east- to northeast-striking fault planes, and a second, found throughout the Lau
Basin and the eastern North Fiji Basin, characterized by east-west extension, along northeast- and northwest-oriented strike-slip faults.

The two teleseismic mechanisms within the platform are for the 1979 Taveuni earthquake (Figure 21) and for the 1953 Suva earthquake (Figure 32). The Taveuni earthquake revealed a mechanism of strike-slip faulting similar to, but rotated slightly from, the mechanisms along the fracture zone. It is discussed in greater detail in the presentation of the Taveuni earthquake.

The Suva earthquake is important not only because of its destructive effects, but also because of its distance from the FFZ: it reflects the stress field within the interior of the Fiji Platform. This earthquake will thus shed light on the causes and the potential for large intraplate events within the platform. A mechanism for this event was obtained by Hodgson (1956), but is considered unreliable because of his reliance on reported first motions, use of reported motions for reflected phases (Pp, Pp', PpP', etc.), and uncritical mixing of short- and long-period observations. In the case of the Suva earthquake, the contradictory first motion reports from stations within the western U.S. and Europe forced him to fit a plane through these fields. Our analysis indicates that both areas are characterized by dilational first motions, significantly altering the earthquake's focal mechanism.

Analysis of the Suva earthquake is difficult because of the paucity of high sensitivity long-period seismographs, as well as the uneven geographical distribution of stations. In order to evaluate the focal mechanism, all available seismograms were gathered from stations operating at the time. Intermediate- or long-period records were obtained from New
Figure 32. Focal mechanism for the 1953 Suva earthquake. Equal-area projection of the lower hemisphere of the focal sphere. Large open and filled circles represent clear dilatational and compressional first motions, respectively, from long-period instruments. Moderate-sized circles are from intermediate- or short-period instruments. Small circles are less reliable first motions. Small + and - symbols are reported first motions, from Hodgson (1956). Solid lines show orientation of S-wave polarizations. P- and T-axes as in Figure 21.
Zealand, Australia, Japan, the western U.S., the eastern USSR, and Europe. Short-period records were also examined, but given less weight than reliable long-period first motions. S-wave polarizations were available only from three short-period stations in Japan, the eastern USSR, and Indonesia, but were of considerable help in constraining the fault planes. The best-fit solution, shown in Figure 32, indicates strike-slip faulting with a significant, but not very well constrained, dip-slip component. The east-west extension, shown by the position of the T-axis, as well as the northwest and northeast strikes of the nodal planes, are remarkably similar to those observed in the neighboring Lau and North Fiji basins. While one mechanism is not necessarily representative of the entire stress field in the platform, this earthquake demonstrates that a major part of the contemporary deformation in the platform takes place by strike-slip faulting in response to extensional stresses.

Houtz (1962a) favored a northwesterly-striking fault plane for the Suva earthquake, based on the orientation of submarine canyons offshore southern Viti Levu. In fact, the canyons strike in a north to north-northeast direction (Houtz, 1959), which parallels neither of the fault planes. Several major structural features contribute to the interpretation of the northeast-striking fault plane: (1) the Suva Peninsula (Figure 29) forms a major northeast-trending promontory along the coast; it is composed of uplifted Pliocene marine sediments of the Medrausucu Group (Suva Marl; Rodda et al., 1985). The western edge of the peninsula defines the deep-water Suva Harbor, dropping to over 20 m depth within 300 m from shore. The edge of the peninsula is marked by parallel lineaments recognized in airmotos, and the sediments in the harbor are sharply truncated against the peninsula,
suggesting active faulting along the basin edge (G. Shorten, personal communication, 1984); (2) the northeast trends are also important in the faulting observed in southeastern Viti Levu (Band, 1968; Figure 29); (3) a major northeast-striking structural fabric is reflected in the unusual submarine morphology near Beqa Island, south of Viti Levu. The barrier reef has a pronounced northeast-striking linear trend, as does the scarp that defines the Kadavu Passage to the south (Figure 29); (4) a major structural high, termed the "Beqa-Vatulele Lineament," separates the deep Suva and Baravi sedimentary basins offshore southern Viti Levu (Brocher and Holmes, 1985). This northeast-trending feature is marked by strong gravity and magnetic anomalies; (5) the overall trend of the seismicity offshore Viti Levu is suggestive of a northeast-striking zone. From the foregoing, the northeast-striking, sinistral shear fault of the Suva earthquake focal mechanism is chosen.

Earthquakes located by the telemetered network provide additional information on intraplate deformation in the platform. The small number of stations that record the microearthquakes in southeastern Viti Levu limits the quality on individual focal mechanism solutions. The first-motion directions recorded on the network stations constrain, but do not uniquely determine, earthquake fault planes. Most events can be satisfied by a range of solutions, from pure strike-slip to nearly pure dip-slip. Upper hemisphere projections for six events in southeastern Viti Levu are shown in Figure 33, with both strike-slip and dip-slip solutions, where possible. Because of the dominance of strike-slip faulting throughout the region, we have chosen the strike-slip solution as primary. However, the first-motion data alone do not demand this.
A commonality to the southeastern Viti Levu focal mechanisms is documented in Figure 34. The earthquakes' T-axes, whether for strike-slip or dip-slip mechanisms, are dominated by an east-west orientation. Similarly, the P-axes are generally oriented north-south. The pattern of stress orientation is very close to that observed in the 1953 Suva earthquake (shown by the letters "P" and "T" in Figure 34), and coincides with the stress field in the North Fiji and Lau basins.

The focal mechanism for the 1953 earthquake is corroborated by a composite focal mechanism for events located immediately offshore Viti Levu, shown in Figure 35. The first-motions for these events are consistent with a strike-slip mechanism with fault planes oriented parallel to the fault planes determined from the Suva earthquake. A normal faulting solution is equally possible (dashed lines in Figure 35). In either case, the east-west T-axis coincides with the regional direction of principal extension.

The stress orientations within the Fiji Platform demonstrate that the platform is not isolated, in a plate tectonic sense, from the interaction of microplates along its boundaries. The seismic deformation in the back-arc basins east and west of Fiji is dominated by the east-west growth of the interarc region. Hamburger (1986) showed that this extension takes place through strike-slip faulting along northeast- and northwest-trending fault planes. The same process is taking place in Fiji. This former arc terrane, once deformed by major compressive stresses, is now being extended by ductile thinning of the lithosphere, by creation of new oceanic crust around its edges, and by major strike-slip faulting both surrounding and within the platform.
Figure 33. Focal mechanisms for earthquakes in southeastern Viti Levu, based on data obtained from the telemetered network. Upper hemisphere projections. Symbols as in Figure 21. Both strike-slip (solid lines) and dip-slip (dashed lines) solutions are compatible with first motion directions.
Figure 34. Summary of P- and T-axes from network focal mechanisms, shown on upper hemisphere projection. P- and T-axes of the 1953 Suva earthquake are given for comparison, at base of letters P and T.
Figure 35. Composite focal mechanism for earthquakes located immediately offshore Viti Levu. Symbols as in Figure 21, lower hemisphere projection. Both strike-slip (solid lines) and dip-slip (dashed lines) solutions are compatible with first motion directions. Large and small letters P and T represent P- and T-axes for strike-slip and dip-slip solutions, respectively.
CONCLUSIONS

Our seismicity studies in Fiji have led to several significant new conclusions that bear directly on the earthquake hazard to Fiji's population.

(1) **Major earthquake zones** are located along the edges of the Fiji Platform, where deformation is concentrated. These zones are continuously active at moderate magnitudes ($M_L 3-5$). The seismic regime along one of these zones (the Fiji Fracture Zone) varies as a function of the zone's orientation relative to the plate motion directions.

(2) **Secondary earthquake zones** are located within the Fiji Platform. Large earthquakes occur more sporadically, separated by long periods of quiescence. Many of these zones are active at low magnitudes ($M_L \leq 3$).

(3) **Earthquake depths** are shallow, concentrated in the upper 18 km of Fiji's crust. The distribution is similar to that in other areas of extension and strike-slip deformation.

(4) **Earthquake magnitudes** in the Fiji region have all been less than 7.1. Despite the large rates of relative plate motion in the area, the thin lithosphere may be incapable of storing large stresses to generate great earthquakes ($M_S \geq 7.8$).

(5) The large 1953 Suva earthquake occurred at $18.2^\circ S$, $178.3^\circ E$ (Houtz's location), at crustal depths, by strike-slip faulting. The stress orientation from the focal mechanism is similar to that observed in the North Fiji and Lau basins, indicating that the platform is not isolated from the regional tectonic stresses. The nodal plane striking N50°E is chosen as the probable fault plane.
Microearthquakes in Viti Levu occur as a result of extensional stresses similar to those determined from the Suva earthquake.

Earthquakes in central Viti Levu may be related to the rapid doming of the island. A group of events near Monasavu Reservoir were induced by rapid filling of a large artificial lake in the interior of the island.

Earthquakes in southeastern Viti Levu occur in discrete nests that are tightly clustered in space and time. They are related to a series of near-vertical east to northeast-striking faults that cut the Mio-Pliocene rocks of southeastern Viti Levu.

These empirical observations, combined with the our regional studies of the Southwest Pacific, described by Hamburger (1986), permit several important tectonic conclusions to be drawn:

1. Fiji is part of a large shear system connecting the Tonga and New Hebrides arcs; extension is taking place throughout the region, along short, irregular spreading centers and "leaky transform" faults, involving both strike-slip and extensional deformation.

2. While convergence appears to have taken place along the Hunter Fracture Zone in the past, there is no evidence for present-day convergence. Rather, this plate boundary appears to be reactivated by extensional or strike-slip deformation of the upper plate.

3. The Fiji Platform is rotating in a clockwise sense, relative to the tectonic blocks that form its northern, western, and southern boundaries. This rotation is interpreted as a relatively stable block resisting more rapid counterclockwise rotational shear of the surrounding matrix.

4. The extension that produced the deep basins west of Viti Levu has
been replaced by strike-slip faulting that follows the basins' strike.

(5) Major "intraplate earthquakes" occur throughout the southern Fiji Platform, but at longer recurrence intervals than the "interplate" events that surround the platform.

ASSESSMENT OF EARTHQUAKE HAZARD

**Earthquake Recurrence Intervals**

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

Instrumental historical records exist from the late 19th century to the present as indicated elsewhere in this report. From this data set, shown in Figure 9, it is evident that the recurrence intervals along even the most active seismic belts surrounding the Fiji Islands exceed the historical records. Thus, the repetition of events along, say, the Fiji Fracture Zone, cannot be resolved. Nonetheless, the data do help constrain the overall recurrence of large earthquakes in the entire Fiji region. This problem is addressed by the frequency-magnitude relation observed by Everingham (1983c) for the period 1918-1960, as shown in Figure 36. This period of observation suggests that earthquakes of magnitude $M_s = 7$ or greater occur at the rate of 4.8 events/100 yrs. (or every 21 years), while earthquakes of magnitude 6.5 or greater occur at the rate of 42.9 events/100 yrs., or every 2 1/2 years. A similar relation was obtained from network studies by Hamburger (1986) and is shown in Figure 15. This magnitude-frequency relation sug-
Figure 36. Magnitude frequency plot for all earthquakes in the Fiji region, 1918-1960 (from Everingham, 1983c).
gests recurrence of magnitude $M_L = 7$ or greater at the rate of 6.5 events/100 years, or every 15 years. Magnitude 6.5 earthquakes, according to this relation, would be expected at a rate of 16.2 events/100 years, or every 6 years. In view of the differences in time sampled, magnitude scale used, and area included in the two studies, the agreement is remarkably good. The studies indicate that large, potentially destructive earthquakes are expected to occur in the Fiji region within the lifetime of critical engineering structures.

**Earthquake Potential**

An estimate of the maximum potential earthquake in this area has been considered by Everingham (1983c), and is shown graphically in Figure 37. In compiling this graph, Everingham computed annual energy release, based on a magnitude-energy relation, for the period 1918-1982. The average rate of energy release for the region is equivalent to that produced by a single yearly earthquake with magnitude $M_s = 6.5$. However, the rate of energy release is not constant, and is marked by periods of activity and quiescence. The range of energy release is shown by the two dashed lines in Figure 37, and the maximum likely energy release may be expected to fall within the bounding curve. Should this energy release be concentrated in a single large event, its magnitude would be approximately 7.5. This is slightly larger than the maximum observed historical event in Fiji, but is a realistic "design earthquake" for the most active zones surrounding the Fiji Islands. From this relation, Everingham also noted a 30-year cyclicity to the energy release in Fiji. Periods of high activity occurred in 1923-32 and 1952-60. A third period of high activity may be expected in the coming
Figure 37. Cumulative energy release in the Fiji region, 1918-1982 (from Everingham, 1983c).
few years, terminating a relatively quiescent period for the period 1961-1982.

Clearly, the earthquake potential is not uniform throughout the Fiji region. Historically, large earthquakes have concentrated in zones surrounding the Fiji Platform, with isolated large events occurring within the platform itself. In Figure 38, we separate the Fiji region into zones of seismic potential, based on the available seismicity data summarized in the previous section.

Zone I (Fiji Fracture Zone, Taveuni-northeast Vanua Levu region, West Viti Levu zone, western Lau Basin): This seismic region is characterized by high levels of seismicity on all time and magnitude scales (Figures 9, 10, 11, 17, 18). These belts apparently accommodate a large portion of the Pacific/Indo-Australian plate motion. The largest recorded earthquake in this belt was a magnitude 7.1 event that occurred northeast of Vanua Levu in 1949. Considering the history of earthquake energy release discussed above, a conservative estimate of $M_{\text{max}}$ along these active zones is $M_{\text{max}} = 7.5$.

Zone II (Kadavu region, Hunter Fracture Zone, Baravi and Suva Basins, Koro Sea): this area is one of moderately high seismic potential, with a history of occasional large earthquakes, separated by long periods of quiescence. This zone includes large events near Kadavu in 1850, 1950, and 1963, the 1932 Koro earthquake, and the 1953 Suva quake. The largest of these events was the magnitude 6.7 Suva earthquake. This zone has been much less active at moderate magnitudes than zone I (Figures 10, 11, 18) but is clearly capable of large and potentially destructive events. We have included southern and eastern Vanua Levu in zone II, based on evidence for small-magnitude activity near southern Vanua Levu (Figure 18), structural
Figure 38. Seismic zoning of the Fiji region. See text for discussion.
disruption of the Caukandrove/Natewa Bay region (Green and Cullen, 1973) and
the confluence of the Hunter Fracture Zone with the Fiji Platform. A
reasonable maximum design earthquake for this zone is $M_{\text{max}} = 7.0$. A larger
event is possible, but is considered less likely here, based on the his­
torical record of seismicity in this zone.

Zone III (central and eastern Viti Levu, Ovalau Island, Vatu-Ira
Channel: this zone is characterized by far lower activity than zones I and
II; with the exception of a single destructive event in the mid-nineteenth
century (Figure 9), is virtually devoid of historical activity. However,
low-magnitude activity is common in this region (Figures 17, 18).
Reservoir-induced activity at Monasavu Reservoir in central Viti Levu
attests to significant tectonic stress accumulation in that area. The
maximum probable earthquake for this zone is $M_{\text{max}} = 6.5$.

Zone IV (northern and western Viti Levu, Bligh Water Basin, northern
Vanua Levu, South Fiji Basin, Lau Ridge): these areas have been virtually
devoid of seismic activity on all time scales. Isolated microearthquakes
have occurred in this zone, but no significant activity has been observed.
These areas represent the most stable blocks within the broad
Pacific/Indo-Australian plate boundary, and are not expected to generate
significant activity in the future. Nonetheless because of its proximity to
the active zones of deformation, earthquakes to magnitude $M_{\text{max}} = 6.0$ should
be considered possible for this area.

Macroseismic Effects of Large Earthquakes

Expected values of strong ground motion are of prime engineering
interest. However, even if the recurrence interval of large earthquakes
near Fiji were reliably forecast, a major difficulty arises in trying to
translate earthquake size into actual values of ground motion at a particular site. To date, a relatively large number of strong-motion accelerograms have been generated in the far field of large earthquakes, especially in California and Japan. The difficulty in using magnitude-acceleration relations developed elsewhere lies in the extreme variability in attenuation of ground acceleration in various geologic environments (e.g., Hays, 1980). The absence of ground acceleration data for Fiji makes direct predictions of structural effects of earthquakes difficult. Hopefully, the presence of strong-motion accelerographs distributed throughout Fiji (Figure 3) will change this situation over the coming decades.

Until that time, we are altogether reliant on observations of intensity of ground shaking. That is, the large historical events in Fiji have been studied by their effects on cultural features (i.e., houses) rather than near-field seismological observations (i.e., strong-motion accelerograms). The magnitude-intensity relations observed for Fiji may then be used to predict the distribution of intensities that may be expected from large earthquakes along the major seismic zones close to the Fiji Islands (Figure 38). In some cases, the predicted intensities can be translated (under rather questionable assumptions) to peak ground accelerations from intensity-acceleration relations obtained elsewhere (e.g., Hays, 1980). For this study, we have used only intensities to avoid the added complication of intensity-acceleration conversion.

Everingham (1984) has summarized the available information on observed intensities in Fiji, based on six moderate to large events during this century. Modified Mercalli intensities observed in Fiji, as a function of magnitude and epicentral distance, are shown in Figure 39. These relations
Figure 39. Earthquake intensities (Modified Mercalli Index) observed in Fiji as a function of magnitude and epicentral distance (from Everingham, 1984).
were used to compute maximum intensities generated by design earthquakes located along each of the seismic zones defined in the previous segment. These predicted maximum intensities, given for population centers in Viti Levu and Vanua Levu and several of the outer islands, are shown in Table 1. These predictions provide a basis for conservative engineering, planning, and civil defense decisions that pertain to development in Fiji.

Several important caveats, however, should be taken into consideration in using these maximum intensities:

(1) they are only estimates, based on extrapolations from the brief historical record of earthquakes in Fiji. The "design earthquakes" for each seismic zone are considered to be realistic upper bounds on the magnitudes expected there. However, anomalous, unpredicted earthquakes that exceed that size are conceivable occurrences;

(2) the estimates contain no information on recurrence of intensities. Thus, the recurrence of a given intensity may be much higher for one site than another site, depending on the return time for large earthquakes on the neighboring seismic zones as well as the substrate of each site;

(3) the estimates are based on far-field effects of earthquakes. Information on near-field effects of even moderate events in Fiji are scanty, and highly unpredictable. Thus, a magnitude 5 event directly beneath a city may produce extremely high intensities in a very restricted area close to the epicenter.

Tsunami Hazard

In addition to the direct damage from ground shaking in the vicinity of an earthquake, large earthquakes in the southwest Pacific have been shown to cause considerable damage, at both regional and global distances, by
Table 1. Predicted maximum intensities of ground shaking (Modified Mercalli Index) generated by maximum probable earthquakes along the seismic zones shown in Figure 37.

<table>
<thead>
<tr>
<th>Location</th>
<th>Zone I $M_{\text{max}} = 7.5$</th>
<th>Zone II $M_{\text{max}} = 7.0$</th>
<th>Zone III $M_{\text{max}} = 6.5$</th>
<th>Zone IV $M_{\text{max}} = 6.0$</th>
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<tr>
<td>Suva</td>
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<td>8-9</td>
<td>8</td>
<td>4-5</td>
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<td>Lautoka</td>
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<td>7-8</td>
<td>7</td>
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<tr>
<td>Nadi</td>
<td>6-7</td>
<td>8</td>
<td>7-8</td>
<td>7</td>
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<tr>
<td>Monasavu</td>
<td>6</td>
<td>8</td>
<td>7-8</td>
<td>7</td>
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<tr>
<td>Ba</td>
<td>6-7</td>
<td>6-7</td>
<td>7-8</td>
<td>7</td>
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<tr>
<td>Sigatoka</td>
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<td>8-9</td>
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<td>9-10</td>
<td>8-9</td>
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<td>6-7</td>
</tr>
</tbody>
</table>
earthquake-generated tsunamis. 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 coast are particularly vulnerable to damage by these waves. The shallow seismic zones of the Southwest Pacific have a history of earthquakes-generated tsunamis (Figure 40). A few tsunamis have originated in the Fiji region. Two significant tsunamis occurred in 1881 and 1953; the latter was associated with the 1953 Suva earthquake. A smaller event located southwest of Suva in 1975 generated a very small sea wave (Everingham, 1983b). Major Pacific-wide tsunamis, such as those generated along the South American or Alaskan plate margins, apparently are not generated near Fiji. Significant local tsunamis, however, may be associated with large shallow earthquakes in the immediate vicinity. The potential for tsunamis is of particular importance in view of the concentration of population and development in low-lying coastal areas of Fiji.

A tsunami education program for the residents of Fiji is recommended (Appendix IV 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.).

Volcanic Hazard

Quaternary volcanic activity is far less prevalent in Fiji than elsewhere in the Southwest Pacific. Volcanism less than 2 million years old has been reported in only six localities in Fiji (Naigani, Kadavu, Koro, Moala, Mago, and Taveuni Islands; see Rodda and Kroenke, 1984). There is no historical record of volcanic activity in Fiji. However, Frost (1974) reported evidence for a prehistoric eruption on Taveuni Island, dated at
Figure 40. Tsunami history of the Southwest Pacific. Filled circles indicate locations of tsunamigenic events; dashed circles indicate inferred locations of tsunamigenic events.
2050 ± 150 years before present, based on carbon dating. Elsewhere, there is no evidence for volcanic activity younger than 250,000 years, and thus volcanic activity presents little threat to the inhabitants of those islands. The recent activity on Taveuni warrants seismic monitoring in the future.

Eruptions elsewhere in the Pacific can also have significant effects on Fiji. The submarine eruptions at Home Reef, Tonga during March 1984 produced large quantities of pumice, which subsequently rafted across vast areas of the Southwest Pacific. The floating pumice piled ashore locally, and resulted in serious problems with shipping in the region (SEAN Bulletin, 1984).

**IMPLICATIONS FOR MITIGATION OF EARTHQUAKE RISK**

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

**Earthquake Education**

First, an earthquake education program in Fiji should be strongly encouraged. At minimal cost to the Government, such a program may be mounted through the schools, Red Cross programs, and through the news media. In other countries, earthquake education programs have taught simple methods of strengthening house construction, and minimizing hazardous conditions within the home; they have warned of tsunami hazards to coastal dwellers; they have instructed on proper behavior during an earthquake; they have helped to encourage storage of emergency food, water and equipment in many
households; and importantly, they have helped avoid panic during an earthquake and stimulated cooperation with government officials following such a disaster. Earthquake education programs are effectively combined with other disaster preparedness programs (e.g., cyclones, floods, and so on).

**Building Codes**

Second, adoption of stringent building codes for all of Fiji is imperative. The experience of the 1953 Suva earthquake (Houtz, 1962a) demonstrates the severe effects of a moderate-sized earthquake near the capital. There is a very real danger of a larger earthquake occurring very close to Suva; the effects of such an event would be multiplied by the increased development since 1953. In general the adequacy of construction is a major factor controlling the damage and loss of life brought on by such an earthquake. Building codes designed for areas of similar earthquake hazard, such as New Zealand Code "A," California Building Codes, or Papua New Guinea Codes 1 or 2, may be appropriate for the portions of Fiji at greatest risk. Certainly, New Zealand Code "B" should be mandated for all public edifices in Fiji. Observation of such codes is most crucial for public multistory buildings in the major towns of Viti Levu and Vanua Levu. 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, specific 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 that has been implemented in Fiji, 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 defense plans already is in place in Fiji. Programs specific to the earthquake hazard may be added, following similar programs in Papua New Guinea and New Zealand.

**Long-term Seismicity Observations**

Fourth, long-term seismicity and strong motion observations should be continued and supported by both the Fiji government and overseas aid programs. In the long-term, such information will help to refine estimates of seismic potential along the plate boundaries that surround Fiji; they will help to more directly and accurately assess the ground motion parameters of direct concern to engineers for building design in Fiji—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 Fiji's population.

**International Cooperation**

Fifth, international cooperation among the island countries of the Southwest Pacific may significantly help in Fiji'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. Fiji may take advantage of the previous, current, and any future efforts of the other countries in the region.
REFERENCES


Iyer, H. M., Geophysical evidence for the locations, shapes and sizes, and internal structures of magma chambers beneath regions of Quaternary volcanism, Phil. Trans. Roy. Soc. Lond., A310, 473-510, 1984.


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 tsunami, 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.


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.


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.
As part of our program of field investigations in Fiji, Tonga and Vanuatu, our researcher was able to visit the neighboring island countries of the Southwest Pacific region. During these visits he was able to meet with scientists and public officials involved with the earthquake hazard problem facing each country. In every case, the governments are aware of and have taken some action to mitigate the potential losses due to destructive earthquakes, but these governmental responses have varied widely from country to country. This report focuses on the seismological institutions and facilities in each of the countries and their capabilities 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.

TONGA

Seismological Facilities

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

Strong Motion Accelerographs

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

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

Critical Facilities

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

Earthquake Preparedness Programs

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

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

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 A1); 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 tiltmeter, 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 A1). 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.

**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 processing and shipping facilities located there. There are several three- and four-story buildings in the center of Luganville. There was significant damage to
Figure A1. 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.
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 gauges 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 accelerographs 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 carried 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 multi-story 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 A2). 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 A2). 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 Kinematics 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 establish an engineering seismologist position to analyze the accumulating data, and to further upgrade the accelerograph network.

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
Figure A2. Papua New Guinea seismograph and accelerograph networks.
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 intensive 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 A3). 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 A5. The network routinely locates all earthquakes of $M_L > 3.8$ within New Zealand, and earthquakes with $M_S > 5.0$ for the region within $10^\circ$ 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 Karori, 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.
Figure A3. Seismic zones for building construction in Papua New Guinea (Jury et al., 1982).
Figure A5. Seismograph stations of the national network (left) and the distribution of large, shallow earthquakes (right) in New Zealand (Seismological Observatory, Wellington, 1980).
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 Apia (Western Samoa), Raratonga (Cook Islands) and Scott Base (Antarctica). Short-period stations operate at Apia (Western Samoa), Campbell Island (New Zealand), Chatham Islands (New Zealand), Nadi (Fiji), Nime, and Raoul Island (Kermadec Island, New Zealand). Readings from these stations are routinely reported to PDE and ISC for global earthquake location.

Wellington Network

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

Pukaki Network

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

Related Seismology Research

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

The New Zealand strong motion accelerograph network now consists of 225 instruments, operated by the Physics and Engineering Laboratory of DSIR. Most of these instruments are of a New Zealand design (Mechanical and Optical Accelerographs), and analog records are made on photographic film. Three digitally recording accelerographs are now in operation in
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New Zealand, and the M.O. records are digitized for computational analysis. Analysis of this empirical data is being used for a revision of New Zealand’s building codes.
REFERENCES


INFORMATION CONTACTS

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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

<table>
<thead>
<tr>
<th>Name</th>
<th>Position/Department</th>
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<tbody>
<tr>
<td>S. Danitofea</td>
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<td>D. Tuni</td>
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<td>R. Walshaw</td>
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<td>J. Vunagi</td>
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<td>D. Gwynn</td>
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### PAPUA NEW GUINEA

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<tr>
<th>Name</th>
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<tbody>
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<td>K. Doble</td>
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<td>I. Ripper</td>
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<td>G. Seidel</td>
<td>Information Officer, Volcanological Observatory</td>
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<td>G. Anderson</td>
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<td>J. Wilkins</td>
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### NEW ZEALAND

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<th>Name</th>
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<tr>
<td>W. Smith</td>
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### UNITED STATES

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<th>Name</th>
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<tr>
<td>G. Burton</td>
<td>Director, Pacific Tsunami Warning Center</td>
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<tr>
<td>R. Sillcox</td>
<td>Seismologist (PTWC)</td>
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<tr>
<td>G. Pararis-Corayannis</td>
<td>Director, International Tsunami Information Center</td>
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<td>Branch of Pacific Marine Geology (USGS)</td>
</tr>
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APPENDIX IV. 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.