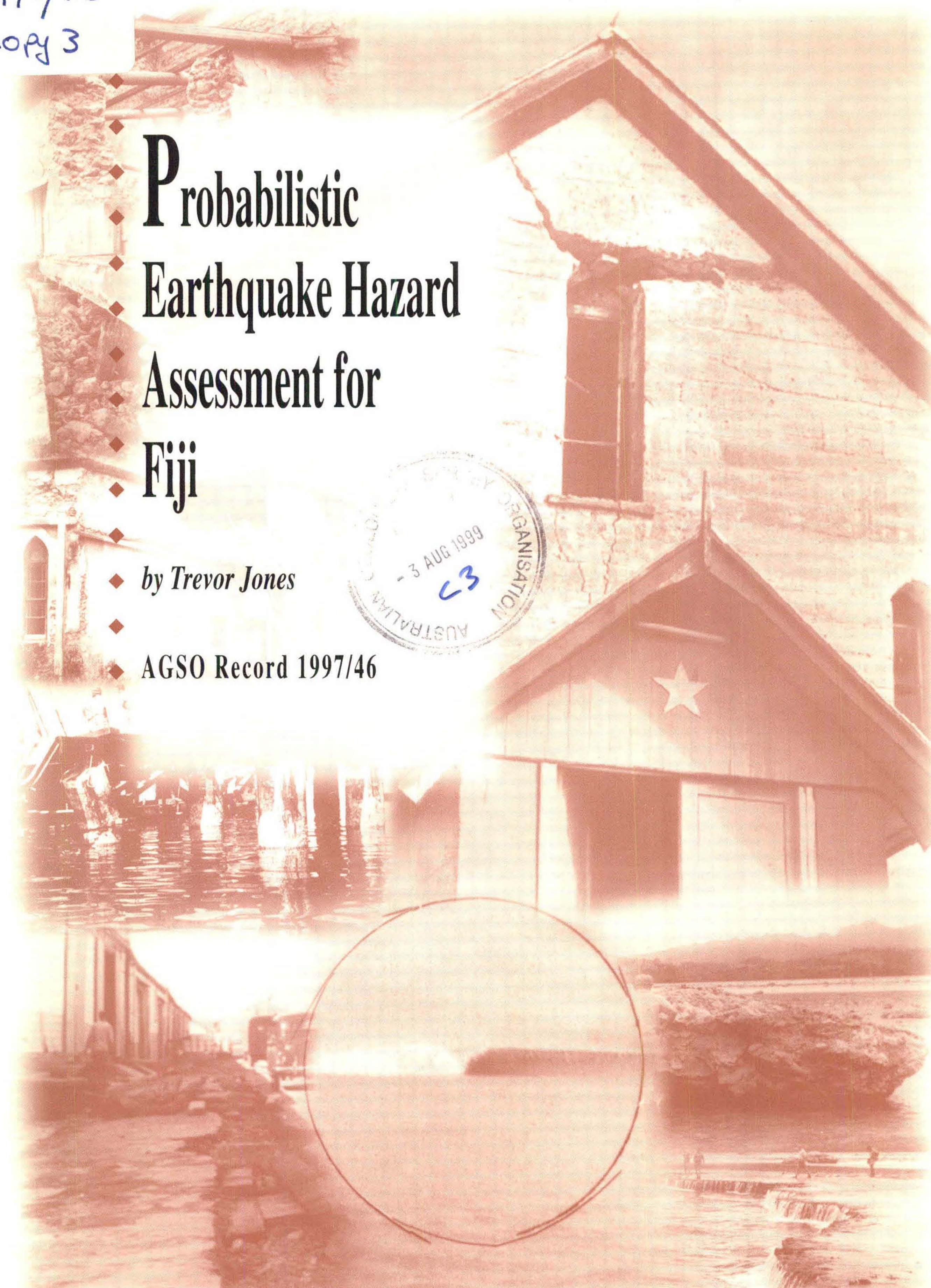

Probabilistic Earthquake Hazard Assessment for Fiji

by Trevor Jones

AGSO Record 1997/46

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AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

MINERAL RESOURCES DEPARTMENT • FIJI •

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PROBABILISTIC EARTHQUAKE HAZARD ASSESSMENT FOR FIJI

by

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Trevor Jones — Australian Geological Survey Organisation

September 1997

SUMMARY

Probabilistic earthquake hazard maps were prepared for the Fiji Islands. Damage has been caused by Fiji earthquakes around 1850, in 1884, 1902, 1919, 1932 (twice), 1953 and 1979. No previous assessment had produced a comprehensive description of the earthquake hazard in Fiji and the present study was initiated in 1990 when the author was attached to the Mineral Resources Department, Fiji. Collection and analysis of data continued at MRD until 1992 and the study was completed at the Australian Geological Survey Organisation in 1993-1997.

The aim of the study was to produce probabilistic earthquake hazard maps which can be used in the National Building Code for Fiji, for design of special structures, for planning, for emergency management and for risk management. Few, if any, similar studies have been undertaken in the seismically active Southwest Pacific.

A catalogue of about 3,200 shallow earthquakes occurring from around 1850 to 1990 in an area extending to 200 km from all populated islands, and featuring about 2,250 earthquakes located by the Fiji National Seismographic Network (FSN), was used in the study. Magnitudes of all earthquakes were converted to moment magnitude Mw and the largest known earthquake had a magnitude of Mw 7.1. Macroseismic data from 16 shallow earthquakes were analysed to produce a relation for the attenuation of Modified Mercalli Intensity in Fiji.

The probabilistic methodology introduced by Cornell (1968) was used. The procedures to calculate earthquake hazard for Fiji paralleled closely the procedures used to prepare the Zone Factor map in NZS 4203:1992; Part 4 Earthquake Provisions. The primary reason for following the New Zealand procedures is that the Structural Provisions for Earthquake Loads in the draft National Building Code for Fiji (Section B1.2 (b); Pacific Building Standards Project, 1990) refer to NZS 4203: Part 4.

All parts of the study area were considered sufficiently seismically active to justify their inclusion in a source zone and seismicity parameters describing nine earthquake source zones were defined. The Modified Katayama relation for the attenuation of strong ground shaking developed for New Zealand was used in the absence of instrumentally recorded data from Fiji. The good agreement between the attenuation of Modified Mercalli Intensity in Fiji and in New Zealand provided some confidence that the Modified Katayama attenuation is similarly appropriate for Fiji and New Zealand.

Probabilistic earthquake hazard maps were prepared for return periods of 50, 150, 450 and 1,000 years. The hazard was represented by values of acceleration for elastic, 5% damped, horizontal response spectra at period T = 0.2 seconds for Katayama ground condition Type 3.

The earthquake hazard in Fiji is estimated to range from moderately low to very high. The hazard estimated for Rotuma is comparable to moderate continental intraplate values. The estimates for most of Viti Levu are comparable to moderate values in New Zealand. Spectral acceleration values in the map for a 450 year return period lie between 0.5 g and 0.7 g for a large area of Fiji: almost all of Viti Levu including Suva, western Vanua Levu, the Lomaiviti Group, and the Lau Group from Vanua Balavu to Nayau (Fig. 1). The estimated hazard is significantly higher in the northern Yasawa Group and

western Kadavu where spectral accelerations of around 1.0 g were calculated for a 450 year return period. The spectral accelerations calculated for eastern Cakaudrove (Taveuni, Udu and Rabi) and Cikobia range from about 1.2 g to 1.5 g and are higher than the maximum spectral acceleration of 1.2 g specified for New Zealand in NZS 4203:1992.

The earthquake hazard map for a 450 year return period is recommended as a basis for the Zone Factor map to replace the Preliminary Earthquake Risk Map in the draft 1990 National Building Code for Fiji. Simultaneous with adopting the new Zone Factor map, Section B1.2 (b) of the National Building Code should be amended to refer to NZS 4203:1992. Failure to make this amendment could result in the misapplication of the Zone Factor in loading calculations with a consequent overspecification of lateral strength requirements of approximately 50%.

The proposed Zone Factor map for Fiji is similar, in broad terms, to the Preliminary Earthquake Risk Map in the 1990 draft National Building Code for Fiji although there are some significant differences. The hazard estimated for western Viti Levu, including Nadi, Lautoka, Ba and Tavua, is similar to estimates in the 1990 map. Estimated hazard at Kadavu, Labasa and the Yasawa Group also is similar to that in the 1990 map. The new hazard estimates for the Lomaiviti Group and southern and eastern Viti Levu including Suva are about 25% lower than the estimates in the 1990 map. Hazard estimates for the Lau Group are lower than previously estimated except for Vanua Balavu where the estimate is little changed. The estimate of hazard for Rotuma is lower by a factor of about three compared to the value in the 1990 map. In eastern Vanua Levu, Taveuni, Rabi and Cikobia the new estimates of hazard range from zero to 40% higher than the estimates in the 1990 map.

The Fiji Seismographic Network has proven extremely valuable in defining the seismicity of Fiji in its first 10 years of operation. Its continued operation will lead to improved estimates of seismic hazard in Fiji, especially in Viti Levu and western Vanua Levu.

Local strong motion data are required to define the attenuation of strong shaking and ultimately to produce uniform hazard response spectra to describe the earthquake hazard. An increase in the number of fixed, free-field digital instruments in the Southwest Pacific, and the deployment of similar instruments to record aftershocks in the epicentral areas of strong earthquakes, is essential to provide such data.

This national hazard assessment does not take into account the different ground conditions which may exist in urban areas and at critical facilities. The site specific hazard may be strongly dependent on local ground conditions and the hazard assessments of this study should be augmented by detailed urban zonation studies and site-dependent risk studies for lifelines and important infrastructure where appropriate.

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1. INTRODUCTION

> 'The first earthquake of importance of which I was a witness occurred at Ba one night in September, 1907. The wooden presbytery was severely shaken and I listened to the creak of the beams straining as if some giant force was trying to tear them apart ... The second quake that I remember and which merits attention occurred in 1919 when I happened to be on a visit to Solevu ... There were two severe tremors. (It brought great destruction to the mission at Tunuloa, Cakaudrove.) The third happened ... at Lomary or Sigatoka in 1921 ... Twelve years later there was another earthquake in the Tunuloa area. I was there at the time ... Rabi, opposite, was severely shaken ... and ... we could observe ... the marks of large landslides on the hills at Rabi. And so we go on. Where did one get the idea that earthquakes in Fiji are not serious affairs.' (sic.)
>
> - Father J. Castanie, S.M., Fiji Times and Herald, 22 September 1953

The report of Father Castanie was published eight days after the 14 September 1953 Mw 6.8 Suva earthquake which caused intensities of Modified Mercalli Intensity (MMI) 8 from Navua to Lami, intensities of MM7 in Suva, and generated a tsunami from a submarine landslide (Houtz, 1962a; Everingham, 1987).

> 'Two persons were killed outright by the earthquake; one by a landslide at Navua, and another by falling masonry at Suva. A third died later of injuries. Three people were drowned in Suva as a result of the tsunami and two more on Kadavu island.'
>
> - Houtz, 1962a

The existence of a Fijian name for earthquake, 'une une', indicates the inhabitants of Fiji have long recognised that the islands are seismically active. However, significant strong and damaging historical earthquakes had been forgotten and it was through reports such as that by Father Castanie that Everingham (1983a, 1987) compiled a list of historic (instrumental and pre-instrumental) earthquakes.

The aim of this study is to examine all significant data on the seismicity and the attenuation of strong ground shaking in Fiji and from these data produce probabilistic earthquake hazard maps which can be used in the National Building Code for Fiji, for design of special structures, for planning, for emergency management and for risk management.

Previous unpublished hazard assessments for Fiji were made, amongst others, by Houtz (1961) who treated Fiji as a single zone of uniform seismicity, Berryman (1979) who produced a seismotectonic zoning map of Fiji based mainly on global epicentral data and late Quaternary coastal uplift, and Everingham (1986b) who made provisional zonations for Fiji based on comparisons of the frequencies of recurrence of MMI with New Zealand and Australia. The loadings of Zone B of the New Zealand Basic Loads Code NZS 4203 (1974) were adopted for Suva in 1974 (Maybin, 1991). Jones et al. (1993) summarised the history of earthquake hazard assessment in Fiji.

None of these assessments produced a comprehensive description of the earthquake hazard in Fiji and the present study was initiated when the author was attached to the Mineral Resources Department, Fiji. During this time the author prepared a 'Preliminary Earthquake Risk Map for Fiji' which was included in the 1990 draft of the National Building Code for Fiji (Pacific Building Standards Project, 1990). The hazard map for a return period of 450 years presented here is intended to replace the preliminary map in the building code.

Apart from its application to the building code, the hazard assessment provides a basis to assess the risk to structures and infrastructure not described by the code. Such infrastructure includes nationally important facilities such as the hydro-electric generating plant at Monasavu dam and port facilities at Suva, Nadi and Lautoka.

The area of interest, for the purposes of vulnerability mitigation, is that area containing all populated islands. The geographical window chosen, therefore, for the determination of seismicity parameters within earthquake source zones, is bounded by latitudes 14°S to 21°S and longitudes 175.5°E to 177°W (Fig. 1). These boundaries extend beyond all populated islands, from Cikobia in the north and Fulaga and the Ogea islands in the south, by at least 200 km so that the effects of potentially hazardous ground shaking in populated areas from large (Mw~7.5) earthquakes at these distances will be included in the probabilistic calculations. The exception is the island of Rotuma (approximate location 12.5°S, 177.2°E; about 570 km north of the northern coast of Viti Levu). Seismicity within the area latitude 10.5°S to 14.5°S, longitude 175°E to 179°E was examined to produce estimates of hazard for Rotuma.

2. DATA

A total of 3,205 shallow earthquakes was contained in the catalogue which was used to determine the seismicity of the source zones (Fig. 2). The catalogue is a subset of the catalogue compiled by Jones and Dropsy (1995). The period of observation extends from about 1850 (Everingham, 1983a) to 1990.

The first important source of data in the catalogue is the list of hypocentres located by the global seismographic network. Sources are the International Seismological Service (ISS) and its successor the International Seismological Centre (ISC), Gutenberg and Richter (1956a), Sykes (1966), and the National Earthquake Information Centre (NEIC) of the US Geological Survey (USGS).

A second important source of hypocentral data is the work on moderate and large historical earthquakes, including pre-instrumental earthquakes, of Everingham (1983a, 1983b, 1986a, 1987). He compiled macroseismic data and discovered information on several strong earthquakes not contained in the global catalogues, determined surface wave magnitudes and redetermined epicentres for earthquakes sometimes grossly mislocated by the global networks.

The third important source of hypocentral data used in this study is the set of 2,262 earthquakes located from data provided by the Fiji Seismographic Network (FSN). The FSN began operation in its modern form in November 1979 and the numerical domination of the catalogue by the events located from data of the FSN points to the importance of this network is assessing the earthquake hazard in Fiji. The events detected by the FSN are mostly located within 100 km of Viti Levu and Vanua Levu, are more accurately located than events located by the global network, and have a much lower magnitude threshold than those located by the global network (Fig. 3). These events most accurately describe the spatial and temporal occurrence of small and moderate earthquakes near the centres of major population and urban and infrastructural development in Fiji. The events detected by the FSN were located either by the Fiji Mineral Resources Department (MRD) or by Hamburger (1986; see Hamburger et al., 1990). The FSN and the earthquake catalogue of Fiji are maintained by MRD.

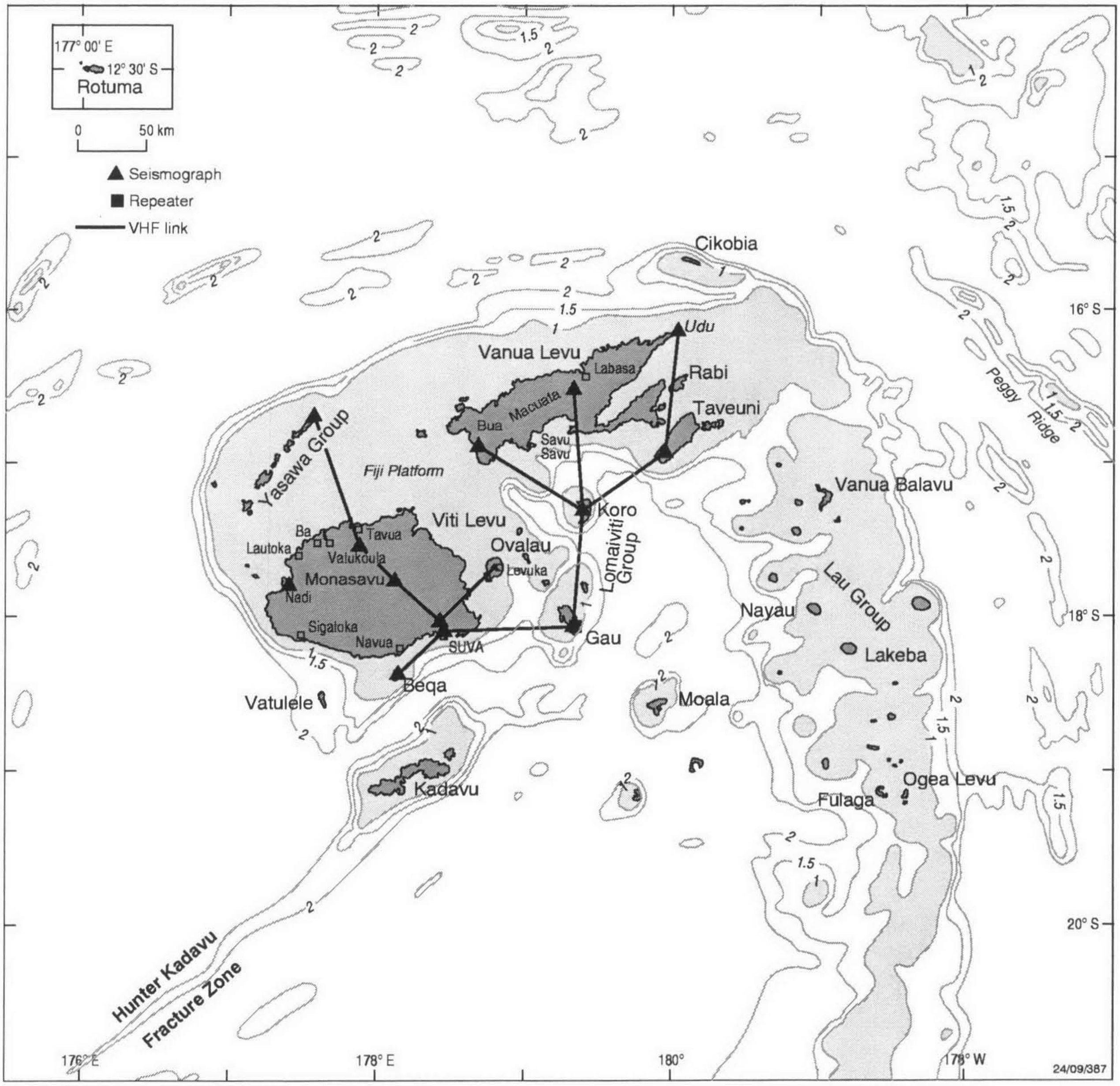

Figure 1 Map of the Fiji Islands showing stations in the Fiji National Seismographic Network around 1993. Isobaths are in kilometres.

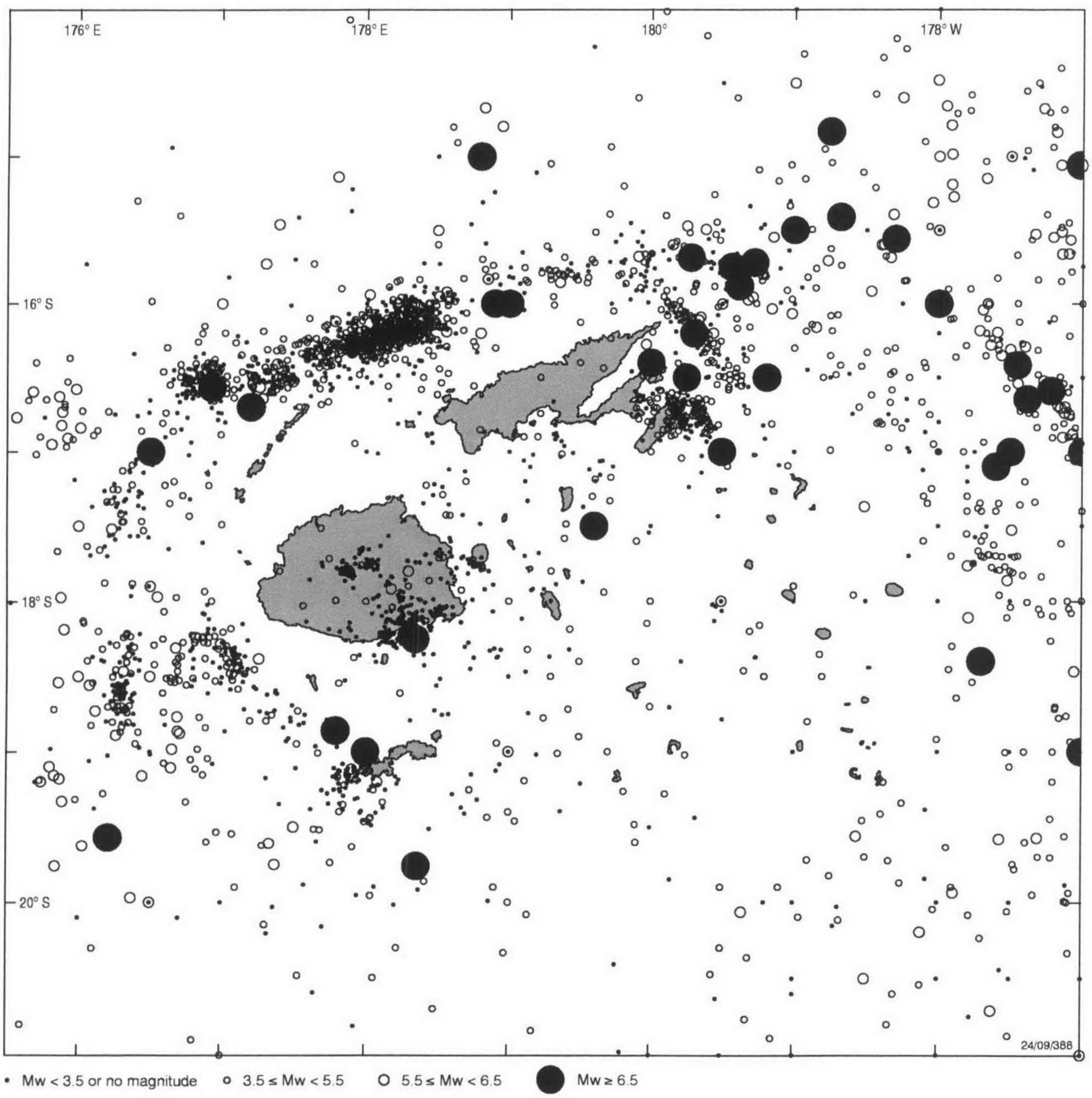

Figure 2 Shallow seismicity of the Fiji Islands (depth ≤ 100 km). Hollow circles represent epicentres of all earthquakes with magnitude Mw < 6.5 to the end of 1990 and filled circles epicentres of events with Mw ≥ 6.5 to the end of 1996.

Figure 1 shows the configuration of the FSN around 1993. The Suva seismograph has operated more or less continuously from 1913 and the Nadi seismograph was installed in 1971. Five short-period seismographs in addition to Suva and Vunikawai were installed in eastern Viti Levu and Ovalau in 1979 and an additional five short period seismographs were installed in Vanua Levu, the Lomaiviti Group and Taveuni in 1981. Continuous data from all stations except Nadi and Monasavu were telemetered in real time to the seismological observatory at MRD in Suva by VHF analogue radio signal where triggered seismograms were dumped to a chart recorder. The FSN largely retained this configuration from 1981 to the mid 1990s. Singh (1985) described the FSN.

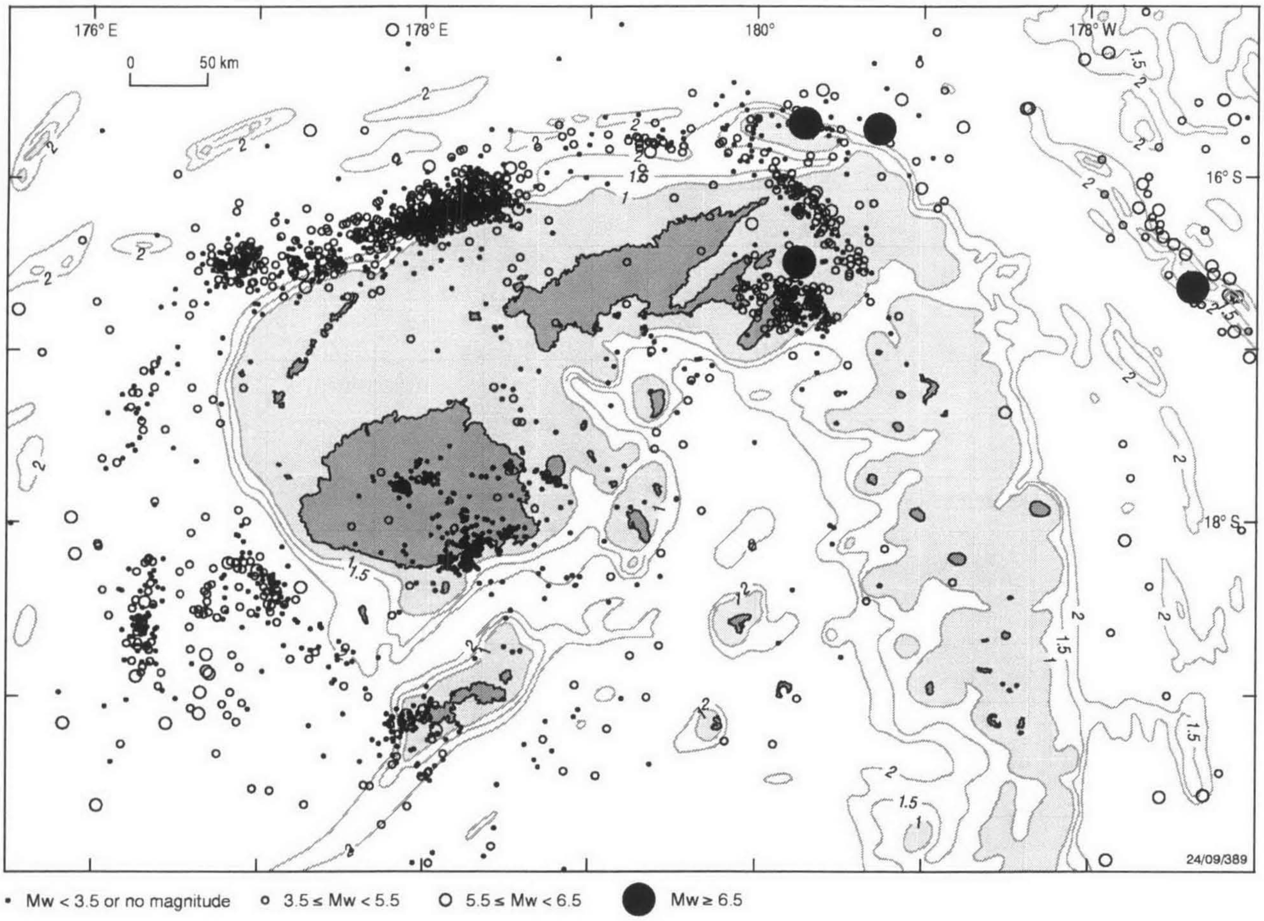

Figure 3 Shallow seismicity of the Fiji Islands from November 1979, time of the establishment of the Fiji Seismographic Network, to the end of 1990 (hollow circles representing epicentres of earthquakes with magnitude Mw < 6.5) or to the end of 1996 (filled circles representing epicentres of events with Mw ≥ 6.5). Isobaths are in kilometres.

The seismographic coverage of Fiji was much poorer prior to the establishment of the FSN. The Afiamalu seismograph began operation in 1958; the Port Vila, Noumea and Honiara seismographs in 1960; and the Raratonga seismograph in 1965. Furthermore, unlike seismographs on continents, seismographs in the Southwest Pacific region are insensitive owing to interference from large-amplitude, surf-generated noise. Before 1965, only five seismographs including the Suva seismograph were operating within 20° of Fiji and, apart from the Suva seismograph, these would have detected fewer shallow Fiji earthquakes than some Australian seismographs.

A maximum of about 11 years of data from the FSN was used in this study. This time may appear to be a relatively brief period in which to accurately describe earthquake source zones. However, the seismicity is sufficiently high that robust definition could be made of most offshore source zones because of their high seismicity, and reasonably good estimates of earthquake hazard could be made for all parts of Fiji.

The other source of data in this study is the attenuation relation of Modified Mercalli Intensity (MMI; Eiby, 1966), developed for this study from an analysis of macroseismic data from 16 shallow earthquakes in Fiji. This relation shows that the attenuation of

MMI is similar to that in New Zealand. Although the MMI relation was not used in the probabilistic hazard calculations, it provided some confidence that the instrumentally derived New Zealand attenuation relations employed in the calculations are similarly appropriate for Fiji and New Zealand.

3. METHODOLOGY

In broad terms, the probabilistic methodology introduced by Cornell (1968) was used. The probabilistic methodology invokes three key steps. The first step is the construction of a seismicity model. Earthquake source zones are defined and for each source zone seismicity parameters *a*, describing the level of seismicity, and *b*, describing the scaling relationship between the numbers of small and large earthquakes, are calculated for the Gutenberg-Richter (1944) magnitude recurrence relation

$$\log N = a + bM \qquad (1)$$

where N is the number of earthquakes with magnitude M. A maximum magnitude M_{max}, considered to be the magnitude of the largest earthquake that could occur in the source zone, and a minimum magnitude, below which significant damage will not occur, usually truncate the distribution.

The second step is the determination of a relation, with its associated uncertainty, describing the attenuation of earthquake ground motion with distance from the earthquake source. An attenuation relation derived for New Zealand was adopted for Fiji for reasons which are discussed below. The third step is the calculation of earthquake hazard at various geographical locations. The calculation of hazard at a site includes the contribution of all potentially damaging earthquakes occurring in all source zones. The hazard is expressed probabilistically; for instance, as the level of ground motion with a certain likelihood of being exceeded within a certain return period. Ground motion may be described by peak or spectral values of ground acceleration, velocity or displacement, or by Modified Mercalli Intensity.

I used procedures to calculate earthquake hazard for Fiji which parallel closely the procedures used to prepare the Zone Factor map in NZS 4203:1992; Part 4 Earthquake Provisions (Standards New Zealand, 1992). The primary reason for following the New Zealand procedures is that the Structural Provisions for Earthquake Loads in the draft National Building Code for Fiji (Section B1.2 (b); Pacific Building Standards Project, 1990) refer to NZS 4203: Part 4. If the hazard is calculated the same way in Fiji and New Zealand then the earthquake design loadings should be similar for sites of similar hazard in each country. The New Zealand Standard is considered appropriate for Fiji, not least because the levels of earthquake hazard in the two countries are comparable.

The hazard assessment methodology of this study is similar to the New Zealand methodology in the definition of the seismicity parameters, the computer software used to calculate earthquake hazard, the attenuation relation, the Katayama ground condition Type considered 'typical', and the use of spectral acceleration as the hazard descriptor.

The essential process by which the Zone Factor map for New Zealand was prepared can be obtained from the following publications. The seismicity model of Smith and

Berryman (1986) was adopted, with the exception that seismicity parameters for Zone H were modified (Matuschka et al., 1985). Katayama (1982) formulated relations for the attenuation of response spectral acceleration from Japanese accelerograms. The Japanese attenuation relations were considerably modified to fit the much higher attenuation of ground shaking observed in New Zealand strong motion data. The uncertainties associated with the attenuation relations were also reduced for New Zealand (McVerry, 1986). Matuschka et al. (1985) produced maps of spectral acceleration for return periods of 50 years, 150 years, 450 years and 1,000 years for Katayama ground condition Type 3 (Table 1). The Commentary (Volume 2) of NZS 4203:1992 (Standards New Zealand, 1992) described how the SANZ Seismic Risk Sub-committee used the results of the hazard analysis to formulate design spectra and lateral force coefficients.

The computer program KATAYAMA and related programs and subroutines (Zhao, 1993) were used to calculate the earthquake hazard. The programs calculate values of elastic, 5% damped, uniform hazard, horizontal, spectral acceleration at a geographical location with respect to a specified return period. The input data for the calculations comprised the Fiji seismicity model (Table 2), the New Zealand Modified Katayama attenuation model (McVerry, 1986) and the uncertainties in the New Zealand attenuation model (Table 3; Matuschka et al., 1985).

Table 1 Magnitude, distance and ground condition categories (reproduced from Katayama, 1982)

Item	Category	Mean for the data in each category
Magnitude M	4.5-5.3	4.96
	5.4-6.0	5.75
	6.1-6.7	6.30
	6.8-7.4	7.06
	7.5-7.9	7.65
Epicentral distance (km)	6-19	11.7
	20-59	38.2
	60-119	82.9
	120-199	158.7
	200-405	271.3
Ground condition at recording site	Type 1 Ground of the Tertiary era or older (defined as bedrock), and diluvial layer with depth less than 10 m above bedrock	
	Type 2 Diluvial layer with depth greater than 10 m above bedrock, and alluvial layer with depth less than 10 m above bedrock	
	Type 3 Alluvial layer with depth less than 25 m having less than a 5 m thick liquefiable layer or soil with a compressive strength less than 0.2 kg cm^{-2}	
	Type 4 Other than the foregoing, usually soft alluvial layer or reclaimed land	

The Modified Katayama model for the attenuation of spectral acceleration in New Zealand was adopted in this study. The uncertainties in the New Zealand attenuation model, expressed by the standard deviation σ, were also adopted. Table 3 lists the values of σ for various periods of vibration, and the sensitivity of the hazard calculations to σ is discussed in Section 7. Significant instrumental strong ground motion data have not been recorded in Fiji and so an attenuation relation for Fiji derived from local instrumental recordings is not available.

Values of spectral acceleration were calculated at a period of vibration T = 0.2 s for return periods of 50, 150, 450 and 1,000 years. At period T = 0.2 s a sharp peak occurs in the Modified Katayama spectra or, more accurately, does so for sites of relatively higher hazard or when the return periods are relatively long. Where the hazard is relatively low or return periods are relatively short, local earthquakes of moderate magnitude make an important contribution to the spectra and the peak occurs around T = 0.15 s. Values of acceleration were calculated on a half degree grid across Fiji and at more closely spaced intervals where better resolution was required. In common with the New Zealand methodology used to produce the Zone Factor map in NZS 4203:1992 (Standards New Zealand, 1992), the Zone Factor map proposed for the National Building Code for Fiji was prepared from calculations of spectral acceleration at a period of T = 0.2 s with a return period of 450 years.

Table 2 Seismicity parameters for earthquake source zones

Zone	Area (km^2)	No. events Mw > 0	h (km)	Measured or calculated values				Adopted values		
				M_{max} (Mw)	a_4	b	σ_b[1]	M_{max} (Mw)	a_4	b
SEVL Southeast Viti Levu	67,399	493	10	6.8	0.02	1.0	0.14	7.5	0.07	1.0
FP Fiji Platform	36,419	33	10	5.8	0.01	0.94		7.5	0.013	0.95
TAV Taveuni	46,496	397	10	7.1	1.26	0.97	0.13	7.5	1.26	0.97
LAU Lau Group	197,053	126	10	6.8	0.02	0.95		7.5	0.02	0.95
WVL Western Viti Levu	55,739	338	10	6.7	0. 27	0.87	0.05	7.5	0.27	0.87
FFZ1 Fiji Fracture Zone 1	21,602	609	10	6.7	0.77	1.02	0.091	7.5	0.77	1.0
FFZ2 Fiji Fracture Zone 2	5,450	35	10	7.0	0.27	0.9		7.5	0.27	0.9
CBZ Cikobia Basin	33,686	33	10	6.6	0.11	0.95		7.5	0.11	0.95
ROTU Rotuma	197,000	19	10	6.0	-	-		7.5	0.002	0.95

[1] Standard deviation of *b* value from maximum likelihood calculation

Table 3 Standard deviation values adopted for the attenuation of spectral acceleration

Natural period T (s)	σ^1
0.1	0.275
0.2	0.285
0.3	0.295
0.4	0.300
0.5	0.305
0.7	0.310
≥ 1.0	0.320

[1] σ is the standard deviation of the logarithm of acceleration

Katayama's ground condition Type 3 (1982; reproduced in Table 1) was chosen for the calculations of spectral accelerations. This ground condition was considered most suitable for New Zealand, it was the foundation on which most of the data from Japan and New Zealand included in the Modified Katayama attenuation relation were recorded, and it was also used to calculate the spectral accelerations for the New Zealand hazard maps (Matuschka et al., 1985). This ground condition may be appropriate for parts of Fiji. Whether or not it is most typical of ground conditions in Fiji, or whether for instance ground condition Type 2 is most typical, is not particularly important in the calculation of hazard for Fiji, as is seen from the response spectra for Suva. Response spectra for all four of Katayama's ground condition types are shown for a return period of 450 years in Fig. 4. At a period of T = 0.2 s there is a difference of only about five percent between the spectral accelerations for ground condition Type 2 and Type 3.

It is important to make a precautionary note here, before the results are presented, that the Zone Factors recommended in this study do not directly substitute for those in the 1990 draft National Building Code for Fiji (Section B1.2 (b) and Figure B1.2). This is because the 1990 draft Fiji code refers to the draft New Zealand standard 2/DZ 4203:1989. The Zone Factor Z in 2/DZ 4203:1989 was derived from calculations of hazard for a 150 year return period whereas the Zone Factor in NZS 4203:1992 was derived from hazard calculations for a 450 year return period. The Zone Factors proposed by this study are intended to be fully compatible with NZS 4203:1992.

4. EARTHQUAKE SOURCE ZONES

Nine earthquake source zones were defined (Fig. 5; Table 2). All parts of the study area were considered sufficiently seismically active to justify their inclusion in a source zone. However, the margins of the source zones were restricted to a maximum distance of about 200 km from populated areas because earthquake activity beyond this distance has a negligible impact on risk. Therefore, source zones were not defined to the north of

FFZ1 and CBZ, to the northeast of TAV, and to the southwest of WVL. Smaller sub-zones were defined in parts of SEVL and WVL where monitoring by the FSN was considered to be superior. Accurate determinations of low-magnitude seismicity were made in these sub-zones and the results were extended across the complete source zones.

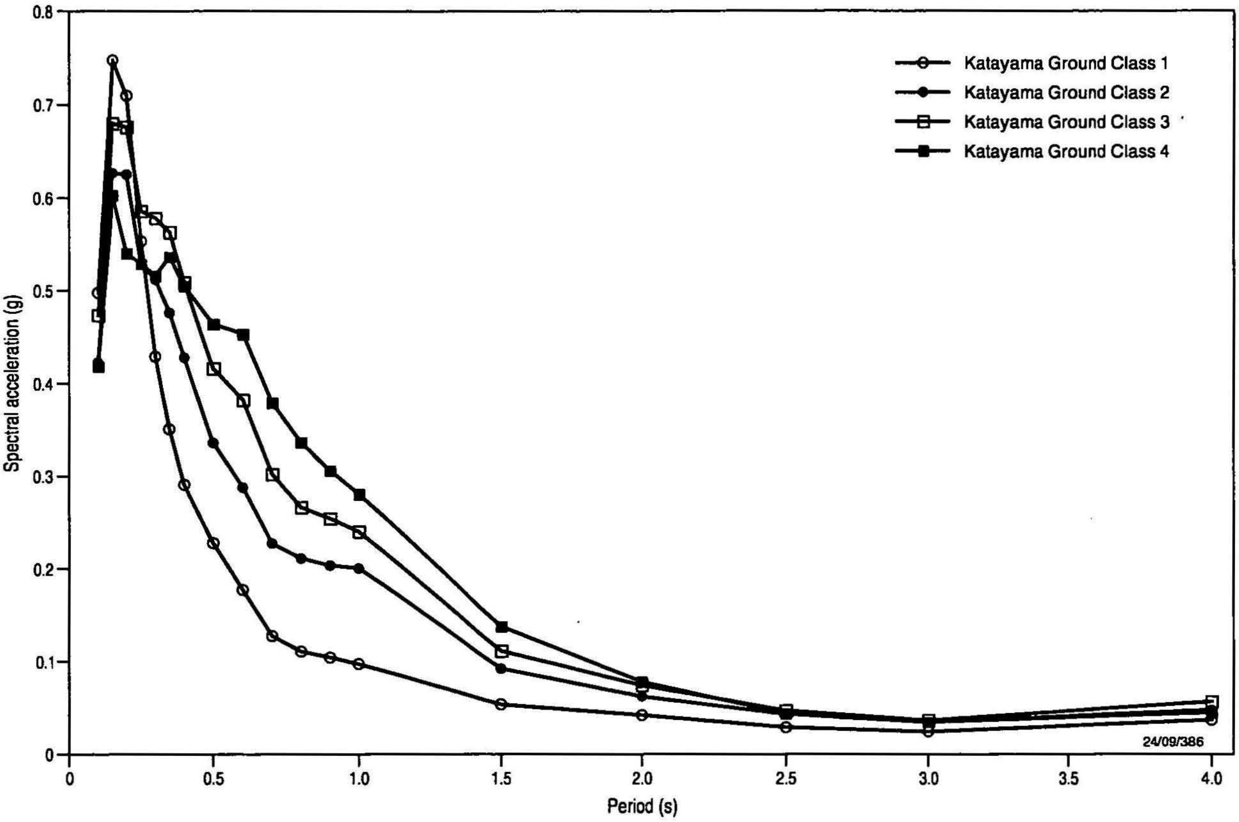

Figure 4 Modified Katayama elastic, 5% damped, horizontal, uniform hazard response spectra for a 450 year return period for Suva. Spectra are shown for four Katayama ground condition Types (Table 1).

The boundaries of the earthquake source zones were determined from considerations of seismicity, geology and tectonics. A thorough interpretation of the shallow seismotectonics from the central North Fiji Basin to the Lau Basin was made by the author in relation to this study.

Alternative configurations of earthquake source zones were investigated but were not pursued. The zones mapped in Fig. 5 are preferred as a result of the seismotectonic interpretations and, in limited tests, the differences calculated in earthquake hazard for different configurations were relatively small, perhaps lower than the those resulting from uncertainties from other sources. The reader is referred to Section 7 for a discussion on the sources of uncertainties and their effects on hazard.

In addition to the many shallow earthquakes, deep earthquakes also occur in Fiji. About 60% of the world's deep earthquakes occur in the Tonga subduction zone (Giardini, 1988) and earthquakes from the northern part of this zone occur beneath the Lau Group, the Lomaiviti Group and Vanua Levu (Billington, 1980; Hamburger and Isacks, 1987).

The largest of these earthquakes may be felt in Fiji. Examples are the 26 May 1986, 1906 UTC, event, which had a depth of 543 km, a magnitude of Mw 7.1 (Harvard) and which was felt in Fiji MM2-3; the 16 June 1986, 1048 UTC, event which had a depth of 557 km, a magnitude of Mw 7.0 (Harvard) and which was felt MM2 in Suva; and the 9 March 1994, 2328 UTC, event, which had a magnitude of Mw 7.5 (USGS) and which was felt in Suva and Lautoka. The subduction zone earthquakes have been omitted from the hazard analysis because of their great depths: even the largest of them is unlikely to cause damage in Fiji.

Descriptions of the source zones, their seismotectonics and the historical seismicity within them are given in Appendix 1.

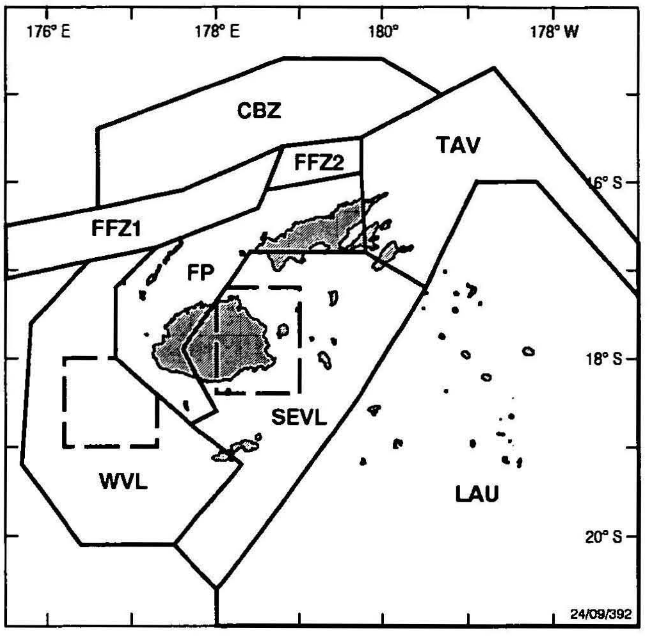

Figure 5 Earthquake source zones for Fiji. Sub-zones of superior instrumental monitoring in SEVL and WVL are shown.

5. DETERMINATION OF SEISMICITY PARAMETERS IN SOURCE ZONES

Conversion to scalar seismic moment magnitude Mw

Two thousand, two hundred and sixty five earthquakes of a total of 3,205 shallow earthquakes ($h \leq 100$ km) considered in this study had a magnitude value assigned which was extracted from the catalogue of Jones and Dropsy (1995).

The magnitudes listed in the catalogue were determined by the local, surface wave or body wave magnitude scales. These magnitude scales do not agree with each other (e.g., Kanamori, 1983) and it is highly desirable to use a common magnitude scale to determine the seismicity parameters of the source zones. Scalar seismic moment magnitude Mw (Kanamori, 1977; Hanks and Kanamori, 1979), or simply moment magnitude, is the globally preferred magnitude because it can be related to the earthquake faulting process and because it can be applied to deep and shallow earthquakes ranging in size from very small to very large without suffering the defects of other magnitude scales (Kanamori, 1983). The magnitudes of all shallow earthquakes in Fiji were converted to moment magnitude Mw prior to the determination of seismicity parameters. Appendix 2 describes the conversion process.

Of the 940 events that did not have an assigned magnitude, 763 were earthquakes which were located from data of the FSN. Information on the magnitudes of these latter earthquakes, had it been available, certainly would have assisted the determination of the seismicity parameters.

Removal of aftershocks

A fundamental assumption of the probabilistic methodology of Cornell (1968) is that the occurrence of any earthquake is independent of any other. This condition is satisfied if the distribution of earthquakes is Poissonian, and the actual earthquake distribution will better resemble a Poisson distribution if aftershocks and foreshocks are removed from the catalogue. The method adopted to remove these dependent events can be objective and arbitrary, for example as used by Gardner and Knopoff (1974) where about two thirds of the Southern California catalogue was removed to produce a Poissonian catalogue, or subjective and following simple rules, as in this study.

The criteria I used to classify and eliminate 'dependent' events were as follows. First, foreshocks or aftershocks must have occurred on the mainshock fault rupture as best as could be determined, with the fault rupture length dependent on magnitude Mw in accordance with the relation of Darragh and Bolt (1987) who examined predominantly strike-slip earthquakes. In practice, the uncertainty ellipses in the epicentres of Fiji earthquakes were larger than the fault dimensions, and so the criterion became that the epicentre of a foreshock or aftershock must lie within the error ellipse of the mainshock. Second, the decay with time of the number of aftershocks depends on the magnitude of the mainshock. For earthquakes with magnitude Mw $\geq$ 6, aftershocks could occur one month or more after the mainshock. Third, special treatment was afforded to 'swarm' activity in the case where several moderate or large events with $\Delta M \leq 0.3$ occurred closely related in space and time. Such events were not removed from the catalogue, even though some would otherwise have qualified as foreshocks or aftershocks, because their removal would have resulted in an understatement of the real level of hazard.

About 71% of the original number of earthquakes of known magnitude remained after this culling process. The most notable aftershock sequence in the catalogue was that following the 16 November 1979 Mw 6.8 Taveuni earthquake.

Completeness periods

A knowledge of the completeness of the earthquake catalogue over time for certain magnitude ranges is necessary to determine the parameters in the recurrence relation (1). Incomplete data will skew the recurrence relation. Completeness depends on factors such as the distribution of the population, the seismographic network coverage and the effectiveness of collection methods. The Fiji catalogue was compiled from macroseismic observations over approximately 150 years and shorter periods of coverage by global and local seismographic networks.

Two considerations on completeness are important. The first is the period over which monitoring of earthquakes is considered adequate such that all events with magnitudes equal to or greater than a certain minimum would have been detected and included in the catalogue. The second consideration is whether, with adequate monitoring, sufficient numbers of events had occurred such that reasonable estimates could be made of their true rate of occurrence.

Stepp's (1972) procedure to determine completeness intervals was applied to each of the earthquake source zones. This simple method analyses the stability of the mean rate of occurrence of earthquakes of a certain magnitude with varying periods of time. It uses the statistical property that the variance σ^2 of the estimate of a sample mean is inversely proportional to the number of observations in the sample. Stepp showed that, for a Poisson process, $\sigma\lambda = (\lambda/t)^{1/2}$ where σ_λ is the standard deviation of the estimate of the mean, λ is the mean annual occurrence of earthquakes of a particular magnitude range, and t is the sample length in years. Thus, for completeness, $\sigma_\lambda \propto (1/t)^{1/2}$. The Stepp test will fail if no earthquakes, or very few earthquakes, occurred within a certain period of time, even though monitoring may have been adequate.

Table 4 shows the completeness intervals determined by the Stepp test. The monitoring by the FSN since 1979 has allowed good estimates of mean rates of occurrence of moderate earthquakes where seismicity is reasonably high near the main islands (source zones FFZ1 and the inset of WVL). An estimate of the seismicity of the sub-zone of SEVL (Fig. 5) for the magnitude range $3.5 \leq Mw < 4$ was also made. Otherwise the catalogue of small and moderate earthquakes was recorded as incomplete (Table 4) even though the FSN was capable of locating earthquakes with magnitudes approximately $Mw \geq 4.0$ or smaller in FP and the sub-zone of SEVL. The reason is twofold. First, too few earthquakes may have occurred to have satisfied the Stepp test. Second, the recording of smaller earthquakes was incomplete for reasons including station downtime due to tropical cyclones, etc. The FSN does not have the capability to locate all small ($Mw \leq 4.5$) earthquakes in the offshore zones SEVL, TAV, LAU, WVL and CBZ.

Table 4 Completeness intervals for earthquake source zones

Zone	Magnitude (Mw)						
	≥ 3.5	≥ 4.0	≥ 4.5	≥ 5.0	≥ 5.5	≥ 6.0	≥ 6.5
SEVL	1979[1,2,3]	-	-	-	-	1951	1918
FP	-	-	-	-	-	1951	1918
TAV	-	-	-	-	1964	1951	1918
LAU	-	-	-	-	-	1951	1918
WVL	-	1979[1,2]	1979[1,2]	1979[1,2]	1964	1951	1918
FFZ1	-	-	1979[1]	1979[1]	1964	1951	1918
FFZ2	-	-	-	-	-	1951	1918
CBZ	-	-	-	-	-	1951	1918
ROTU	-	-	-	-	-	1951	1918

[1] From commencement of MRD network; [2] Sub-zone only (see Fig. 5);
[3] Complete for Mw 3.5 - Mw 4.0 only (see text).

The rate of occurrence of earthquakes with magnitude $Mw \geq 6$ is small for individual source zones, and the resolution of epicentres determined before 1964 (the commencement of effective operation of the WWSSN) is often insufficient to place them unambiguously in one source zone or another. Therefore the annual rate of events with magnitude Mw ≥ 6 was calculated by counting the total number of shallow events which occurred in all places in Fiji, and the completeness periods for earthquakes Mw ≥ 6 and Mw ≥ 6.5 apply to Fiji as a whole (Table 4).

Maximum magnitude, minimum magnitude, and earthquake depth

The largest known shallow earthquake in Fiji occurred on 26 December 1949 and had a magnitude of Mw 7.1. Its epicentre in the TAV source zone is about 75 km east-northeast of the northernmost point of Taveuni (Fig. 2). Everingham (1987) did not record any felt effects for this event.

Table 2 lists the magnitude of the largest known earthquake in each of the source zones. Two features are remarkable. First, the maximum magnitudes are low, especially when the high seismicity of some source zones is considered. The calculated return period for a shallow earthquake in the magnitude range 7.25 ≤ Mw < 7.5 occurring anywhere in the eight earthquake source zones excluding Rotuma in the period 1918-1990 is approximately 21-50 years, yet none is known to have occurred in this period. This indicative return period was calculated by applying the maximum likelihood method of Weichert (1980) to data of magnitude Mw ≥ 5.5, and M_{max} 8.0, with completeness criteria identical to those of the TAV source zone (Table 4).

Second, the maximum recorded magnitudes for the source zones are similar. For seven of the nine source zones, they range from Mw 6.6 to Mw 7.1. Not surprisingly perhaps, the maxima are larger for zones of higher seismicity and smaller for zones of lower seismicity. The source zones FP and ROTU have the lowest seismicity and the lowest recorded maxima (Mw 5.8 and Mw 6.0 respectively).

The relatively low magnitudes of the largest recorded earthquakes, and their relatively short return periods in some source zones, indicate that the magnitude of the maximum expected earthquake in Fiji may be low and may be similar in each source zone. I chose a maximum magnitude M_{max} = 7.5 Mw for each source zone.

The source zone SEVL may be the exception. An earthquake of magnitude up to Mw 8 could rupture along a northeast trend with a left lateral strike slip mechanism in this zone (see Appendix 1). I consider the sensitivity of the hazard at Suva to maximum magnitudes of Mw 7.5 to Mw 8.5 in Section 7.

A minimum magnitude of Mw 5.25 was used in the hazard calculations. In calculations for NZS 4203:1992 in New Zealand, the lower limit of 5.25 was adopted because 'it was considered that structures designed in accordance with current design code standards would not be susceptible to damage from the effects of earthquakes with magnitudes less than 5.25' (Matuschka et al., 1985). I note that earthquakes with smaller magnitudes than 5.25 may damage structures in Fiji not designed in accordance with current design code standards.

Hypocentral depth was set at 10 km for all source zones. All A grade solutions of earthquakes located by Hamburger (1990) in southeastern Viti Levu, where seismograph coverage has been most dense, had depths between 3 km and 18 km. I calculated a mean depth of 10.1 km for 39 A grade solutions. Hypocentral depths may be less in other parts of Fiji, for instance in the oceanic crust surrounding the Fiji Platform.

Magnitude frequency recurrence relations

The magnitude frequency relations for each source zone (Fig. 6) were compiled from the Poissonian catalogue. In Fig. 6, filled circles indicate the frequency of occurrence for earthquakes in increments of ¼ magnitude units and the hollow circles indicate cumulative data for the frequency of earthquakes greater than or equal to the specified magnitude. Incremental data are plotted at the central magnitude value of each interval and cumulative data are plotted at the lower limit of each magnitude interval. The magnitude frequency data are considered complete for source zones TAV, WVL and FFZ1. For other source zones where complete data were not available incomplete data, that is, rates of earthquake activity derived from incomplete parts of the catalogue, were also included for periods commencing 1964, 1979, etc., and were interpreted as described below.

Lines were fitted to the data to obtain estimates of the seismicity parameters in the recurrence relation (1). The magnitude range over which the lines of fit are drawn indicates the extent of reliable data. The seismicity parameter b was estimated from the incremental data for each source zone. Parameter a in equation (1) depends on the size of the source zone and the period of observation. So that seismicity levels could be directly compared between different source zones, parameter a was normalised by defining the parameter a_4 as the number of earthquakes of magnitude 4 or greater occurring per year, per 1000 km^2, in a source zone. The definition of parameters a_4 and b is consistent with the methods used by Smith and Berryman (1986) to prepare the seismicity model for New Zealand.

The maximum likelihood method of Weichert (1980) for unequal periods of observation was used to estimate values of the seismicity parameters a_4 and b for zones where sufficiently large numbers of events had occurred. These zones were SEVL, TAV, WVL, and FFZ1.

Maximum likelihood methods are preferred over least squares fitting and other methods to estimate the parameters a and b (e.g., Bender, 1983). Gaussian least squares methods are often used to estimate b but the premise that the data are independent is violated if a cumulative distribution is used and earthquake data are better represented by a Poissonian distribution than a Gaussian distribution (Weichert, 1980). Maximum likelihood methods allow for zero occurrences of events in magnitude intervals, including intervals beyond the maximum observed magnitude and below the maximum magnitude specified for the source zone, whereas least squares regressions ignore zero occurrences.

In the five remaining source zones the data were considered incomplete (Table 4), creating difficulty in using the formal methods of parameter estimation mentioned above. In particular, the use of a least squares fitting would have resulted in unrealistically low b values and consequent exaggeration of the hazard in these zones. A mean value of $b = 0.95$ was calculated for the well determined seismicity of zones TAV, WVL and FFZ1. Lines with $b = 0.95$ were then fitted to the data considered most complete for source zones FP, LAU, ROTU and CBZ. A value of $b = 0.9$ was used for

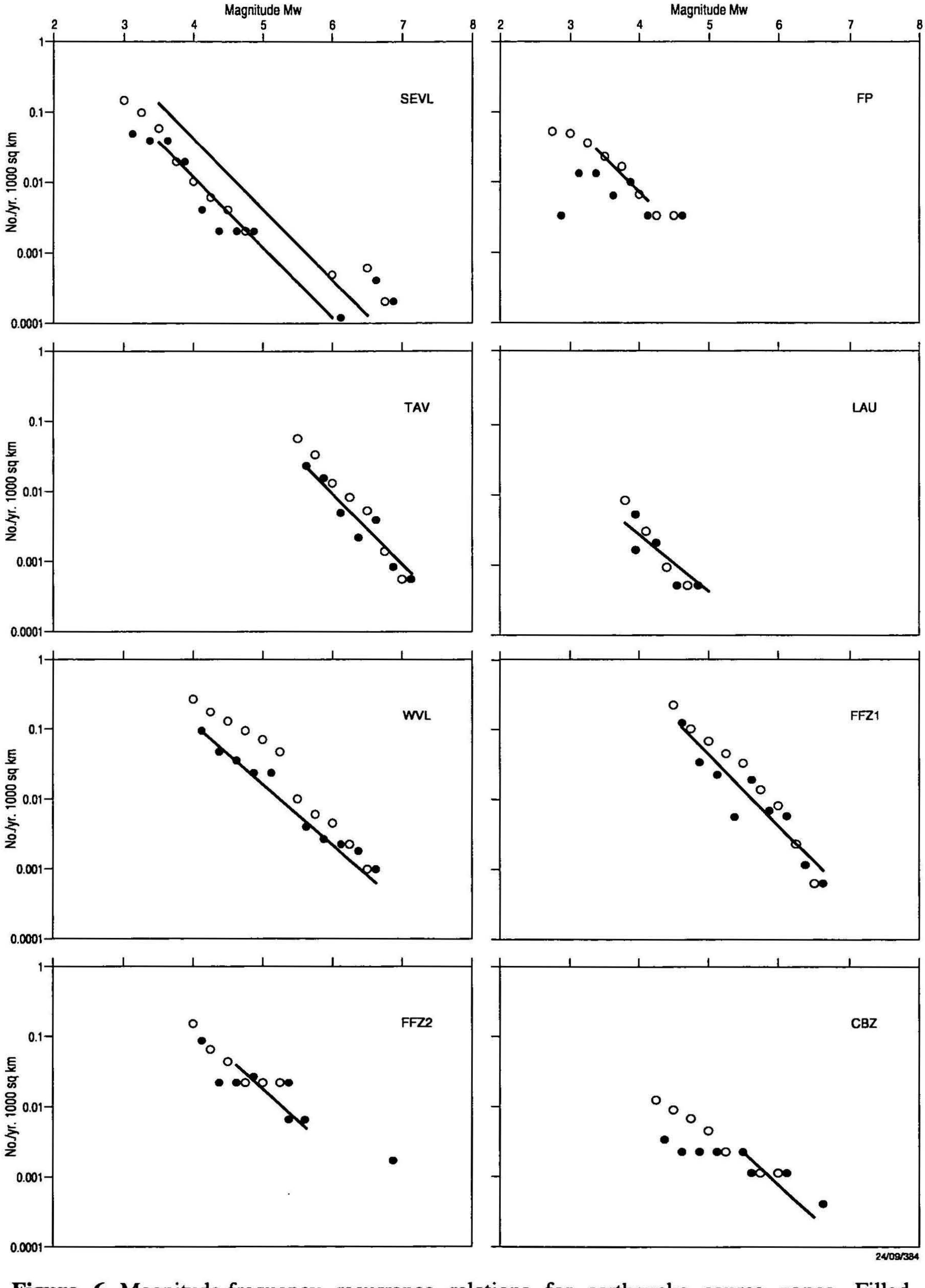

Figure 6 Magnitude-frequency recurrence relations for earthquake source zones. Filled symbols represent incremental data and open symbols, cumulative data. Adopted magnitude frequency relations and the range of magnitudes over which the relations are considered robust are indicated by the lines of fit.

source zone FFZ2 in recognition of the occurrence of at least one large earthquake in the 1880s (Appendix 1). The data point for this earthquake is plotted in Fig. 6.

Source zone SEVL warrants special mention because it contains Suva. The maximum likelihood estimation of the seismicity parameters gives $b = 1.0$ and $a_4 = 0.02$, shown by the lower line in Fig. 6. The occurrence of one earthquake of estimated magnitude Mw 6 in the sub-zone of SEVL for the period 1869-1990 (Appendix 1) is plotted in Fig. 6 and appears to fit this estimation. However, the recurrence relation line is misfit by the data for three earthquakes of magnitude Mw ≥ 6.5 which have occurred since 1918. Has the rate of occurrence of these large earthquakes been extraordinarily high or are the (largely incomplete) data for smaller earthquakes deficient? As a precaution, I increased the value of parameter a_4 to 0.07 in the seismicity model. This value of a_4 places the recurrence relation approximately midway between the rates observed for small earthquakes and large earthquakes (Fig. 6).

The seismicity model is shown in Table 2.

6. ATTENUATION OF STRONG GROUND MOTION

The model for the attenuation of strong ground shaking is the second essential input into the probabilistic hazard methodology. The Modified Katayama model for the attenuation of spectral acceleration in New Zealand was adopted in this study. The uncertainties in the New Zealand attenuation model, expressed by the standard deviation σ, were also adopted. Table 3 lists the values of σ for various periods of vibration and the sensitivity of the hazard calculations to σ is discussed in Section 7.

Macroseismic data of Modified Mercalli Intensities reported from Fiji earthquakes were analysed to formulate a relation for the attenuation of Modified Mercalli Intensity with distance for Fiji.

Method

Macroseismic data from 16 earthquakes were compiled (Table 5). These 16 events comprise all available shallow events in the magnitude range Mw ≥ 5 for which reliable macroseismic data were available. Data were obtained from isoseismal maps for the 1953, 1975 and 1979 earthquakes and other felt reports (Everingham, 1983a; Everingham, 1987), MRD Annual Reports and MRD files. The felt intensities of Everingham were used where available and Modified Mercalli intensities were assigned to other reports. Maximum magnitude of the earthquakes is Mw 7. All available focal mechanisms for the earthquakes indicate strike-slip faulting.

Table 5 List of Fiji earthquakes used to construct attenuation function

Date	Event name or place	Epicentre °S	Epicentre °E	Depth km	Magnitude	Mw
1919 10 03	Rabi	16.4	180.0	10	6.9 Ms	6.9
1928 06 21	SE of Taveuni	17.0	-179.5	10	7.0 Ms	7.0
1931 11 11	N of Vanua Levu	16.2	178.8	10	5.2 Ms	5.6
1932 03 08	Koro	17.5	179.6	10	6.5 Ms	6.6
1950 02 12	Kadavu	18.86	177.79	10	6.4 Ms	6.5
1953 09 14	Suva	18.25	178.35	10	6.75 Ms	6.8
1956 09 11	Fiji Fracture Zone	16.24	178.33	10	6.0 Ms	6.1
1957 06 19	Fiji Fracture Zone	16.57	176.93	10	6.5 Ms	6.6
1963 04 17	S of Kadavu	19.76	178.36	10	6.3 Ms	6.4
1975 12 16	Kadavu Passage	18.611	178.245	10	4.9 mb	5.1
1979 11 16	Taveuni	16.5	-179.75	10	6.9 Ms	6.8
1984 06 28	SW of Viti Levu	18.383	177.259	10	5.4 Ms	5.7
1984 10 12	Fiji Fracture Zone	16.643	177.279	10	6.1 Ms	6.3
1985 05 03	SW of Viti Levu	18.241	176.822	10	5.0 MD	5.0
1990 02 02	SW of Viti Levu	18.284	176.995	10	5.7 Ms	5.9
1991 03 24	Fiji Fracture Zone	16.83	177.30	10	5.1 Ms	5.5

This study is a comprehensive update of the work of Everingham (1987) who used data from shallow earthquakes occurring in 1919, 1932, 1953, 1961, 1975 and 1979 to obtain the preliminary attenuation relation

$$MMI = 1.5\ Ms - 2.1 \log (D^2+335) + 3.8 \qquad (2)$$

where MMI is Modified Mercalli Intensity (Eiby, 1966), Ms is surface wave magnitude, D is the epicentral distance and a depth of 15 km was considered to be most likely.

Isoseismal radii calculated from the arithmetic mean of measurements in two orthogonal directions were determined from existing isoseismal maps for the 1953, 1975 and 1979 earthquakes, and intensities and hypocentral distances were estimated for other events where insufficient data existed to prepare isoseismal maps. The locations of the epicentres were reassessed and were adjusted for some events. Uncertainties in the epicentres were considered in deciding the hypocentral distances for each earthquake.

Regression analysis

I developed an attenuation relation of the form

$$\text{Intensity} = a + bMw + cr + d \log r \qquad (3)$$

where a, b, c and d are constants to be determined, Mw is scalar moment magnitude, and r is hypocentral distance. This form for the attenuation relationship allows a direct comparison with the attenuation of MMI in New Zealand (Dowrick, 1991; Dowrick, 1992). Moment magnitudes Mw were derived for the earthquakes using the technique in Appendix 2. Hypocentral depth was set at 10 km (see Section 5).

A modification of the two-stage regression analysis of Dowrick (1992) and Joyner and Boore (1981, 1988) was used to determine the constants a, b, c and d.

Results

The Modified Mercalli intensity attenuation relation determined for shallow Fiji earthquakes is:

$$MMI = 1.977\ (\pm 1.277) + 1.333\ (\pm 0.207)\ Mw - 0.008799\ (\pm 0.00381)\ r - 2.298\ (\pm 0.677) \log r \qquad (4),$$

for $5 \leq Mw \leq 7$, where MMI is Modified Mercalli Intensity (Eiby, 1966) and r is hypocentral distance. The result should be regarded as provisional.

Dowrick (1991, 1992) used a slant distance R to the effective centre of main energy release, which he placed directly below the centre of the isoseismal pattern for each earthquake considered. As a first approximation Dowrick's distance term is equivalent to the hypocentral radius used here. The two distance terms will be equivalent if the nucleation of a Fiji earthquake occurs at the same place as the main energy release during the earthquake.

Values of MMI calculated from the attenuation relations for Fiji, equation (4), and New Zealand earthquakes with normal and strike slip mechanisms (Dowrick, 1992), are within 0.4 units of MMI of each other over the hypocentral distance range of 10 km to 100 km, for magnitudes $5 \leq Mw \leq 7$. The two relations match more closely than this in the important middle distances $20\ km \leq r \leq 70\ km$ and magnitudes $5 \leq Mw \leq 6.5$ (Fig. 7). The Fiji attenuation is higher at distances beyond 100 km but the hazard from earthquakes at these distances become increasingly insignificant, even when magnitudes are large ($Mw \approx 7$).

The good agreement between the attenuation of MMI in Fiji and in New Zealand provides some confidence that the Modified Katayama attenuation is similarly appropriate for Fiji and New Zealand.

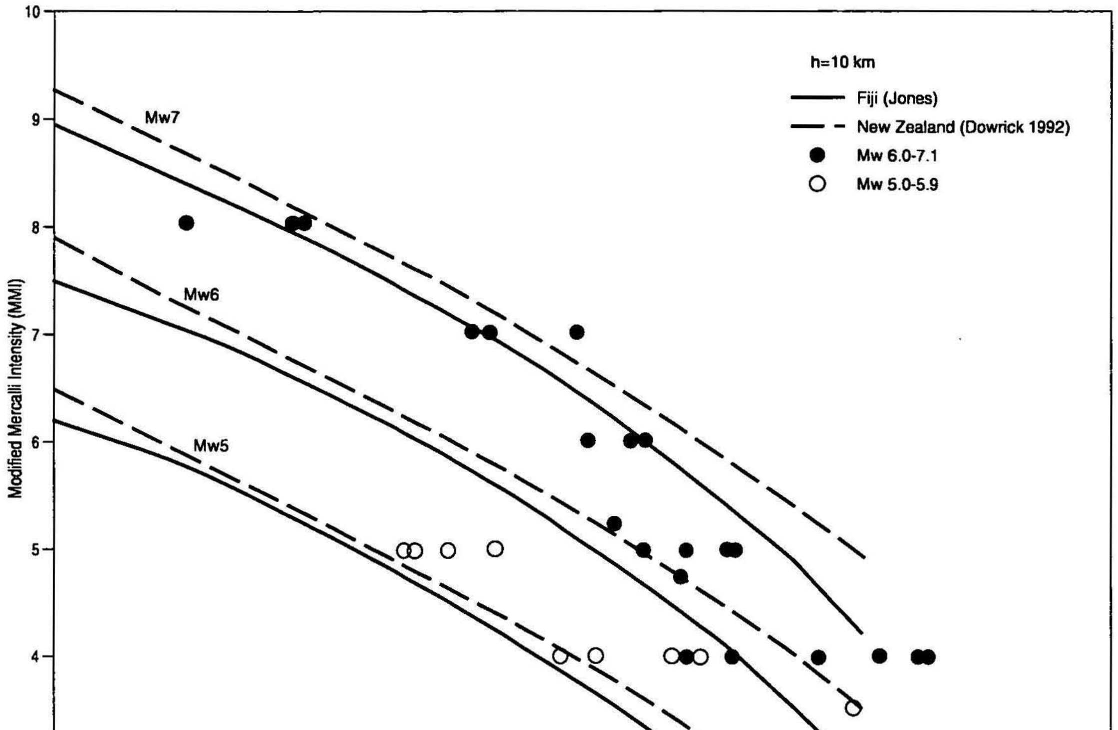

Figure 7 Attenuation of Modified Mercalli Intensity for Fiji (solid lines) and for shallow New Zealand earthquakes with normal and strike slip mechanisms (dashed lines; Dowrick, 1992).

7. EARTHQUAKE HAZARD ESTIMATES

Earthquake hazard maps for Fiji are shown in Fig. 8. The hazard is expressed in terms of the elastic, 5% damped, horizontal response spectral acceleration at a period T = 0.2 s for Katayama ground condition Type 3. Maps for return periods of 50, 150, 450 and 1,000 years are shown. Spectral accelerations used to prepare the maps are listed in Appendix 3 and were gridded using the minimum curvature technique. The acceleration contours continue beyond the land masses to indicate the general pattern of the hazard maps, but the accelerations apply only on the land masses and they cannot be used for the design of marine or submarine structures.

The general pattern of the hazard contours is similar for all four maps and the highest gradients in the hazard are associated with the boundaries between adjacent source zones with a high contrast in hazard. Examples are FP and FFZ1, and SEVL and TAV.

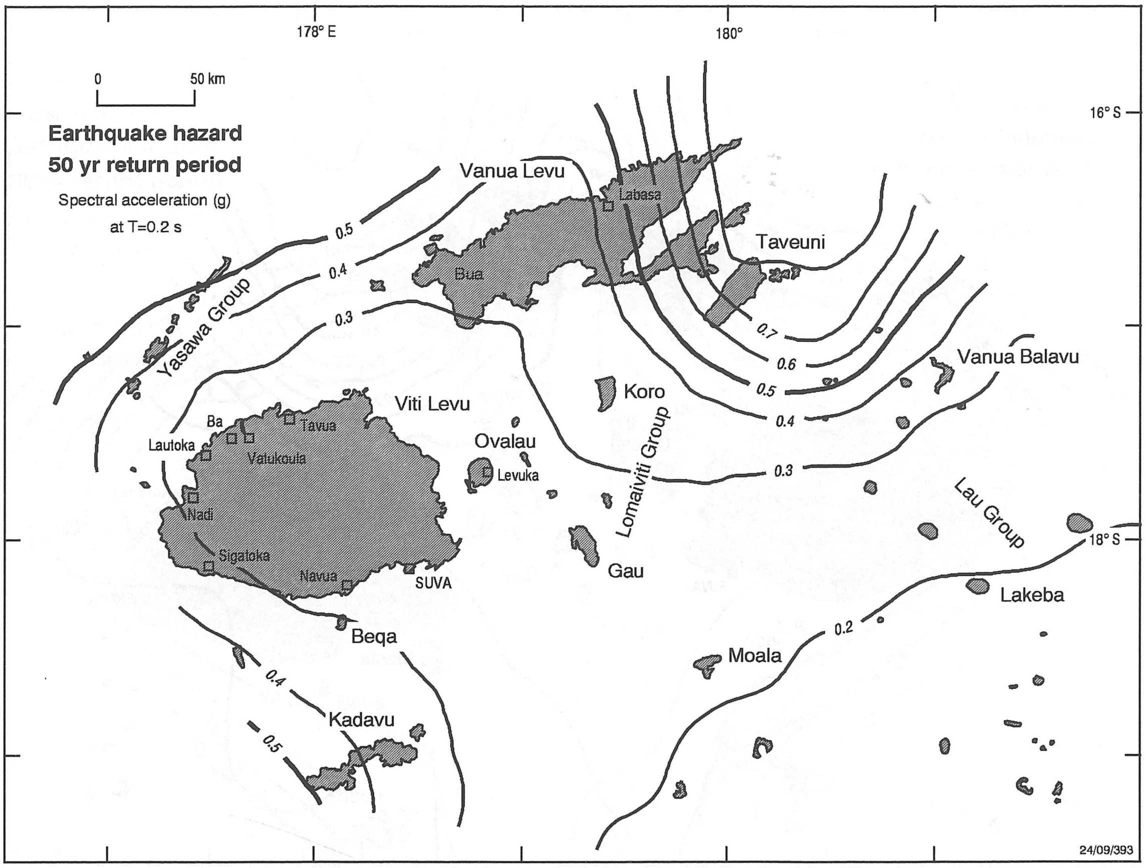

Figure 8 (a) Earthquake hazard map for Fiji, for a return period of 50 years. Contours are shown for values of elastic, 5% damped, horizontal response spectral acceleration (in units of the acceleration due to gravity, g), Katayama ground condition Type 3, at a period of T = 0.2 s. The acceleration contours over marine areas indicate the general pattern of the hazard but cannot be used for the design of marine or submarine structures.

Table 6 gives spectral acceleration values for major Fiji urban areas. The hazard is similar in all these cities and towns except for Labasa and Rotuma. In Labasa the hazard is higher due to the presence of the TAV source zone to the east. In Rotuma the hazard is relatively low and the Modified Katayama response spectra have a sharp peak at period T = 0.15 s. Table 6 quotes the spectral acceleration for Rotuma at T = 0.15 s as a conservative measure. Spectral accelerations at T = 0.15 s are about 40% higher than the accelerations at T = 0.2 s.

Proposed earthquake hazard map for National Building Code for Fiji

Fig. 8 (c) shows the spectral accelerations in Fiji for a return period of 450 years. This return period corresponds approximately to a 10% in 50 years chance of the spectral accelerations being met or exceeded. As I have described, this map was produced using the same techniques as those used in New Zealand to produce the Zone Factor map in NZS 4203:1992 (Standards New Zealand, 1992).

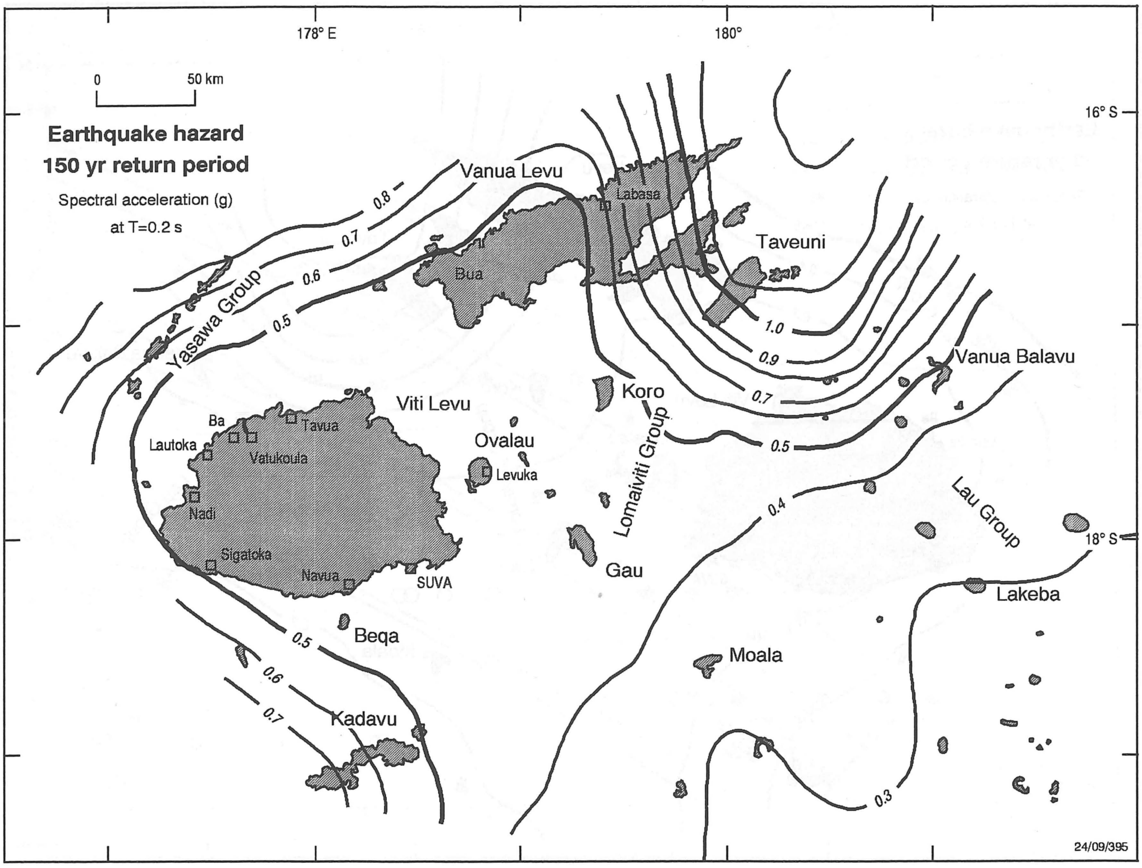

Figure 8 (b) Earthquake hazard map for Fiji, for a return period of 150 years. Contours are shown for values of elastic, 5% damped, horizontal response spectral acceleration (in units of the acceleration due to gravity, g), Katayama ground condition Type 3, at a period of T = 0.2 s. The acceleration contours over marine areas indicate the general pattern of the hazard but cannot be used for the design of marine or submarine structures.

I recommend that the 450-year return period hazard map (Fig. 8 (c)) serves as the basis for a new Zone Factor map in the National Building Code for Fiji to replace the Preliminary Earthquake Risk Map, Figure B1.2, in the 1990 draft National Building Code for Fiji. The 450 year values of spectral acceleration are identical to the Zone Factor. At the same time, the reference to the Zone Number, which equals the Zone Factor multiplied by 10 (Section B1.2 (b) Dead, Live and earthquake loads), should be eliminated because it serves no useful purpose.

Spectral acceleration values in the 450 year map lie between 0.5 g and 0.7 g for a large area of Fiji: almost all of Viti Levu including Suva, western Vanua Levu, the Lomaiviti Group, and the Lau Group from Vanua Balavu to Nayau. Peak horizontal ground accelerations (pga) for a 450 year return period are about 40% of the spectral acceleration values (Standards New Zealand, 1992, Volume 2, p. 33). The estimated hazard increases significantly closer to the more seismically active source zones flanking the Fiji Platform to the west, north and east. Areas marginal to the Fiji Platform such as the Yasawa Group and northern Bua are affected by this seismicity.

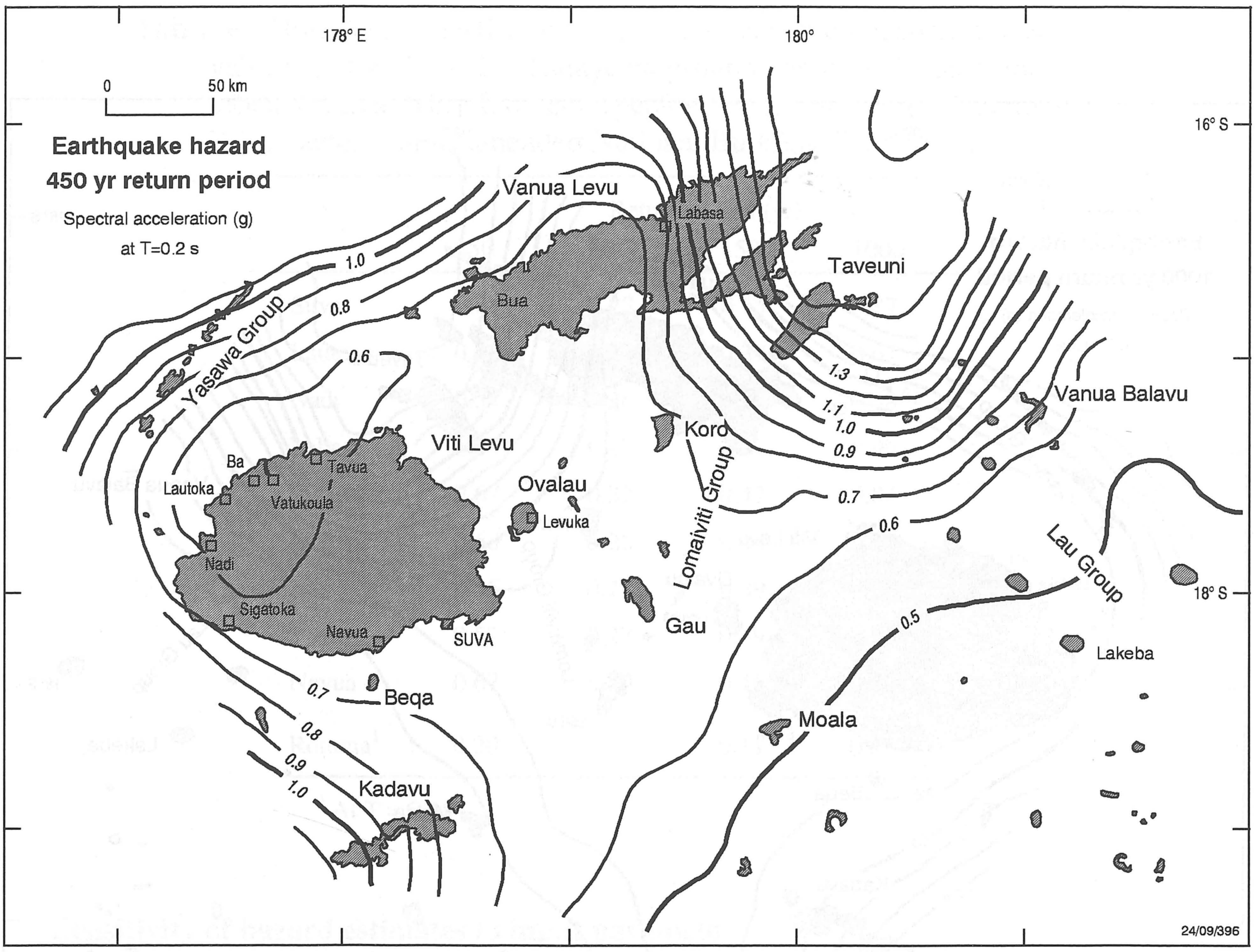

Figure 8 (c) Earthquake hazard map for Fiji, for a return period of 450 years. Contours are shown for values of elastic, 5% damped, horizontal response spectral acceleration (in units of the acceleration due to gravity, g), Katayama ground condition Type 3, at a period of T = 0.2 s. The acceleration contours over marine areas indicate the general pattern of the hazard but cannot be used for the design of marine or submarine structures. This map is recommended as the Zone Factor map for the National Building Code for Fiji.

The TAV source zone has a dramatic effect on the hazard of areas within it and also areas within about 40 km of its boundaries. Western Kadavu also is subject to relatively high seismic hazard because it is situated within the WVL source zone.

The proposed Zone Factor map for Fiji (Fig. 8 (c)) is similar, in broad terms, to that in the 1990 draft National Building Code for Fiji (Fig. 9) although there are some significant differences. The estimated hazard in western Viti Levu, including Nadi, Lautoka, Ba and Tavua is similar to estimates in the 1990 map. Hazard estimated for Kadavu, Labasa and the Yasawa Group also is similar to that in the 1990 map. The new hazard estimates for the Lomaiviti Group and southern and eastern Viti Levu including Suva are about 25% lower than the estimates in the 1990 map. Hazard estimated for the Lau Group is lower than previously estimated except for Vanua Balavu where the estimate is little changed. The estimate of hazard for Rotuma is lower by a factor of about three than the value in the 1990 map. The estimated hazard is similar to the 1990 values about 20 km east of Labasa and in southern Taveuni. From there to the northeast,

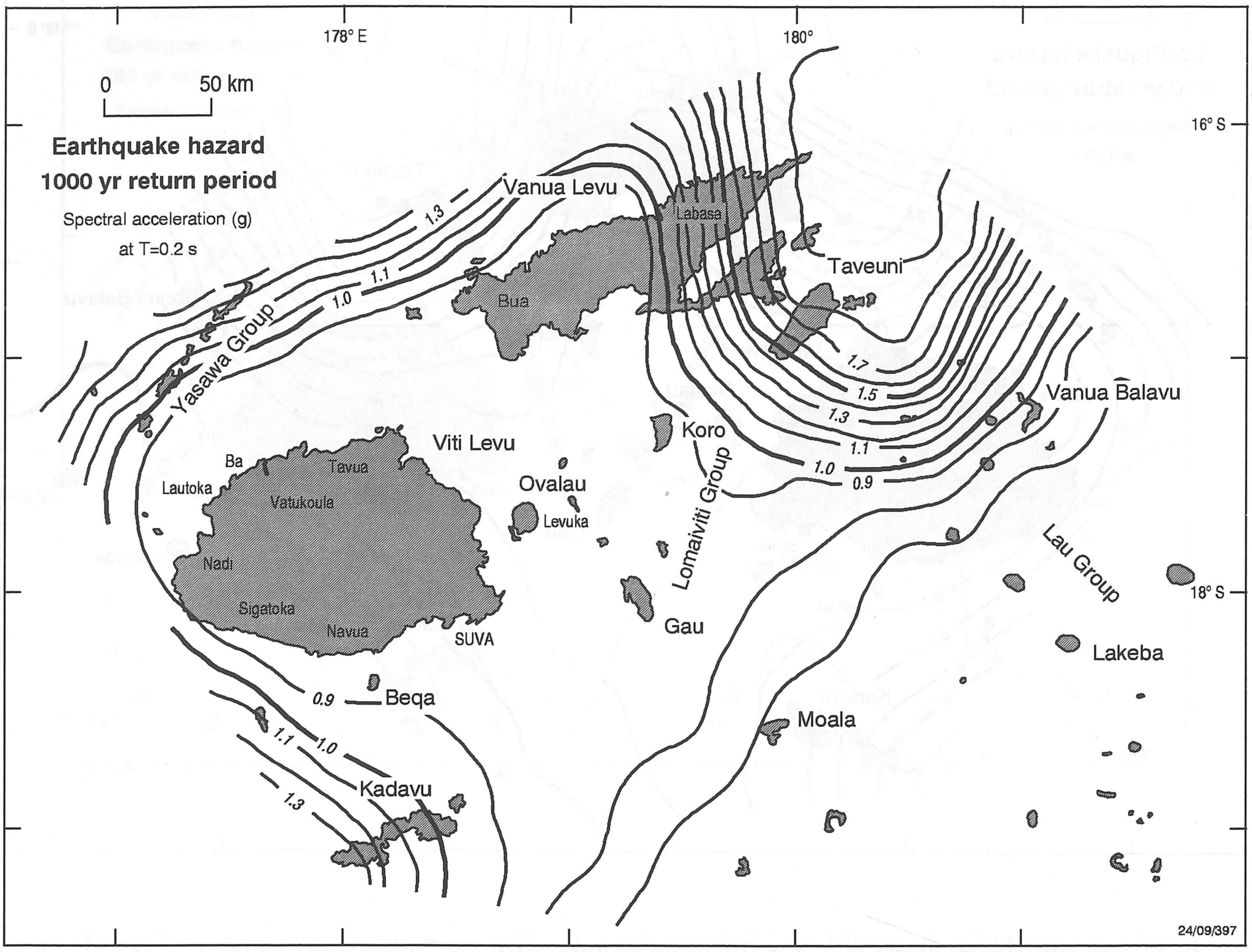

Figure 8 (d) Earthquake hazard map for Fiji, for a return period of 1,000 years. Contours are shown for values of elastic, 5% damped, horizontal response spectral acceleration (in units of the acceleration due to gravity, g), Katayama ground condition Type 3, at a period of T = 0.2 s. The acceleration contours over marine areas indicate the general pattern of the hazard but cannot be used for the design of marine or submarine structures.

the strong gradient in hazard results in an increase of the hazard compared to the 1990 estimates of approximately 40% in eastern Taveuni, Udu, Rabi and Cikobia.

The estimated earthquake hazard in Fiji ranges from moderately low to very high. The estimated hazard at Rotuma is comparable to moderate continental intraplate values such as the hazard for Geelong, Australia (Gaull et al., 1990). The estimates for most of Viti Levu are comparable to middle values in New Zealand. The Zone Factors for northeastern Fiji are higher than the maximum of Z = 1.2 specified in New Zealand.

Table 6 Horizontal, elastic, 5% damped acceleration response spectral values (g) for T = 0.2 s, Katayama ground condition Type 3, for Fiji urban centres. The 450-year spectral values are equivalent to the Zone Factor Z in an amended National Building Code for Fiji.

	Return period (yr)			
	450	50	150	1000
Suva	0.68	0.28	0.45	0.87
Lautoka	0.54	0.28	0.39	0.67
Nadi	0.54	0.28	0.39	0.68
Labasa	0.81	0.42	0.59	0.99
Sigatoka	0.67	0.32	0.47	0.84
Levuka	0.68	0.28	0.45	0.87
Ba	0.55	0.27	0.39	0.70
Tavua	0.57	0.27	0.39	0.73
Navua	0.67	0.29	0.45	0.86
Rotuma[1]	0.20	-	0.11	0.28

[1] At T = 0.15 s

Sensitivity of hazard estimates to input parameters

Uncertainties are associated with all of the input parameters used in the calculation of earthquake hazard in Fiji. I investigated the sensitivity of the estimates of hazard to perturbations in both the seismicity model and the attenuation model to indicate the reliability of the hazard calculated for Fiji.

Suva is the site of many of these test cases. Significant national risk is concentrated in Suva and the earthquake hazard at Suva is representative of the hazard across a broad area of the Fiji Platform where the differences in earthquake hazard are relatively small. Moreover, the magnitude frequency data for Suva (Fig. 6) contain an undesirable discrepancy between the rates of occurrence of large earthquakes and small earthquakes.

The first sensitivity test was to test the effect of varying the parameters M_{max}, a_4 and b in the SEVL seismicity model. New spectral acceleration values were calculated for Katayama ground condition Type 3, return period 450 years, as before. The seismicity parameters of all other source zones were not altered because the hazard at Suva is dominated by the seismicity of the SEVL source zone.

Spectral acceleration values for maximum magnitudes of Mw 7.5, Mw 8.0 and Mw 8.5 in the SEVL seismicity model are shown in Table 7 for Suva at periods in the range T = 0.2 s to T = 4.0 s. The results show that the choice of maximum magnitude has little effect on the spectral accelerations across all periods in this range.

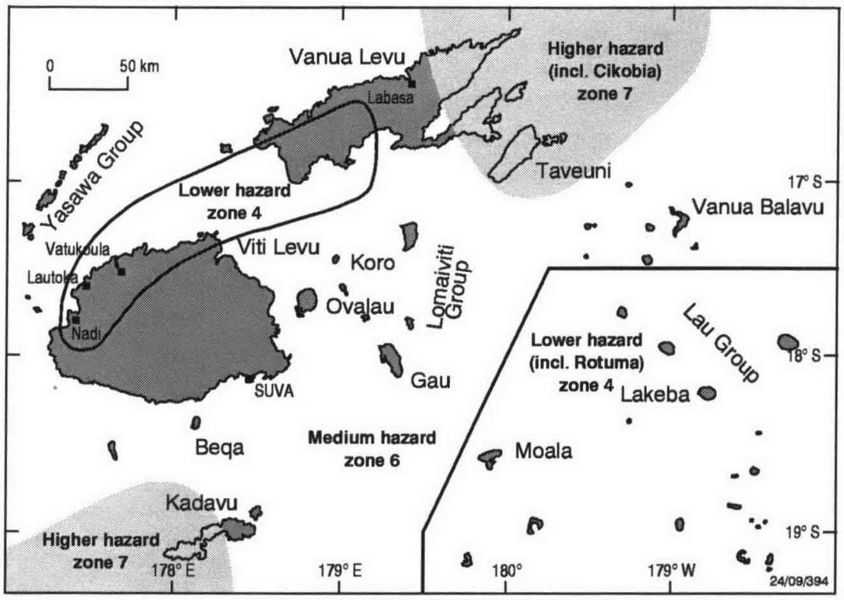

Figure 9 Preliminary Earthquake Risk Map for Fiji, after the draft 1990 National Building Code for Fiji (Pacific Building Standards Project, 1990).

The effect on the spectral accelerations at period T = 0.2 s for Suva of varying seismicity parameters a_4 and b is shown in Fig. 10. Curves are shown for three values of b and σ (spectral acceleration increases with increasing σ, and the influence of σ on hazard is discussed below). The value of a_4 has a moderate influence on the hazard at Suva. For $b = 1.0$ and $\sigma = 0.285$ (the values adopted for the SEVL model), increasing a_4 from 0.02 to 0.24 increases the spectral acceleration by a factor of 2.2. The hazard is less sensitive to a range of 'reasonable' b values. For b in the range $b = 0.95$ to $b = 1.05$, and with $\sigma = 0.285$, the spectral acceleration varies by a maximum of only about 11%.

Table 7 Effect on spectral acceleration (g) at Suva of varying maximum magnitude[1]

Magnitude	Period T (s)			
Mw	0.2	0.5	1.0	4.0
7.5	0.676	0.417	0.241	0.057
8.0	0.691	0.428	0.247	0.0583
8.5	0.694	0.431	0.250	0.0587

[1] Maximum magnitude in SEVL source zone. Accelerations are for 5% damped elastic horizontal response spectra, RP = 450 yr, Katayama ground condition Type 3.

Although I have specified the depth of earthquakes as 10 km for all source zones in Fiji, there is no provision in the Modified Katayama methodology to test the effect of depth on the calculated hazard. Katayama (1982) included earthquakes with depths of 60 km or less in his dataset, and the depths of New Zealand earthquakes which supplement the

Japanese dataset are also undifferentiated beyond this criterion. The hypocentral depth can have a profound effect on epicentral ground shaking (Reiter, 1990, p.44) and consequently a moderate effect on the hazard.

Next, I examined the effect on estimates of hazard of uncertainty in the location of the boundaries of the earthquake source zones. The southern boundary of FFZ1 had been placed about 10 km south of where tectonics may have dictated so that earthquakes which probably originated in FFZ1 but which had been mislocated further south would be counted in the seismicity of FFZ1 (Figs 2 and 5). In a trial the southern boundary of FFZ1 was relocated north by about 10 km, and spectral accelerations were recalculated. The result was that the spectral acceleration contours in the northern Yasawas were also translated north by a similar distance, and spectral acceleration at the northern extreme of the Yasawas, Yasawa-i-rara, was decreased from SA ≈ 1.1 g to SA ≈ 1.0 g for a 450 year return period. The effect was negligible some tens of kilometres south of Yasawa-i-rara. This moderate uncertainty in earthquake hazard is relevant to areas near zone boundaries in eastern Vanua Levu, Kadavu and the Yasawas.

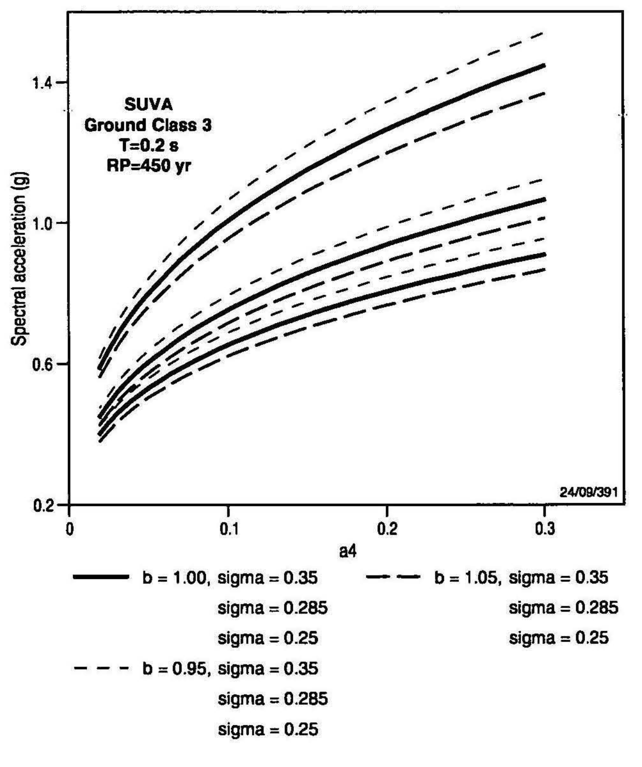

Figure 10 Sensitivity of earthquake hazard at Suva to changes of seismicity parameters a_4 and b for SEVL, and to the standard deviation of the logarithm of the spectral acceleration, σ, in the attenuation relation. For each value of b, curves are shown for three values of σ. Spectral accelerations are calculated for Katayama ground condition Type 3, period T = 0.2 s, return period = 450 yr.

As was mentioned in Section 4, alternative configurations for earthquake source zones were considered and discarded. The effect of alternative source zone configurations on earthquake hazard estimates is not reported here.

Another sensitivity test relates to the attenuation of strong ground shaking with distance. Significant variability in strong ground shaking is always observed in recordings used to derive attenuation relations such as equation (3), even when accelerographs in close proximity record the same earthquake. The distribution of accelerations for earthquakes at each magnitude and distance is described probabilistically and is usually considered log normal; that is, y = ln (a), with standard deviation σ in ln (acceleration), where σ is considered independent of magnitude and distance. The Katayama model makes this assumption. [If ln (a) is normally distributed with mean y_{av}, exp (y_{av}) is the median of a.] Maximum accelerations with a log normal distribution are unbounded and large accelerations in the hazard models originate from both the extreme tail of accelerations for moderate magnitudes and from the median values of acceleration for large earthquakes. Consequently, the acceleration for a given return period is higher than the median value. This phenomenon was called 'probabilistic enhancement' by McVerry (1986). The amount of enhancement is strongly dependent on the value of σ which for many countries is known poorly and which in Fiji is unknown because no significant strong motion data have been recorded there.

In many cases, the attenuation of acceleration with distance is described in the form

$$\log a = d + cM + f(R) \qquad (5)$$

where R is a distance, and the rate of earthquake occurrence is of the form

$$\log N = A - bM \qquad (6)$$

where N is the rate of occurrence. Under these conditions, the 'probabilistic enhancement' of acceleration for a given return period, compared to the median acceleration, is approximately (Bender, 1984)

$$\text{'probabilistic enhancement'} = \exp\,(2.303\, b\, \sigma^2/2c) \qquad (7).$$

The approximation is good for $a_{min} << a << a_{max}$ and for $M_{min} << M_{max}$. McVerry (1986) lucidly discussed the phenomenon of 'probabilistic enhancement' but erroneously quoted equation (7).

Because σ is not known accurately for Fiji, it is of interest to observe the dependence of the enhancement on σ for Fiji conditions. To make this observation, values of *c* and *b* typical for Fiji were substituted into equation (7). The values of *c* for the Katayama (1982) attenuation relation are shown in Table 8 for the period T = 0.2 s, at which the hazard for Fiji was calculated. The values in Table 8 are also used in the Modified Katayama computer program KATAYAMA. Earthquakes with magnitudes M5.4 to M6.7 are major contributors to the earthquake hazard in Fiji and the mean of Katayama's values of *c* for these magnitudes is approximately *c* = 0.285.

Another estimate for an appropriate value of *c* for Fiji can be made from the relationship for attenuation of Modified Mercalli Intensity, equation (4). In equation (4), C = 1.333 ± 0.207. Murphy and O'Brien (1977) correlated Modified Mercalli Intensity with Peak Ground Acceleration, obtaining

$$\log a = 0.25\ \text{MMI} + 0.25 \qquad (8),$$

where a is peak horizontal ground acceleration in cm s^{-2}. Substitution of the expression for MMI, equation (4), into Murphy and O'Brien's relation (8) gives a value for Fiji of c = 0.33 ± 0.05.

Table 8 Value of magnitude factor *c* in Katayama attenuation relation (T = 0.2 s)

Magnitude				
4.5-5.3	5.4-6.0	6.1-6.7	6.8-7.4	7.5-7.9
0.185	0.280	0.288	0.499	1.00

The 'probabilistic enhancement', plotted as a function of σ from Bender's equation (7), is shown in Fig. 11 for values of *c* = 0.285 and *c* = 0.33. A *b* value of 1.0, adopted for SEVL, is used.

The curves show that the enhancement of acceleration is highly sensitive to σ, particularly for larger σ. The enhancement is also moderately sensitive to the values of *c* and *b* (for *b* = 0.95 and *c* = 0.285, the curve would lie between the two curves shown in Fig. 11).

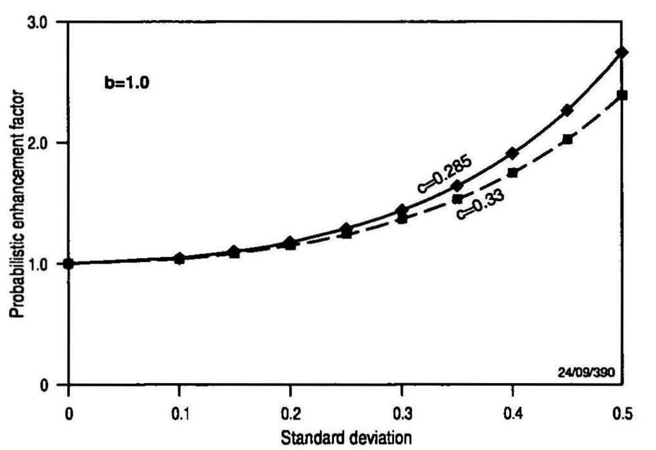

Figure 11 'Probabilistic enhancement' of spectral acceleration. The enhancement is relative to an attenuation relation with no variability in acceleration (σ = 0). Curves are derived from equation (7) with appropriate values for SEVL: c = 0.285, *b* = 1.0 (solid line); c = 0.33, *b* = 1.0 (dashed line).

Significant enhancement effects are also seen in the spectral accelerations for three values of σ calculated by the Modified Katayama method for Suva (Fig. 10). I used accelerations calculated with σ = 0.285, *b* = 1 and a_4 = 0.07 (the preferred SEVL model) as a benchmark. Spectral accelerations are decreased by approximately 12% and increased by approximately 30% for σ = 0.25 and σ = 0.35 respectively, compared to this benchmark. Bender's (1984) approximation (equation (7)), gives corresponding enhancements in acceleration of around -10% and +18%.

The empirical enhancements observed in the Fiji calculations agree well with those considered by Bender, although the Fiji enhancement effects are slightly higher. The magnitude range used in the hazard calculations for Fiji is relatively small ($5.25 \leq Mw \leq 7.5$) and accelerations high in the tail of the log normal distribution may have been sampled for magnitudes near M_{max} in the Fiji Modified Katayama calculations. Bender's approximation (equation (7)) underestimates the enhancement for values of acceleration near a_{max}.

In summary, estimates of the spectral acceleration, and hence the earthquake hazard, at Suva are highly dependent on the uncertainty in the attenuation with distance of ground shaking, measured by σ, the standard deviation of the logarithm of the acceleration. Estimates of hazard for Suva may be strongly sensitive to the attenuation relation used, although this sensitivity has not been tested here. Singh (1996) calculated the earthquake hazard for Monasavu Dam with various attenuation relationships. Spectral accelerations for Suva are moderately sensitive to the seismicity parameters a_4 and b and to the magnitude coefficient c in the attenuation equation (5). The accelerations are weakly dependent on the maximum magnitude truncating the magnitude frequency relation (1). The hazard at a site near the boundary of two source zones of widely differing seismicity is moderately dependent on the location of the zone boundary. The northern Yasawa Group, eastern Vanua Levu and Kadavu are such places. The hazard may be moderately dependent on earthquake depth but this dependence has not been tested here. The hazard may also have a low or moderate dependence on the configuration of the earthquake source zones but this also has not been tested.

A 450 year spectral acceleration of 0.676 g was calculated for Suva using the preferred values of a_4, b and σ (Table 6). Spectral accelerations were also calculated for 'reasonable' excursions in b and σ (Fig. 10). Seismicity parameter a_4 may also be expected 'reasonably' to lie in the range $a_4 = 0.02$ to $a_4 = 0.10$ in which case the 450 year spectral acceleration at period T = 0.2 s for Suva would lie approximately between SA = 0.4 g and SA = 1.0 g.

Comparison of calculated hazard with historic ground shaking

A preliminary comparison was made between the peak earthquake ground motion calculated in this study for several sites in Fiji and the historic record of macroseismic earthquake shaking at these places. Good agreement between the observed ground shaking and estimates of it may increase confidence in the results of the study although 50 years is a short time over which to make a reasonable comparison. The comparison is not an independent check of the accuracy of the results in the hazard maps because the observations of strong ground shaking were used in assessing the attenuation relation used to calculate the seismic hazard (see Methodology).

Table 9 shows a comparison between the calculated 50-year hazard and the maximum intensity of ground shaking observed for the 50-year period 1941-1990 in six places in Fiji. No significant instrumental recordings of strong ground shaking in Fiji were available to use in the comparison and the observations of ground shaking are limited to estimates of seismic intensity.

Table 9 Comparison of calculated and observed ground motions

	Calculated, this study		Observed
	Peak ground acceleration RP 50 yr (g)	Approximate equivalent MMI	Max. ground motion 1941-1990 (MMI) and year
Suva	0.11	7	7 (1953)
Lautoka	0.11	7	6 (1953)
Southwest Kadavu	0.18	8	6 (1950, 1983)
Yasawas (Naviti)	0.18	8	6 (1984)
Labasa	0.17	8	6 (1979)
N. Taveuni	0.32	9	8 (1979)

In Table 9, the peak ground acceleration (pga) is 40% of the value of the spectral acceleration at T = 0.2 s (Standards New Zealand, 1992, Volume 2, p. 33). The approximate equivalent seismic intensity was calculated from the peak ground acceleration using the relation of Murphy and O'Brien (1977),

$$\log a = 0.25 \text{ MMI} + 0.25 \qquad (8),$$

where MMI is the Modified Mercalli Intensity and a is peak horizontal ground acceleration in cm s-2. Other relations between MMI and peak ground acceleration were examined (Krinitsky and Chang, 1988; Gaull, 1979), but the median (i.e., the mean of a log-normal distribution) of the three relations is little different from that of Murphy and O'Brien.

In this limited comparison, the estimated 50-year maximum seismic intensity based on calculations is equivalent to, or greater than, the observed maximum intensity for the period 1941-1990. However, severe limitations in the data, that bear directly on this comparison, should be pointed out.

First, the conversion between MMI and instrumentally-measurable parameters such as peak ground acceleration is problematical globally. Possibly the most comprehensive dataset assembled to assess such relationships is that of Murphy and O'Brien (1977), containing approximately 1500 station recordings. However, they reported that Southern European data indicated peak horizontal accelerations at fixed values of intensity that were a factor of two higher than the corresponding values for Western United States and Japan, and could not determine whether this difference was due to a consistent measurement bias or to variations in tectonic environment. Nearly all the estimates of seismic intensity for Fiji were made by Everingham and, although there is no doubt of Everingham's competence, there may be a systematic bias in his assignment of seismic intensities. Furthermore, published conversions between MMI and peak ground acceleration do not include data from recent earthquakes where accelerations were remarkably high, such as the 1995 Kobe and 1994 Northridge events. The inclusion of such data in conversions between MMI and pga may alter the relationships.

Second, the written historic record of observed ground shaking in Fiji is both brief and incomplete. The record is incomplete because of the remoteness of many parts of the country until recent times and because no single agency was responsible for reporting earthquakes until 1976 when MRD was given that responsibility. The incompleteness of the historical record is noted by Everingham (1987), who observed that of 90 felt earthquakes documented for the period 1941-1981, half occurred in the first 35 years and half occurred in the remaining six years from 1975-1981. For some events, the reports upon which the intensity estimates are based are brief and singular. Indeed, in some places there may have been few buildings or other structures of the type described in the Modified Mercalli Scale (Eiby, 1966) on which to base an intensity estimate. For example, the sole report of the effects on Kadavu of the 12 February 1950 earthquake (Table 9) states

> 'A Capt. Frewin visited Kadavu where landsliding on the top of Mt Washington (Nabukelevu) was observed. Villagers reported a considerable shake and were very frightened. No reports of damage or casualties were made.'
>
> - Meteorological Office File 71, f.49, quoted by Everingham, 1987.

There can be a temptation to adjust the hazard model so that a better match between the observed and calculated hazard will be achieved. This can be done, for example, by adjusting the factor σ described on Page 28 (the estimated hazard will increase or decrease with a similar movement in σ). In this study I have not modified the hazard model. The importance of the attenuation model to hazard estimates for Fiji is discussed in the next section.

8. DISCUSSION

The probabilistic methodology is based on the fundamental premises that the earthquake process is stationary and that the distribution of events is Poissonian; that is, the rate of occurrence of earthquakes will be constant. The method does not allow secular temporal variation in seismicity: it forecasts that the future occurrence of earthquakes will be like the past occurrence. However, temporal variation in seismicity has been observed in Fiji, where an extraordinary ten shallow earthquakes with magnitudes Mw $\geq$ 6.5 occurred from 1950 to 1960 compared to only seven from 1961 to 1990. Temporal variation has also been observed elsewhere; e.g. in China (McGuire, 1979) and southwestern Western Australia (Michael-Leiba, 1987). Probabilistic estimates of future rates of earthquake occurrence are most reliable over a period approximating that in which the data used to make the estimates were obtained. In Fiji, milestones for compiling complete data for moderate and small earthquakes are 1964 and 1979. Estimates of the frequency of occurrence of moderate earthquakes in Fiji, in areas where the data are complete, are more reliable than estimates for the recurrence of large earthquakes. The maximum likelihood method was used to determine the seismicity parameters and it also treats the rate of occurrence of more numerous small earthquakes as more reliable than the rate of occurrence of infrequent, larger earthquakes in determining the parameters.

The estimated return periods of large earthquakes approaches or exceeds the length of the historical record. The written history of Fiji earthquakes is perhaps 150 years and this time period is short compared to the calculated return periods of damaging (Mw ≥ 6) earthquakes affecting populated areas. These return periods, normalised to an area of 1,000 km^2, are approximately 1,375 years for SEVL (with a_4 = 0.07), 6,100 years for FP, and 4,000 years for the LAU source zone.

The earthquake source zones are moderately well defined by seismicity, physiography, and other evidence of tectonic activity such as submarine volcanism. Their definition has been assisted particularly by the results obtained from the FSN. The description of seismicity within the source zones is very good in TAV, WVL and FFZ1. Seismicity is lower and less well defined in the populated source zones SEVL, FP and LAU. I described in Section 5 how the ambiguous seismicity data for SEVL were interpreted conservatively.

Improved estimates of the hazard to major population areas from relatively rare, strong earthquakes will become available through better determinations of the seismicity parameters *a* and *b*. These parameters in turn will be more accurately determined by compiling an earthquake catalogue complete near the main islands above a minimum magnitude of Mw 3 and this requires the continued operation of the FSN. Monitoring by the global network is inadequate to produce reliable estimates of hazard in Fiji because the magnitude threshold above which data are complete is high (Table 4), the uncertainties associated with the epicentral locations are high (still probably tens of kilometres), constraints are weak on the depths of shallow earthquakes, and mislocated deep Tonga subduction zone earthquakes contaminate the shallow earthquake catalogue.

A primary source of uncertainty in the hazard estimates originates from the relations for the attenuation of strong ground shaking. The Modified Katayama attenuation relation used in this study and in New Zealand is based largely on Japanese data and its appropriateness is not certain. There is a suggestion that the calculated 50-year hazard may be higher for some places in Fiji than the observed hazard over a 50-year period. The cause could be attenuation that is higher in Fiji than in New Zealand. On the other hand, the attenuation of Modified Mercalli Intensity in Fiji and New Zealand appears to be similar, although the comparison is based on sparse Fiji data. Valuable new data recorded from several moderate and strong New Zealand earthquakes since 1990 will strengthen the New Zealand attenuation relations. Until more suitable relations are identified, these can be used for Fiji.

A major step forward would be achieved through the development of Southwest Pacific uniform hazard response spectra to be used in the building codes of the respective countries. The present day Solomon Islands, Vanuatu and Fiji are related tectonically through their common ancestry in the Miocene Vitiaz arc. These countries are moderately or highly seismically active and a network of strong motion instruments installed in these countries and in Tonga would quickly acquire valuable recordings. Relations for the attenuation of strong earthquake ground shaking as well as uniform hazard response spectra could be produced from the strong motion data and applied in each country. In the meantime the New Zealand uniform hazard response spectra in NZS 4203:1992 are a good reference for Fiji.

I repeat the note of caution mentioned in the 'Methodology' section. The Zone Factors recommended in this study do not directly substitute for those in the 1990 draft National Building Code for Fiji (Section B1.2 (b) and Figure B1.2). This is because the 1990 draft Fiji code refers to the draft New Zealand standard 2/DZ 4203:1989. The Zone Factor Z in 2/DZ 4203:1989 was derived from calculations of hazard for a 150 year return period whereas the Zone Factor in NZS 4203:1992 was derived from hazard calculations for a 450 year return period. The Zone Factors proposed by this study are intended to be fully compatible with NZS 4203:1992.

9. CONCLUSIONS

This study has produced the first probabilistic earthquake hazard maps for Fiji. Few, if any, similar studies have been undertaken in the seismically active Southwest Pacific. Maps of values of 5% damped, elastic, horizontal response spectral acceleration at a period of T = 0.2 s, for Katayama ground condition Type 3, were produced for return periods of 50, 150, 450 and 1,000 years.

The spectral acceleration map for a 450 year return period (Fig. 8 (c)) is recommended as the basis for the Zone Factor map in the National Building Code for Fiji to replace the 'Preliminary Earthquake Risk Map', Figure B1.2, in the 1990 draft National Building Code for Fiji. The 450 year spectral accelerations are equivalent to values of the Zone Factor referred to in the National Building Code, subject to the following caution.

Simultaneous with adopting the new Zone Factor map, Section B1.2 (b) of the National Building Code should be amended to refer to NZS 4203:1992. Failure to do this could result in the misapplication of the Zone Factor in loading calculations with a consequent overspecification of lateral strength requirements of approximately 50%.

Section B1.2 (b) Dead, Live and earthquake loads of the National Building Code should be further revised by eliminating the reference to the Zone Number which serves no useful purpose.

The Fiji Seismographic Network has proven extremely valuable in defining the seismicity of Fiji in its first 10 years of operation. Its continued operation will lead to improved estimates of seismic hazard in Fiji, especially in Viti Levu and western Vanua Levu.

Local strong motion data are required to define the attenuation of strong shaking and ultimately to produce uniform hazard response spectra to describe the earthquake hazard. An increase in the number of fixed, free-field digital instruments in the Southwest Pacific, and the deployment of similar instruments to record aftershocks in the epicentral areas of strong earthquakes, is essential to provide such data.

This national hazard assessment does not take into account the different ground conditions which may exist in urban areas and at critical facilities. The site specific hazard may be strongly dependent on local ground conditions and the hazard assessments of this study should be augmented by detailed urban zonation studies and site-dependent risk studies for lifelines and important infrastructure where appropriate.

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APPENDIX ONE REGIONAL TECTONICS AND EARTHQUAKE SOURCE ZONES

REGIONAL TECTONICS

Fiji is located in a broad back-arc region between the subduction zones of Vanuatu and Tonga. The Vanuatu (New Hebrides) trench lies to the west of the islands and convergence is accommodated by subduction of the Australian plate beneath the lithosphere of the North Fiji Basin. Along the Tonga-Kermadec region, east-west convergence is accommodated by subduction of the Pacific plate beneath the Tonga ridge.

Over the past 8 million years tectonic activity in the Southwest Pacific region has produced rapid physiographic change which continues in the present day. Subduction of the Pacific plate along the Vitiaz Trench was superseded in the late Miocene by subduction of the Australian plate at the Vanuatu (New Hebrides) Trench, a clockwise rotation of the Vanuatu arc and the formation of the North Fiji Basin. This was followed by an anticlockwise rotation of the Fiji Islands and the opening of the Lau Basin (Chase, 1971; Malahoff et al., 1982a; Malahoff et al., 1982b). Current tectonic activity in the Southwest Pacific is a result of approximately east-west convergence of the Australian and Pacific plates (Hamburger et al., 1990).

The main islands of Fiji are situated on the Fiji Platform, a remnant fragment of island arc which was situated along the Vitiaz subduction zone before the opening of the North Fiji Basin in the late Miocene. The Fiji Platform is relatively strong compared with the thin oceanic crust of the North Fiji Basin where heat flow (Chase, 1971) and seismic attenuation (Hamburger et al., 1990) are high and so most tectonism and, with it, seismicity is transferred to the margins of the platform.

In addition to the very high rate of shallow earthquake activity, approximately 60% of the world's deep earthquakes including some of the deepest, at 700 km depth, occur in the Southwest Pacific region (Sykes, 1966; Hamburger and Isacks, 1987; Giardini, 1988). However these deep earthquakes beneath Fiji contribute a negligible amount to earthquake hazard in Fiji.

The broad regional tectonic pattern in the Fiji region is one of east-west extension and this is shown in spreading centres to the north, east and west of Fiji and by the strike-slip mechanisms of nearly all significant shallow earthquakes in the region, the tension axes of which are aligned horizontally and, in a gross sense, east-west.

The crust of the Fiji Platform has a thickness of the order of 19 km and the best located Fiji Platform earthquakes, in southeastern Viti Levu, are confined almost exclusively to the top 15 km of the crust (Hamburger et al., 1990).

EARTHQUAKE SOURCE ZONES

Southeast Viti Levu Zone (SEVL)

The Southeast Viti Levu Zone extends from the Hunter-Kadavu Fracture Zone (HKFZ) northeast to the Taveuni Zone. The zone includes areas of both oceanic crust and island arc crust of the Fiji Platform.

The largest earthquake recorded in this zone was the 1953 Suva earthquake (Houtz, 1962a; Everingham, 1987). The Suva earthquake had a magnitude of Ms 6¾ (Mw 6.8) and killed eight people, five of them through drowning from a tsunami generated by a submarine landslide.

Several other strong earthquakes are also known to have occurred in SEVL. A strong, shallow earthquake was felt MM7 in the Vunisiga area in the interior of Viti Levu on 2 October 1869 (Fig. 2; Everingham, 1983a). Everingham assigned a magnitude of at least Ms 6 (Mw $\geq$ 6.1) to this event. The Koro earthquake of 8 March 1932 (Fig. 2; Everingham, 1982) had a magnitude of Ms 6.5 (Mw 6.6). It was felt MM7 on Koro where the lighthouse was seriously damaged and the village of Mudu was partly destroyed by a landslide. The event was felt MM4-5 in Suva and MM6 on Ovalau (Everingham, 1983a). The 17 April 1963 earthquake occurred to the south of Kadavu (Fig. 2). Its magnitude was Mw 6.5 and it was felt MM5 at Kadavu (Everingham, 1987).

Because of the concentration of population and risk on Viti Levu, its seismicity is worthy of attention. Numerous earthquake epicentres appear in the seismicity map of Viti Levu (Fig. 3). Many of these events are microearthquakes with magnitudes as low as Mw = -1.0 and their proliferation owes much to the distribution of seismographs (Hamburger, 1990). In fact, seismicity in Viti Levu and nearby is moderate. About 31 earthquakes per year of magnitude Mw $\geq$ 4 were detected by the FSN in the years 1984-1990, but only one of these occurred near Viti Levu (10 February 1985). The catalogue to 1990 for Viti Levu and within about 20 km of its coastline contains only 5 shallow earthquakes with magnitudes Mw $\geq$ 4 when spurious locations, notably from the Large Aperture Array, Montana (LAO), but also from ISC, are removed. These five events include the 1869 and 1953 earthquakes mentioned above and the magnitude Mw 5.8 aftershock of the 1953 earthquake (Sykes, 1966).

The close proximity of the epicentre of the 1953 earthquake to Suva (Houtz, 1962a) raises the concern that this earthquake may have occurred in a Suva-Beqa source zone from which large earthquakes will continue to threaten Suva. The catalogue contains many microearthquakes originating in this zone, and small earthquakes such as the 4 June 1961 earthquake (Houtz, 1962b; Everingham, 1987) which probably had a magnitude around Mw 4.5. Another small earthquake was felt in the Navua area on 19 June 1935 (Everingham, 1983a) indicating that the Suva-Beqa area was seismically active prior to the 1953 earthquake. However, the seismicity is not remarkably different from the seismicity of eastern Viti Levu, or the entire SEVL source zone, and does not warrant its quarantine as a separate source zone. Nonetheless, continued monitoring of the area is prudent.

A large earthquake (Mw 7.6) occurred on 3 March 1990 in a tectonic regime arguably similar to that of southern SEVL. The earthquake, at 1216 UTC, occurred about 500 km southwest of Suva. This event did not occur within SEVL but rather on the Hunter Kadavu Fracture Zone (HKFZ) about 350 km southwest of the southwest margin of SEVL. Focal mechanisms, including that of the 1953 Suva earthquake (Hamburger et al., 1990), are consistent along the length of the HKFZ, from Hunter Island in the southwest to the Koro Sea Basin in the northeast. Left-lateral strike-slip faulting along the nodal plane parallel to the northeasterly bathymetric trends (Kroenke et al., 1983) is probable for the western HKFZ earthquakes and possible for all HKFZ earthquakes including those near southeastern Viti Levu. (Right-lateral earthquake activity on more recent faults orthogonal to the ridge axis may also occur in the SEVL zone.) Because of the occurrence of the 1990 earthquake, the hazard from a major earthquake of magnitude Mw 8 was investigated in the hazard calculations of this study.

Fiji Platform Zone (FP)

The Fiji Platform source zone includes the western part of Viti Levu and most of Vanua Levu. The zone, in the western and northwestern Fiji Platform, is defined by seismicity which is relatively low compared to other parts of the platform (Figs 2 and 5). The southernmost border of this zone, southeast of Vatulele, corresponds to the 2 km isobath.

A knowledge of the earthquake hazard in this zone, like the SEVL source zone, is of national importance because the cities Nadi and Lautoka, major industry such as the Fiji Sugar Mill and the Vatukoula gold mine, and key infrastructure such as the international airport at Nadi and seaport facilities at Lautoka, are located in this zone.

The two largest known events included in this zone occurred in 1931. Macroseismic data are recorded from an event on 11 November 1931, 0400 UTC, magnitude Mw 5.2, which was felt in Vanua Levu, Lautoka and Suva with a maximum recorded intensity of MM5 in Bua (Fig. 2; Everingham, 1983a). This event was closely followed by another on 12 November 1931, 1618 UTC, with magnitude Mw 5.6, which was also felt MM5 in Bua. The relatively high intensities and moderate magnitudes, referred to the attenuation relation for MMI derived for Fiji (Fig. 7), suggest that the events occurred at around latitude 16.3°S, longitude 178.75°E, within FP and not within the more active FFZ2 to the north.

The part of FP north of western Vanua Levu, from longitude 178°E to 179°E, contains 17 of the 33 catalogue hypocentres used for hazard calculations. These events have sources from ISC and also include events located by the FSN. Although some of the events listed by ISC are probably mislocated and are more likely to have occurred in the eastern extremity of FFZ1, it is probably also true that, since 1963, this area has experienced the highest seismicity in FP. The effect of smearing the seismicity of this localised source across the entire FP zone is to slightly enhance the level of seismicity for the entire zone and to slightly understate the seismicity of the area between longitudes 178°E to 179°E.

Taveuni Zone (TAV)

The Taveuni zone is situated in the far east of Vanua Levu and extends southeast east of the Lau Ridge. It is truncated for the purposes of this study near the southeastern end of the Peggy Ridge at 177°W. Seismicity is very high - the highest of any of the source zones - and mostly occurs on transform faults oriented northwest where dextral strike slip is indicated by the earthquake focal mechanisms.

The 16 October 1979, 1521 UTC, Taveuni earthquake was the most recent damaging earthquake in Fiji. It had a magnitude of Mw 6.9 and caused Modified Mercalli Intensities of MM8 in northern Taveuni, with damage caused by both shaking and landslide activity (Everingham, 1987). A further 19 earthquakes with magnitudes Mw ≥ 6.5 occurred in this zone in the period 1918 to 1996 (Fig. 2). Remarkably, the largest of these, on 30 March 1949 at 1447 UTC, had a magnitude of only Mw 7.1 and it is also the largest shallow earthquake recorded in Fiji.

Three other earthquakes in the TAV zone are known to have caused strong shaking in populated areas. The Rabi earthquake of 3 October 1919, 0937 UTC, located at latitude 16.4°S, longitude 180°E by Everingham (1983a), had a magnitude of Mw 6.9 and intensities of MM8 were recorded at Rabi, where large landslides and liquefaction were observed. The earthquake was felt MM7 at Savusavu (Everingham, 1983a). The earthquake of 21 June 1928, 1040 UTC, was felt MM6 at Taveuni and was felt mildly at Suva. Its magnitude was Mw 7.0 and the epicentre of Everingham (1983a) is latitude 17.0°S, longitude 179.5°W (Fig. 2). An earthquake of magnitude Mw 6.6 occurred on 16 February 1932, 1348 UTC, with an epicentre at about latitude 16.2°S, longitude 179.7°W. Intensities of MM7 at Rabi and MM6 at Labasa were recorded (Everingham, 1983a).

The ISC catalogue shows a zone of shallow seismicity, about 100 km southwest of the Peggy Ridge and trending subparallel to the ridge between latitudes 16° and 18° approximately (Fig. 2). Hughes Clarke et al. (1993) commented on this seismicity.

A closer inspection indicates that nearly all of the earthquakes in this 'zone' are probably mislocations. I considered events during the period 1964-1990. The maximum magnitude of more than 90 events in this area is Mw 5.2. The great majority of these events occurred in the period 1970-1975 and no event was recorded in this zone after 1981 (Table 10). It would seem to be highly unlikely, if shallow seismicity did originate from this area, that no events would have been recorded in the 10-year period from 1981. A more likely explanation is that the location methodology of ISC improved from about 1979 and similar events were located more accurately.

Table 10 Frequency of shallow earthquakes adjacent to southern boundary of TAV earthquake source zone

Year	1964-1969	1970-1975	1976-1981	1982-1990
No. events	16	63	10	-

Where did these events originate? Two alternatives are the most probable. The first suggestion is that the events occurred on the Peggy Ridge. In this case they have no effect on the seismicity rates determined for the TAV zone because their magnitudes are smaller than the minimum magnitude used. The second possibility is that the events are mislocated intermediate depth earthquakes from the Tonga subduction zone. Epicentres of these events are in the same area as the epicentres of interplate events at depths of 300-400 km (e.g. Hamburger and Isacks, 1987). If so, they do not affect the hazard for the Lau Group of islands, because of their great depth.

Regardless of the origin of these earthquakes, they were discarded. The TAV zone was positioned northeast of these events and the events were not included in calculations of LAU zone seismicity.

Lau Zone (LAU)

The LAU zone is the largest source zone in Fiji. The seismicity maps (Fig. 2) show many shallow earthquake epicentres in the zone, especially in the eastern part. However, many Lau Ridge events in the global catalogues are mislocated deep events associated with the Tonga subduction zone. The higher seismicity in the east is coincident with the upward projection of the structure of the Tonga subduction zone at depths of up to 700 km (e.g., Billington, 1980; Hamburger and Isacks, 1987) and many of the shallow catalogue earthquakes probably occurred at depth.

The global catalogues list nine earthquakes from 1918 to 1936 occurring at latitude 17°S, 177°W (Fig. 2). No depths are assigned but Everingham (1983b) calculated surface wave magnitudes for these events ranging from Ms 5.4 to Ms 6.8, indicating that most were shallow earthquakes. Their locations, however, are uncertain and they were not considered in estimates of the seismicity of LAU.

Shallow seismicity is relatively low. No genuine shallow earthquake with magnitude Mw ≥ 5 or number of reporting stations ≥ 15 occurred in the LAU zone in the period from November 1979 to December 1990, although numerous but spurious events were indicated prior to this. However, hypocentres for eight shallow earthquakes near the Lau Group of islands were determined from data of the FSN to 1990 and at least one shallow earthquake has been felt at Matuku.

The contamination of the shallow earthquake catalogue by deep earthquakes created difficulties in making an accurate assessment of the seismicity in the LAU zone. Seismicity was estimated to be lower than that indicated since 1964, due the contamination of the catalogue, and higher than that indicated since November 1979, after which few genuine shallow events have been recorded.

West of Viti Levu Zone (WVL)

Major back-arc, east-west extension occurs to the west and southwest of the Fiji Platform in this zone. Earthquake focal mechanisms have a horizontal, east-west tension axis and mostly indicate strike slip faulting along northeast and southwest nodal planes, although several normal faulting mechanisms exist for earthquakes in the west of the zone. The eastern border of this zone corresponds to the 2 km isobath. Tectonic activity supersedes that on the northeast trending Kadavu Ridge (Fig. 1), and the southeastern border of the WVL zone (Fig. 5) corresponds to the 2 km isobath on the southeastern flank of the Kadavu Ridge.

The WVL zone affects seismic hazard in western Viti Levu, the Yasawa Group, Vatulele and Kadavu. Four earthquakes of magnitude Mw ≥ 6.5 are known to have occurred in WVL, three of which were felt. The first is the earliest earthquake in the Fiji catalogue. Around 1850 an earthquake occurred near Kadavu which 'shook down a large cave and buried 30 or 40 women' (Jackson's 'Narrative', 1853; see Everingham, 1983a). The 19 September 1921, 2316 UTC, Mw 6.7 earthquake was felt MM5 in Lautoka, and at least 14 aftershocks were also felt (Everingham, 1983a). The data for attenuation of Modified Mercalli Intensity in Fiji (Fig. 7), and the number of aftershocks felt in Lautoka, suggest that the epicentre of this earthquake must have been about 70-80 km away from Lautoka near the western margin of the Fiji Platform. The earthquake on 12 February 1950, 2214 UTC, had a magnitude of Mw 6.6 and an epicentre some 40 km northwest of Kadavu, where it was felt MM6 and caused landsliding on Nabukelevu (Everingham, 1983a).

Fiji Fracture Zone

The Fiji Fracture Zone (FFZ) is a major transform fault on which east-west relative motion of the Pacific and Australian plates occurs at the north of the back arc region between the convergent Vanuatu and Tonga arcs (Hamburger and Isacks, 1988). The FFZ extends east from about longitude 175°E in the central North Fiji Basin along the northern margin of the Fiji Platform and toward the Samoa corner.

North of Viti Levu and Vanua Levu it steps around the Fiji Platform, offset by a number of spreading centres (Hughes Clarke et al., 1993). In the western part of the FFZ the slip is sinistral along east-trending transform faults which link adjacent spreading centres. However, north of Vanua Levu, from around 179.5°E east to the Peggy Ridge, dextral faulting along northwest trends is also observed in seafloor fabric (Hughes Clarke et al., 1993) and in earthquake focal mechanisms. The character of the seismicity is markedly different east and west of about 178.7°E (Fig. 3), where a segment of fracture zone has its eastern terminus at the north-south aligned West Cikobia Basin Volcanic Zone of Hughes Clarke et al. (1993). I have subdivided the FFZ into two discrete parts, FFZ1 and FFZ2, to reflect the different character of the seismicity (Fig. 3). The transition between the east-west, sinistral style of tectonism in FFZ1 and the northwest trending, dextral tectonism further east occurs in FFZ2. Unfortunately the mapping of Hughes Clarke et al. (1993) did not extend far enough south in the area of FFZ2 to have mapped the Australian-Pacific plate boundary at this location.

Fiji Fracture Zone One (FFZ1)

The southern boundary of this zone corresponds to the 1 km isobath. The seismicity is some tens of kilometres north of the island of Yasawa, northern Yasawa Group, and earthquakes are commonly felt on Yasawa. Seismicity is marked by intense activity of small and moderate earthquakes. Although the seismicity is high the maximum magnitudes are low. Only two earthquakes have had magnitudes of Mw 6.5 or more. These occurred in 1902 on 2 August, 2240 UTC (Mw ≥ 6.7), and in 1957 on 19 June, 0801 UTC (Mw 6.6). The 1902 earthquake was felt in the Yasawas MM7, Ba MM6 and Lautoka MM5-6 (Everingham, 1983a). The 1957 earthquake was felt at Yasawa-i-rara with intensity MM5.

Fiji Fracture Zone Two (FFZ2)

The southern boundary of this zone corresponds to the 1.5 km isobath. Historic seismicity in FFZ2 is less well defined than seismicity in FFZ1 and is lower than the seismicity there and in the TAV zone to the east. However, there is evidence large earthquakes may have occurred in FFZ2 in 1881 and in 1884 (Everingham, 1983a). A tsunami of at least '18 inches above the highest mark' was observed at Levuka (Fig. 1) from the 1881 event and it may also have caused a 'rise and fall ... (of) six feet' reported by a correspondent from Macuata who commented on the 1884 event and referred to an undated, earlier event (Fiji Times and Herald, 16 January, 1884). Everingham (1983a) assigned a magnitude of Ms ≥ 7 (Mw ≥ 7) to the 1881 event. The event of January 1884 was felt MM7 in Macuata and Everingham (1983a) ascribed a magnitude of Ms 6.8 (Mw 6.8) to this event.

The occurrence of these two events would have relieved localised stresses and this stress release may partly explain why the post 1963 seismicity of FFZ2 is several times lower than that of adjacent FFZ1. The low seismicity in FFZ2 between about 178.7°E and 179.3°E may indicate the location of these events and Everingham (1983a) puts their location near 16°S, 179°E (Fig. 2). Events located by the FSN have mostly occurred in the east of FFZ2 (Fig. 3) and the largest of these, on 22 January 1986 at 2047 UTC, had a magnitude of Mw 5.4.

An event of Mw 6.4 on 22 March 1920, 2001 UTC, was felt at Savusavu. Everingham (1983a) suggested that this event occurred in FFZ2 but, in the absence of other felt reports, the event with equal probability may have occurred in FFZ1 or TAV.

Rotuma (ROTU)

The island of Rotuma is remote from all other islands of Fiji and is about 570 km north of the northern coast of Viti Levu at approximate latitude 12.5°S, longitude 177.2°E. Its location, on the east-northeast trending Rotuma Ridge, is between the probably inactive remnant plate boundary of the Vitiaz arc (Falvey, 1978) to the north and the low-activity spreading of the Tripartite Ridge to the south and southwest (Ruellen et al., 1996).

Several earthquakes have been felt in Rotuma. Everingham (1987) recorded four earthquake reports: 20 August 1950 (MM4), 28 August 1950 (MM5), 27 August 1969 ('slight tremor') and 22 February 1977 (MM4). The report from 20 August 1950 of 'lasted one minute' suggests an earthquake of Mw ≥ 6 at a distance of 100 km or more from Rotuma. However, none of these earthquakes is listed in the ISC catalogue.

The ISC catalogue lists 19 earthquakes in the area described by latitude 10.5°S to 14.5°S, longitude 175°E to 179°E in the period to the end of 1994. These coordinates were used as the vertices for the ROTU source zone. The zone has Rotuma at its centre and its margins are about 200 km from Rotuma. Seventeen of the 19 events lie to the south of Rotuma in latitudes 13°S to 14.1°S and these earthquakes may be associated with the N110°E trending Tripartite Ridge. The seismicity is low and unremarkable except for a cluster of eight moderate earthquakes, of magnitudes 4.9 ≤ Mw ≤ 6.0, around 13.25°S, 175.25°E, about 200 km west-southwest of Rotuma. The first of these events occurred on 31 December 1973 and the remainder occurred from 3 March 1993 to 8 March 1993. The location of these earthquakes is associated with the western segment of the Tripartite Ridge near its intersection with the eastern segment of the active South Pandora Ridge, which trends arcuately west-southwest from this area, and the southwestern end of the Rotuma Ridge, which trends east-northeast from this area (Ruellen et al., 1996). The focal mechanism of the largest earthquake indicates normal faulting with the azimuth of the tension axis at N193°E, in excellent agreement with the tectonic extension of the Tripartite Ridge mapped by the swath imaging of Ruellen et al. (1996). Earthquakes with magnitudes less than Mw 7.5 in this area are unlikely to cause damage at Rotuma.

A magnitude recurrence relation was prepared from the catalogue for the ROTU source zone (Table 2) and, in common with the parameters for several other source zones, a *b* value of 0.95 and a maximum magnitude of Mw 7.5 were chosen.

Cikobia Basin Zone (CBZ)

Relatively minor seismicity, compared to the seismicity of the FFZ, occurs north of the FFZ and within about 1 degree of it. The CBZ lies within 200 km of northern Vanua Levu and the Yasawa Group and has been included in the hazard calculations because of its proximity to these areas. The earthquakes in this area are marginal to the main interplate boundary marked by FFZ.

Some of the earthquakes in the catalogue with locations in this zone probably occurred within the Fiji Fracture Zone and have been mislocated. A case in point is the earthquake of 12 July 1923. Everingham (1983b) determined a magnitude of Ms 6.5 (Mw 6.6) for this earthquake from the Riverview seismograph. Sykes et al. (1969) relocated the earthquake (Fig. 2) which previously had been located by ISS and by Gutenberg and Richter (1956a). Sykes et al. assigned Quality C ('very large standard errors') to their location and the three locations differ by up to two degrees.

However, other strong, shallow earthquakes almost certainly occurred in this zone. The largest known is a well-located event of magnitude Mw 6.2 which occurred on 13 October 1984. This earthquake was the third of three with magnitudes Mw 6.1 or Mw 6.2 occurring in 12 hours on 12 and 13 October (Fig. 3). The epicentres of the two earlier events were about 1 degree south of the 13 October event in an area of higher seismicity (Hamburger et al., 1990) and all had strike-slip mechanisms possibly indicating east-west sinistral faulting.

The seismicity of this zone has negligible effect on the hazard (less than 1% for periods T=0.2 s to T=1.0 s) in the nearest populated areas such as Yasawa-i-rara and Cikobia because zones of higher seismicity such as FFZ1, FFZ2 and TAV separate the populated areas from CBZ.

APPENDIX TWO CALCULATION OF SEISMIC SCALAR MOMENT MAGNITUDE Mw FOR CATALOGUE EARTHQUAKES

Magnitude scales in use for Fiji earthquakes

Local magnitude determined by MRD is the most common magnitude for shallow earthquakes in Fiji. About 1,600 events, or approximately 70% of all earthquakes with a magnitude value available, occurring from late 1979 to 1990 had local magnitude as the default magnitude. The local magnitude scales used by MRD are ML (Richter magnitude) and MD (duration magnitude). The ML scale for Fiji is derived from Richter's original definition for California (Richter, 1935) and has been measured from Vunikawai (VUN) or Suva (SVA) seismograms, allowing for the differences in magnification between the Fiji seismographs and a reference Wood-Anderson seismograph. A relation between ML (VUN) and the duration of the seismic coda for shallow Fiji earthquakes was determined by Prasad (1984) and adopted as the formula for MD by MRD.

Everingham (1983a, 1987) compiled lists of felt earthquakes in Fiji, some of which were pre-instrumental, and estimated surface wave magnitudes for several events using macroseismic data. Everingham (1983b, 1986) also determined surface wave magnitudes Ms from Riverview and Scott Base seismograms for 125 of the largest shallow Fiji earthquakes known to have occurred between 1907 and 1983. Most but not all of these events were listed in the global catalogues but prior to Everingham's work many did not have magnitudes assigned.

The surface wave magnitudes of Everingham and other values of Ms from global hypocentral sources were assigned as default magnitudes to about 165 shallow earthquakes with surface wave magnitudes Ms $\geq$ 5.3 occurring from 1907-1990 by Jones and Dropsy (1995) in their catalogue.

Surface wave magnitude is a more reliable indicator of the size of an earthquake than body wave magnitude although, generally, values of the latter are more readily available in global catalogues such as the ISC catalogue.

Body wave magnitude was the default magnitude for the remainder of events in the original Fiji catalogue. Three hundred and seventy six events included in this study had body wave magnitude equal to the default magnitude in the catalogue. The magnitude data for these events originated from global sources, predominantly ISC, and USGS and its predecessors.

Body wave magnitude mB was defined by Gutenberg (1945) and about 10 catalogue events prior to 1961 have body wave magnitude mB assigned as default magnitude. Magnitude mB was measured from mechanical short- and long-period seismographs in the period range approximately T = 0.5 s to T = 12 s (Kanamori, 1983). In the years 1961 to 1964 the World Wide Standard Seismographic Network (WWSSN) was established by the US Coast and Geodetic Survey (CGS) and from then body wave magnitude was measured from the short period (T = 1 s) Benioff seismographs of the WWSSN. The CGS instruction was to measure the 'maximum amplitude in the first few cycles of P' (McGregor and Ripper, 1976) rather than the maximum amplitude, which may be larger, in the entire body wave train. This practice continued at least until 1979. I refer to body wave magnitude measured post 1960 as mb.

Although commonly reported in the global catalogues since 1964, body wave magnitude mb measured from short period WWSSN instruments is the least useful magnitude for earthquake hazard analysis. The main reasons are that 'the mb values deviate very substantially from those of any existing scales' (Kanamori, 1983) and that mb saturates around mb~6 to 6.5 (e.g. Wyss and Habermann, 1982; Giardini, 1988).

Conversion to Mw

Moment magnitude Mw for all shallow earthquakes was calculated according to the following hierarchy of processes. That is, for a particular earthquake, Mw was calculated if possible from Step 1 and, if not possible, from Step 2, and so on.

Step 1. The formula Mw = (2/3) log Mo - 10.73 (Kanamori, 1977; Hanks and Kanamori, 1979) was used to calculate Mw for events for which a scalar seismic moment Mo was available. These events included all those listed in the Harvard Centroid, Moment Tensor (CMT) catalogue from 1977 to 1990. The global threshold magnitude for this catalogue is about magnitude 5¼ (Dziewonski et al., 1988).

Step 2. If a surface wave magnitude value Ms was available, it was converted to Mw using the formulae of Ekström and Dziewonski (1988) derived from global data.

Step 3. Where a value of local magnitude, either MD or ML, was available, it was converted to Mw using the relation ML = MD = Mw. The Fiji local magnitude scales were determined using Californian attenuation (Prasad, 1984) and in California the scalar seismic moment magnitude scale is in good agreement with the local magnitude scale for the magnitude ranges $3 \leq ML \leq 7$ (Hanks and Kanamori, 1979; Thatcher and Hanks, 1973). I present indirect evidence in Step 4 that local magnitudes determined in Fiji and California are in agreement.

Step 4. About 10 pre-WWSSN events in Fiji had Gutenberg and Richter (1956a) listed as the hypocentral source and body wave magnitude mB (Gutenberg, 1945) as the default magnitude. These mB values were converted to Ms using the relation recommended by IASPEI in Zurich in 1967

$$Ms = 1.79\ mB - 5.2 \qquad (9).$$

The Ms values were then converted to Mw using the procedure described in Step 2.

Step 5. The remainder of the events had body wave magnitudes mb. A relationship between mb and local magnitude reported by the FSN was developed from earthquakes for which both magnitudes were available (Fig. 12). This relationship was then used to calculate local magnitudes from body wave magnitudes mb values for earthquakes occurring both before and after the establishment of the FSN. About two-thirds of the earthquakes with default magnitude mb occurred from February 1963 to the time of the establishment of the FSN in November 1979, and about one-third occurred from November 1979 to 1990.

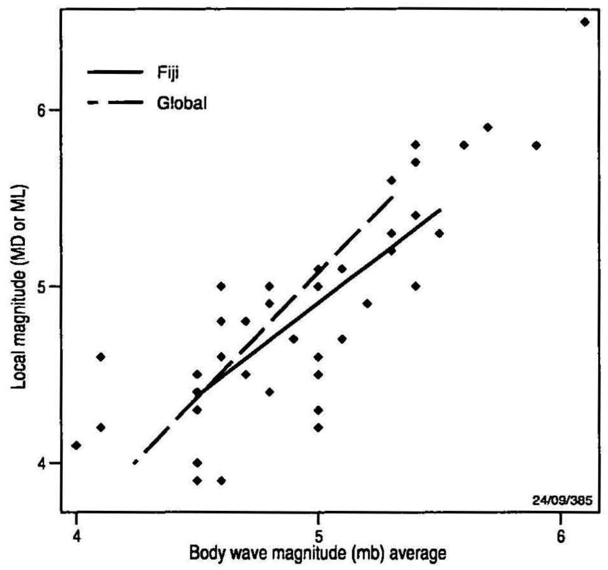

Figure 12 Linear regression (solid line) between ISC average body wave magnitude mb, reported from more than one station, and local magnitude (ML or MD) calculated by MRD for earthquakes occurring September 1979 - 1990. Dashed line for global data is derived from Wyss and Habermann (1982), Båth (1966), and Gutenberg and Richter (1956b); see text.

A potential difficulty arises in formulating a relation between mb and local magnitude because of the uncertainty that exists in the means of measuring mb after 1979; that is, mb measured post 1979 may be somewhat different from mb measured from 1961 to 1979. Willmore (1979) recommended a reversion to the pre-1961 practice but Denham (1982) reported that the adoption of this practice had been slow and measurement of mb from the first few cycles of P may have continued well into the 1980s in many observatories. Because it is likely that both practices continued in the 1980s, the difference between average mb measured from 1961 to 1979 and average mb measured from 1979 to 1990 may be small.

Values of both local magnitude (MD in all but five cases) and ISC body wave magnitude mb were available for 56 shallow earthquakes occurring from November 1979 to the end of 1990. Earthquakes for which mb was reported from one station only were omitted, as were two outlier events with MD = 4.4 and mb > 5.1. The remaining 45 data are shown in Fig. 12.

A linear regression was performed on the 45 data points to give the relationship

$$(\text{MD or ML}) = 1.0489\ \text{mb} - 0.3376; \qquad R^2 = 0.6949 \qquad (10)$$

where R is the correlation coefficient.

A linear relationship between local magnitude and mb rather than a more complicated relation is considered adequate because the magnitudes of interest lie in a small range, approximately $4 \leq \text{mb} \leq 5.5$. Earthquakes with smaller magnitudes were not detected by the global network and earthquakes with larger magnitudes will normally have a value for surface wave magnitude or moment magnitude available.

The comparison of the Fiji relationship (equation (10)) with a relation derived from global data is shown in Fig. 12. The two give similar results for moderate magnitudes. The global relation was derived from Wyss and Haberman (1982), Båth (1966) and Gutenberg and Richter (1956b) in the following way.

The empirical Gutenberg and Richter (1956b) relationship

$$\text{mB} = 1.7 + 0.8\ \text{ML} - 0.01\ \text{ML}^2 \qquad (11)$$

relates the original body wave magnitude to local magnitude. Wyss and Haberman (1982) determined an mb-Ms relationship for 6,925 earthquakes from 1968 to 1980 reported globally:

$$Ms = 1.8\ mb - 4.3 \qquad (12).$$

A comparison between this relationship and the mB-Ms relationship reported by Båth (1966) and adopted by the International Association for Seismology and Physics of the Earth's Interior in 1967,

$$mB = 0.56\ Ms + 2.9 \qquad (13),$$

produces mb values that are systematically 0.5 units lower than mB.

Substitution of mb = mB - 0.5 into equation (11) gives

$$mb = 1.2 + 0.8\ ML - 0.01\ ML^2 \qquad (14).$$

This is the global relation plotted on Fig. 12.

The local magnitudes in equation (11) were determined from Californian earthquakes and so the similarity of the two curves in Fig. 12 may suggest that the local magnitudes determined by MRD are in agreement with those determined in California. If so, the equivalence of ML and Mw found in California for $3 \leq Mw \leq 7$ (Hanks and Kanamori, 1979; Thatcher and Hanks, 1973) may also apply in Fiji.

Body wave magnitudes for 368 earthquakes were converted to local magnitude (and, from Step 3, to moment magnitude Mw) using equation (10).

APPENDIX THREE EARTHQUAKE HAZARD VALUES FOR FIJI

Spectral acceleration values (SA) are in units of the acceleration due to gravity (g) and refer to a period of T = 0.2s and Katayama ground condition Type 3.

Latitude	Longitude	SA RP 450 yr	SA RP 50 yr	SA RP 150 yr	SA RP 1000 yr
-15	177	0.472	0.212	0.321	0.609
-15	178	0.734	0.308	0.492	0.948
-15	179	0.816	0.365	0.563	1.04
-15	180	0.989	0.5	0.719	1.22
-15	181	1.5	0.8	1.12	1.85
-15.5	178	0.884	0.415	0.624	1.11
-15.5	178.5	0.95	0.461	0.682	1.18
-15.5	179	0.973	0.468	0.694	1.21
-15.5	179.5	1.08	0.548	0.788	1.34
-15.5	180	1.51	0.793	1.12	1.84
-15.75	179	1.07	0.508	0.761	1.34
-15.75	179.25	1.07	0.51	0.758	1.34
-15.75	179.5	1.17	0.596	0.855	1.44
-15.75	179.75	1.4	0.732	1.04	1.72
-15.75	180	1.56	0.838	1.17	1.9
-16	178.5	1.24	0.604	0.893	1.54
-16	178.75	1.09	0.525	0.778	1.54
-16	179	0.996	0.479	0.709	1.25
-16	179.25	0.949	0.464	0.677	1.19
-16	179.5	1.08	0.566	0.8	1.32
-16	179.75	1.38	0.727	1.02	1.68
-16	180	1.57	0.848	1.18	1.91
-16	180.5	1.61	0.885	1.22	1.95
-16	181	1.53	0.821	1.14	1.86
-16.25	178.25	1.25	0.614	0.903	1.55
-16.25	178.5	1.12	0.545	0.803	1.38
-16.25	178.75	0.878	0.442	0.641	1.09
-16.25	179	0.779	0.393	0.565	0.967
-16.25	179.25	0.751	0.39	0.548	0.927
-16.25	179.5	0.99	0.521	0.733	1.21
-16.25	179.75	1.34	0.704	0.99	1.63
-16.25	180	1.57	0.84	1.17	1.91
-16.5	177.5	1.28	0.637	0.928	1.58
-16.5	178	1.12	0.557	0.813	1.39
-16.5	178.5	0.827	0.41	0.6	1.03
-16.5	178.75	0.717	0.353	0.516	0.9
-16.5	179	0.612	0.323	0.45	0.764
-16.5	179.25	0.638	0.343	0.471	0.783
-16.5	179.5	0.941	0.491	0.695	1.15
-16.5	179.75	1.29	0.672	0.951	1.58
-16.5	180	1.56	0.827	1.16	1.89
-16.5	180.5	1.58	0.857	1.19	1.92
-16.5	180.75	1.48	0.782	1.1	1.81
-16.5	181	1.12	0.596	0.832	1.36
-16.5	181.5	0.682	0.38	0.513	0.832
-16.75	177.25	1.17	0.583	0.849	1.45

-16.75	177.5	1.04	0.519	0.755	1.29
-16.75	178	0.816	0.404	0.592	1.01
-16.75	178.5	0.669	0.323	0.474	0.847
-16.75	179.25	0.641	0.33	0.463	0.8
-16.75	179.5	0.907	0.451	0.648	1.09
-16.75	179.75	1.21	0.617	0.883	1.49
-16.75	180	1.51	0.788	1.12	1.84
-16.75	181	0.982	0.516	0.727	1.2
-16.75	181.5	0.627	0.346	0.47	0.767
-17	176.75	1.17	0.582	0.847	1.45
-17	177	1.05	0.52	0.758	1.31
-17	177.25	0.884	0.444	0.644	1.9
-17	177.5	0.779	0.387	0.564	0.971
-17	178	0.602	0.3	0.434	0.762
-17	178.25	0.597	0.288	0.421	0.768
-17	178.5	0.64	0.29	0.438	0.831
-17	179	0.659	0.3	0.451	0.85
-17	179.25	0.676	0.321	0.47	0.86
-17	179.5	0.826	0.4	0.58	1.02
-17	180	1.22	0.632	0.9	1.5
-17	180.25	1.41	0.725	1.04	1.73
-17	180.5	1.43	0.725	1.04	1.75
-17	181	0.853	0.432	0.621	1.05
-17	181.25	0.587	0.314	0.433	0.727
-17	181.5	0.574	0.304	0.421	0.715
-17.25	176.5	1.14	0.554	0.815	1.42
-17.25	176.75	1.06	0.513	0.758	1.33
-17.25	177	0.841	0.42	0.61	1.05
-17.25	177.5	0.546	0.29	0.404	0.689
-17.25	178	0.576	0.276	0.406	0.742
-17.25	178.25	0.636	0.282	0.43	0.828
-17.25	178.5	0.66	0.286	0.441	0.856
-17.25	179.25	0.69	0.314	0.473	0.88
-17.25	179.5	0.704	0.334	0.491	0.89
-17.25	179.75	0.842	0.403	0.592	1.03
-17.25	180	0.959	0.486	0.7	1.18
-17.25	180.5	1.05	0.52	0.756	1.3
-17.25	181	0.678	0.337	0.485	0.848
-17.5	176	1.03	0.481	0.725	1.29
-17.5	176.5	1.13	0.538	0.8	1.4
-17.5	177	0.771	0.379	0.555	0.963
-17.5	177.25	0.592	0.304	0.433	0.751
-17.5	177.5	0.53	0.276	0.389	0.675
-17.5	178	0.61	0.264	0.41	0.8
-17.5	178.5	0.671	0.28	0.447	0.868
-17.5	179		0.287		
-17.5	179.5	0.694	0.316	0.476	0.886
-17.5	180	0.719	0.337	0.5	0.906
-17.5	180.5	0.748	0.364	0.534	0.932
-17.5	181	0.541	0.274	0.387	0.683
-17.5	181.5	0.491	0.237	0.34	0.637
-17.5	182	0.512	0.248	0.359	0.66
-17.75	176.5	1.14	0.547	0.812	1.42
-17.75	177	0.78	0.381	0.561	0.977
-17.75	177.25	0.61	0.304	0.439	0.775
-17.75	177.75	0.585	0.266	0.4	0.766

-17.75	180.5	0.554	0.268	0.389	0.704
-18	176	1.12	0.528	0.793	1.4
-18	176.5				1.427
-18	176.75	1.07	0.511	0.763	1.34
-18	177	0.857	0.417	0.615	1.07
-18	177.25	0.707	0.342	0.505	0.893
-18	177.5	0.591	0.289	0.421	0.754
-18	177.75	0.608	0.277	0.416	0.792
-18	178	0.651	0.282	0.438	0.846
-18	178.5	0.674	0.278	0.448	0.871
-18	179	0.674	0.278	0.448	0.871
-18	179.5	0.665	0.274	0.441	0.863
-18	180	0.59	0.258	0.4	0.777
-18	180.5	0.506	0.233	0.345	0.658
-18	182	0.459	0.193	0.298	0.615
-18.25	176.75	1.13	0.544	0.808	1.41
-18.25	177	1.04	0.491	0.736	1.31
-18.25	177.25	0.858	0.407	0.609	1.08
-18.25	177.5	0.725	0.348	0.517	0.914
-18.25	177.75	0.656	0.307	0.459	0.838
-18.25	178	0.655	0.291	0.446	0.848
-18.5	177	1.13	0.542	0.805	1.41
-18.5	177.5	0.903	0.426	0.64	1.14
-18.5	177.75	0.765	0.366	0.546	0.959
-18.5	178	0.721	0.329	0.5	0.917
-18.5	178.5	0.68	0.291	0.459	0.877
-18.5	179	0.672	0.273	0.446	0.87
-18.5	179.5	0.624	0.246	0.407	0.822
-18.5	180	0.509	0.212	0.333	0.67
-18.5	180.5	0.463	0.196	0.301	0.618
-18.5	181	0.456	0.185	0.29	0.612
-18.75	177.5	1.09	0.512	0.771	1.36
-18.75	178	0.832	0.389	0.588	1.04
-18.75	178.25	0.765	0.345	0.531	0.97
-19	176	1.12	0.533	0.798	1.4
-19	177	1.17	0.578	0.843	1.45
-19	177.5	1.14	0.553	0.818	1.42
-19	177.75	1.11	0.525	0.789	1.39
-19	178	0.999	0.461	0.702	1.26
-19	178.25	0.92	0.38	0.583	1.06
-19	178.5	0.735	0.322	0.504	0.938
-19	178.75	0.68	0.286	0.455	0.876
-19	179	0.645	0.261	0.426	0.843
-19	179.5	0.528	0.214	0.344	0.692
-19	180	0.461	0.187	0.295	0.616
-19	182	0.449	0.166	0.276	0.609
-19.25	177.75	1.13	0.543	0.809	1.41
-19.25	178	1.08	0.5	0.759	1.36
-19.25	178.25	0.909	0.404	0.629	1.15
-19.25	178.5	0.753	0.332	0.519	0.958
-19.5	177.5	1.15	0.561	0.828	1.43
-19.5	177.75	1.13	0.534	0.8	1.4
-19.5	178	1.01	0.47	0.713	1.27
-19.5	178.25	0.832	0.382	0.584	1.05
-19.5	178.5	0.723	0.315	0.495	0.927
-19.5	179	0.564	0.233	0.372	0.735

-19.5	179.5	0.471	0.189	0.303	0.627
-19.5	180	0.454	0.172	0.284	0.613
-20	176	0.662	0.302	0.462	0.833
-20	177.5	0.998	0.452	0.696	1.26
-20	179	0.487	0.196	0.315	0.645
-20	181	0.449	0.155	0.273	0.609
-17	177.34	0.844			
-17.33	177.1	0.753			
-16.2	180	1.57			
-16.4	179.5	0.962			
-16.3	179.7	1.25			
-16.75	179.4	0.789			
-16.6	179.9	1.49			
-16.7	180.1	1.55			
-16.85	180	1.43			
-17	179.9	1.13			
-19	178.4	0.769			
-19	178.2	0.871			
-19.1	178	1.05			
-12.5	177	0.143		0.0684	0.225