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# FINAL REPORT

*Submitted to.*

*The US Agency for International Cooperation – CDR Program*

# *SEISMIC MICROZONING IN CAPITAL CITIES IN THE SOUTH PACIFIC*

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*GRANT NO.: TA-MOU-95-C13-024*

**US-AID Grant Project Officer**

**William Craine, Science Attache, US Embassy, Israel**

**Project Duration. Aug 1995 - March 1999**

## EXECUTIVE SUMMARY

We have accomplished the main objectives of the project namely the production of seismic hazard maps for four capital cities in the South Pacific based on the SvE method The cities studied are Honiara (Solomon Islands), Port Vila (Vanuatu), Suva (Fiji Islands) and Nuku'alofa (Tonga)

The SvE method (Shapira and van Eck, 1994) is a semi-empirical approach that incorporates theoretical models of the earthquake source (Brune, 1970, 1971, Boore, 1983, Boore and Atkinson, 1987) empirical scaling laws of seismic parameters, empirical assessments of the long term distribution of seismicity in and around the city and locally determined site response functions In order to obtain the necessary data that facilitated the analysis, we have upgraded the seismic monitoring capabilities in the investigated areas, developed and implemented PC based data acquisition and data processing software, collected and compiled geological, seismological and geotechnical data from the study regions which we assembled on a GIS and performed site response investigations (i e applying the Nakamura (1989) method and the "receiver-function" approach)

Appreciating the importance of the anticipated results of this study, the local governments were very cooperative and helpful This was also reflected in the dedicated work and intense involvement of all the national centers cooperating in the project The GII and SOPAC provided technical assistance, organized workshops and training courses at each step of the project Training was provided over a wide spectrum of subjects operation of monitoring systems, seismograms analysis, site response evaluations, fundamentals in Seismology and Engineering Geology, geological surveying, application of GIS and principles of seismic engineering In the last months of the project we integrated all the information, compiled seismic zonation maps for each city and evaluated the site specific spectral accelerations at each zone in every city These earthquake hazard functions were computed for a probability of occurrence of 10% in an exposure time of 50 years and under the assumption that the damping ratio for all the building is 5% These criteria comply with an almost universal standard for a-seismic building codes

As the last stage of the project, the results were presented to the authorities as well as to the engineering communities in the South Pacific countries that participated in the project It has been fully realized that these results should be integrated into building regulations in an attempt to reduce the earthquake risk to the capital cities of Tonga, Fiji Islands, Vanuatu and the Solomon Islands This project clearly demonstrates the applicability of the SvE method in evaluating earthquake hazard in areas where data of strong earthquakes is limited and often non-existant

# SECTION I

## A) RESEARCH OBJECTIVES

The overall aim of the project was to develop, test and improve a semi-empirical method, the SvE, to estimate the uniform-hazard site-specific acceleration response spectrum The testing grounds for this study were the main capital cities of the South Pacific islands, Honiara in the Solomon Islands, Port Vila in Vanuatu, Suva in Fiji and Nuku'alofa in Tonga The overall aim of the project incorporated the following objectives

* To implement the SvE method and establish a microzoning map for each of the cities, Suva, Nuku'alofa, Honiara and Port Vila by
  - evaluating and mapping the response of different sites in the city to earthquake motions,
  - evaluating seismological scaling lows relevant to the region, and
  - establishing a geological - seismological data base for the city using GIS
* To introduce to the nations of the South Pacific islands modern approaches for assessing earthquake hazards and implementing them in the form of regulations and building codes
* To facilitate preparation of earthquake scenarios and activate preparedeness plans against the eventuality of a strong earthquake
* To promote seismological knowledge and understanding by local researchers, students and trainees, including earthquake monitoring and site investigations

## B) RESEARCH ACCOMPLISHMENTS

When the project proposal was formulated and just approved, the SvE was merely a suggested concept to approach the problem of assessing earthquake hazard in applied engineering terms At this stage the methodology associated with the SvE is well defined (see the list of references associated with the application of the SvE method) This study demonstrates the applicability of the SvE approach and its great advantages when addressing the problem of earthquake hazard assessments in less developed areas and in regions where real strong ground motions are virtually unavailable Much of the work in the South Pacific has been implemented in Israel as shown in the annexed reference list A schematic description of the SvE is shown in Fig 1 and involves

1 Definition of the seismogenic zones around the investigated site(s) and their corresponding seismicity parameters These data define the parameters needed for simulating the seismicity which will affect the investigated site(s) in the future

We jointly defined the distribution of the seismogenic zones relevant to the project and estimated the frequency-magnitude relationships for each of these zones

The results are presented in a paper by Hofstetter et al (1999) which is currently under review (see attached pre-print)

2 Determination of dynamic source parameters of earthquakes in the region(s) and their inter-relationships, e g , Seismic Moment vs Magnitude, attenuation of seismic energy with distance, expected stress drop etc These data, based on the stochastic approach, are used to synthesize expected ground motions (accelerograms) at the bottom of the surface layer(s) of the investigated site

We used earthquake data from Tonga, Vanuatu and the Solomon Isands, together with parametric data provided by the USGS/NEIC and ORSTROM (office in Vanuatu) to determine an empirical attenuation function of the zero-frequency displacement level This, in turn, enabled us to determine the Seismic Moments of earthquakes in the region, to define a unified magnitude scale for the South Pacific region and to develop the relationship to the commonly used $m_b$ magnitude scale

The results are presented in a paper by Mafi and Shapira (1998) presently under review (see attached pre-print) Other information about the geology, seismic activity and tectonics of the areas under investigation is presented in the final report on empirical site investigations (to be sent under separate cover)

3 The synthetic accelerograms which correspond to hardrock site conditions were then used to compute the expected vibratory motions on the free surface of the investigated site (using the Joyner (1977) program) by taking into consideration possible site effects (due to soils and soft rocks overlying the hard rock layer)

The principal approach we adopted for determining the site response function is the Nakamura method (1987) which also uses data of recorded earthquakes (receiver function technique) Site response measurements and analysis were performed at 100 sites in Port Vila, 60 sites in Suva, 16 sites in Nuku'alofa and 24 sites in Honiara The details are provided in the final report prepared for the local authorities (to be sent under separate cover) Site response analysis in Port Vila (Vanuatu) is also summarized in the paper by Regnier et al (1999) submitted for publication (see attached copy)

4 The next stage of the SvE process involves the computation of the response spectrum from each of the synthetic site specific accelerograms followed by the application of simple statistics in order to obtain the expected acceleration spectra for a prescribed probability, exposure time and damping ratio A summary of the results is presented in Figures 2, 3, 4 and 5 with the corresponding seismic zonation maps

5 Software Development During the course of the project, GII has developed a number of programs as follows

- ***PC-SDA*** a PC-based data acquisition system operating under MS-DOS that facilitates digital recordings of up to 16 channels of seismic data This system was used to monitor earthquakes and to perform the site response investigations (see also Avirav and Shapira, 1995)
- ***PC-SDP*** PC-based data processing software operating under MS-DOS It was used mainly to manage the data base of the monitoring systems and to perform basic analysis of recorded earthquakes (see also Malitzky and Shapira, 1996)
- ***PC-FDA*** a preliminary version of the software package operating under MS-DOS that was used to compute the spectra and spectral ratios of seismograms
- ***GII-SDP*** an updated version of PC-SDP operating under Windows95 that enables a great variety of routine earthquake data processing including hypocenter location, magnitudes and seismic moment determinations, data base management, arrangement of earthquake bulletins and catalogues The latest version of GII-SDP was updated on the computers of the collaborating organizations in March 1999
- ***GII-SRD*** an updated version of PC-FDA, operating under Window95 This software complements GII-SDP and enables spectral analysis and site response determinations The latest version of GII-SDP was updated on the computers of the collaborating organizations in March 1999
- ***GII-SDA*** an upgraded version of PC-SDA operating under Windows95/NT and providing a wider range of possibilities regarding analog to digital devices and the application of triggering algorithms

All new software programs are free of the Y2K bug The attached CD-ROM includes the latest versions of GII-SDA, GII-SDP and GII-SRD

## C) SCIENTIFIC IMPACT OF COLLABORATION

It must be admitted that, despite the fact that the region where the project was performed is one of the most seismically active areas on our planet, seismology and its related technical aspects are not sufficiently developed The introduction of the "Earthquake Microzoning" project increased the awareness of the administrations in the different countries and simultaneously stimulated interest in a better knowledge of seismology and related topics There are now more people in Tonga, Vanuatu, the Solomon Islands and Fiji involved in different scientific aspects of seismology Collaboration between the local institutions, the international scientific community of SOPAC, GII (Israel) and ORSTROM (Vanuatu and New Caledonia) has enabled better training of young local scientists through the workshops and daily involvement in the project We were successful in collecting important earthquake data that shared through the implementation of the monitoring systems provided by the project (see attached CD-ROM of collected data) We are also confident that the new results, soon to be presented in international publications, will also be appreciated by the scientific community worldwide

One of the main goals of the project was to enhance the practical application of results Consequently, we organized a number of open meetings with the engineering community at which we emphasized the improvement of the sustainability of engineered structures to be designed using the results We also trust that the newly developed software, which was basically designed for seismological centers with limited resources, will also contribute to the scientific progress in the field of seismology by other small nations For example, this same software has been adopted for routine operations of the small seismological centers in Turkmenistan, Jamaica and Cyprus and is soon be implemented in several countries in the Middle East

## D) PROJECT IMPACT

We wish to repeat and emphasize, as already reported in previous annual and semi-annual reports, the great impact this project has on the local administration and decision makers to assure governmental support and increasing awareness of the problem of earthquake hazard and how this may be mitigated The seismic microzoning project nucleated a wide scope of activities in the South Pacific which are gathered under the so-called Pacific GeoCitiPlan coordinated by SOPAC Basically itt involves natural hazards assessment to the people of the Pacific islands Through SOPAC, our project is known to other island nations in the Pacific and some of them are now seeking opportunities to be integrated into our project (See also leaflet in Attachment A distributed to our audience during the presentation of the

results to local professionals and decision makes in Tonga, Fiji Islands, Samoa, Vanuatu and the Solomon Islands) Apparently, our project, mainly through the building of a GIS, has been a catalyst for addressing other risks in the South Pacific

While we were in the process of finalizing our results in the form of reports and maps, SOPAC member countries approached us with requests to extend the project to other countries and cities in the Fiji Islands, the Solomon Islands, Tonga and Vanuatu The software and the instrumentation provided by our project will be used to expand the work over other population centers in the South Pacific

## E STRENGTHENING DC INSTITUTIONS

Paragraphs A to D above elaborate this issue (see also previous annual and semi-annual reports) Every step in the project was associated with an appropriate workshop In terms of technology, our PC-SDA systems were the first to provide digital earthquake data useful for the DC institutions in the Solomon Islands and Tonga and were an upgraded a generation on the old systems in Fiji Islands Fiji and the Solomon Islands were also assisted with radio telemetry systems for the existing analog local networks The project also provided the Solomon Islands, Vanuatu and Tonga with the first (and currently only) strong motion accelerometers

## F FUTURE WORK

This final report concludes our project However, the impact it has made on the area and its success in providing useful results have already initiated complementary studies and work In agreement with the countries involved in this project, and under the leadership of SOPAC, the work planned for the future is

1 The upgraded data acquisition systems (GII-SDA) will be used to perform site response investigations and produce earthquake zonation maps in other cities in the Fiji Islands, Vanuatu and Tonga and in other countries (currently planned are Papua New Guinea and Samoa) The GII will assist in performing the SvE computations for the new sites

2 The GII-SDA systems of Fiji and Vanuatu will be transferred to Tonga to build a small local network for monitoring seismicity Among the four countries that participated in the project, Tonga is the only one not yet equipped to perform continuous seismic monitoring

3 The strong motion accelerometer of Tonga will be installed at Port Vila (Vanuatu) The results of this study demonstrate that of all the cities participating in the project, there are higher chances of activating these instruments if placed in Port Vila

4 SOPAC has made a commitment to service the instruments provided by the project GII will continue supporting the DC by s/w maintenance

5 The collaborating institutions will continue to seek funds to extend earthquake hazard assessments to other countries and cities in the region and also to try to obtain funds for extending this project to earthquake risk and loss assessments

# SECTION II

## A) MANAGERIAL ISSUES

We had to postpone the completion of the reports by couple of months mainly due to budgetary limitations We trust that it is obvious that the US-AID funds allocated to this project could not really provide for all the work and effort we have invested Matching funds from our parent organizations were of crucial assistance However, above all, it was the devotion and enthusiasm of the people collaborating on this project that made the work possible and provided its important results

## B) BUDGET

The final financial report is presented in Attachment B

## C) SPECIAL CONCERNS

None

## D-1 TRAVEL AND TRAINING

| | |
|---|---|
| February 1996 | Drs A Shapira, G Shorten, A Simpson and T Jones for the presentation and planning of the project in Suva, Port Vila, Honiara and Nuku'alofa |
| September 1996 | Dr A Shapira with a GII team for the installation of equipment and technical training in using the instrumentation, PC-SDA and PC-SDP in Suva, Port Vila, Honiara and Nuku'alofa |
| October 1997 | Workshop in Suva with delegations from the four participating countries |
| March 1998 | Mr U Peled to check strong motion accelerometers and supervise site response measurements in Honiara |
| April 1998 | Workshop in Suva with delegations from the 4 participating countries |
| May, 1998 | Dr M Rengier to supervise site response measurements in Nuku'alofa |
| March 1999 | Ms A Malitzky to upgrade software (GII-SDA, GII-SDP and GII-SRD) |
| March 1999 | Drs G Shorten, M Regnier and A Shapira to sumarize the results and present the reports in all four capital cities |

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Figure 1 Schematic description of the SvE method

Figure 2 Seismic zonation map for Honiara, Solomon Islands and the acceleration response functions associated with each zone

Figure 3 Seismic zonation map for Port Vila, Vanuatu and the acceleration response functions associated with each zone

Figure 4 Seismic zonation map for Suva, Fiji Islands and the acceleration response functions associated with each zone

Figure 5 Seismic zonation map for Nuku'alofa, Kingdom of Tonga and the acceleration response functions associated with each zone

# THE SvE APPROACH

**Simulate Earthquake Catalogs** for several thousand years

Constrain Events within seismogenic zones, $j=1,J$
Adhere to the freq _mag relationship for each zone
$\log N(M)_j = \Phi(a_j - b_j M, \sigma_j)$

For each catalog

For each event (Lat.Long., Depth,M)

**ASSUME**
$\Phi$ = Normal distribution
$\psi$ = Uniform distribution

$\log Mo = \Phi[c+dM, \sigma]$
stress drop = $\psi[\nu 1, \nu 2]$
fmax = $\psi[\xi 1, \xi 2]$
Q_value = $\psi[\kappa 1, \kappa 2]$
Zero frequency Displacement = $\Omega o$
Hypocentral distance = R
$\Omega o = f(Mo, R)$ [Empirical relation !]

**COMPUTE A SYNTHETIC ACCELEROGRAM FOR**
AN *HARDROCK SITE*, FROM A *MAGNITUDE M*
EARTHQUAKE AT *DISTANCE R*
***[ Apply the Stochastic Method]***

USE SUBSURFACE INFORMATION OF THE SITE
**TO COMPUTE THE NON-LINEAR SITE RESPONSE**
output
***FREE FIELD GROUND MOTION***

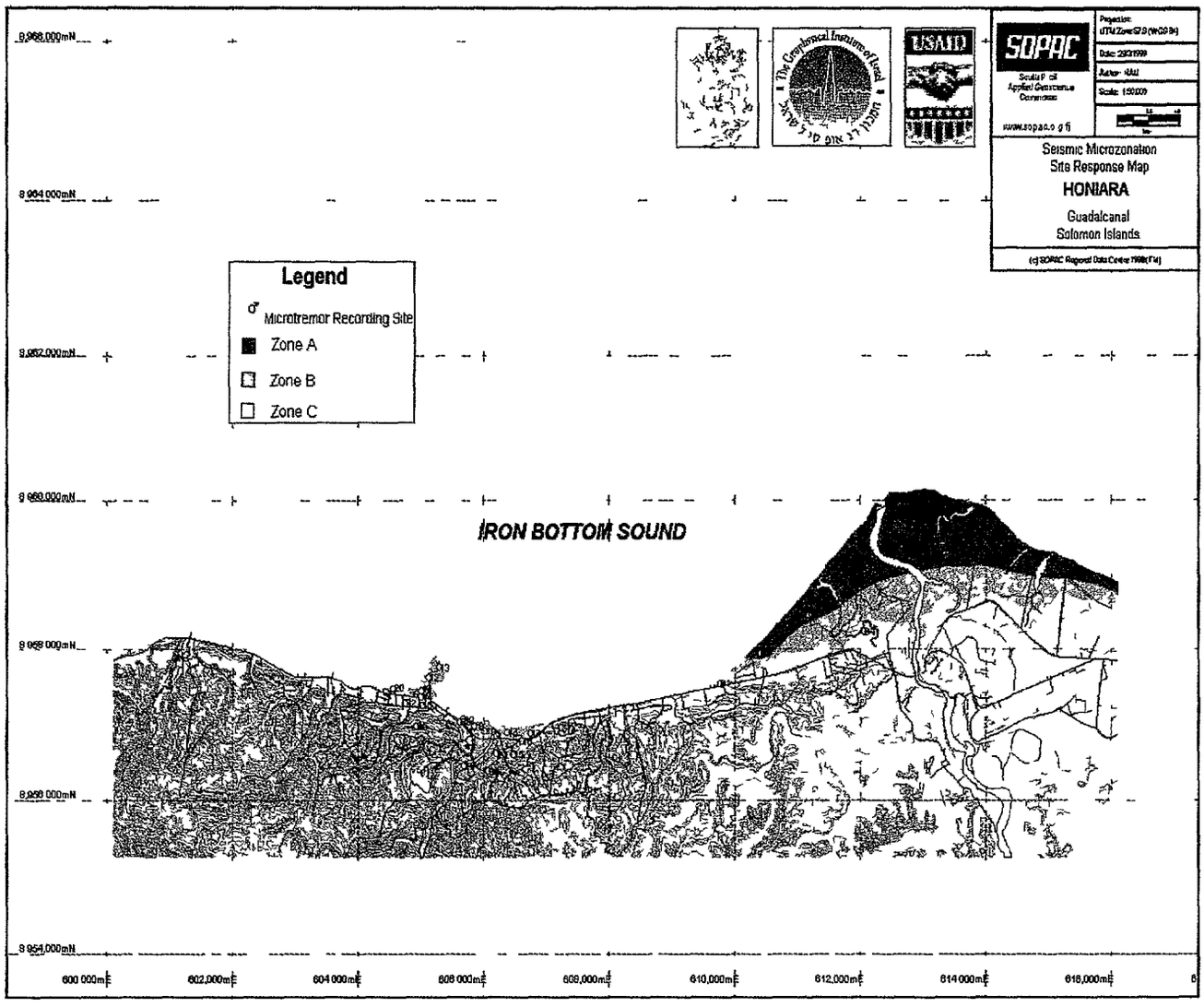
**COMPUTE & STORE**
***SITE SPECIFIC RESPONSE SPECTRUM***
***PEAK ACCELERATION, VELOCITY, DISPLACEMENT***

yes ← more events ? → no

**DO STATISTICS**

***Uniform Hazard Site Specific Response Spectrum***

***Peak Horizontal Ground Motion***


SOPAC
Seismic Microzonation
Site Response Map
HONIARA
Guadalcanal
Solomon Islands
Legend
Microtremor Recording Site
Zone A
Zone B
Zone C
IRON BOTTOM SOUND
USAID
8 968 000mN
8 964 000mN
8 962 000mN
8 960 000mN
8 958 000mN
8 956 000mN
8 954 000mN
600 000mE
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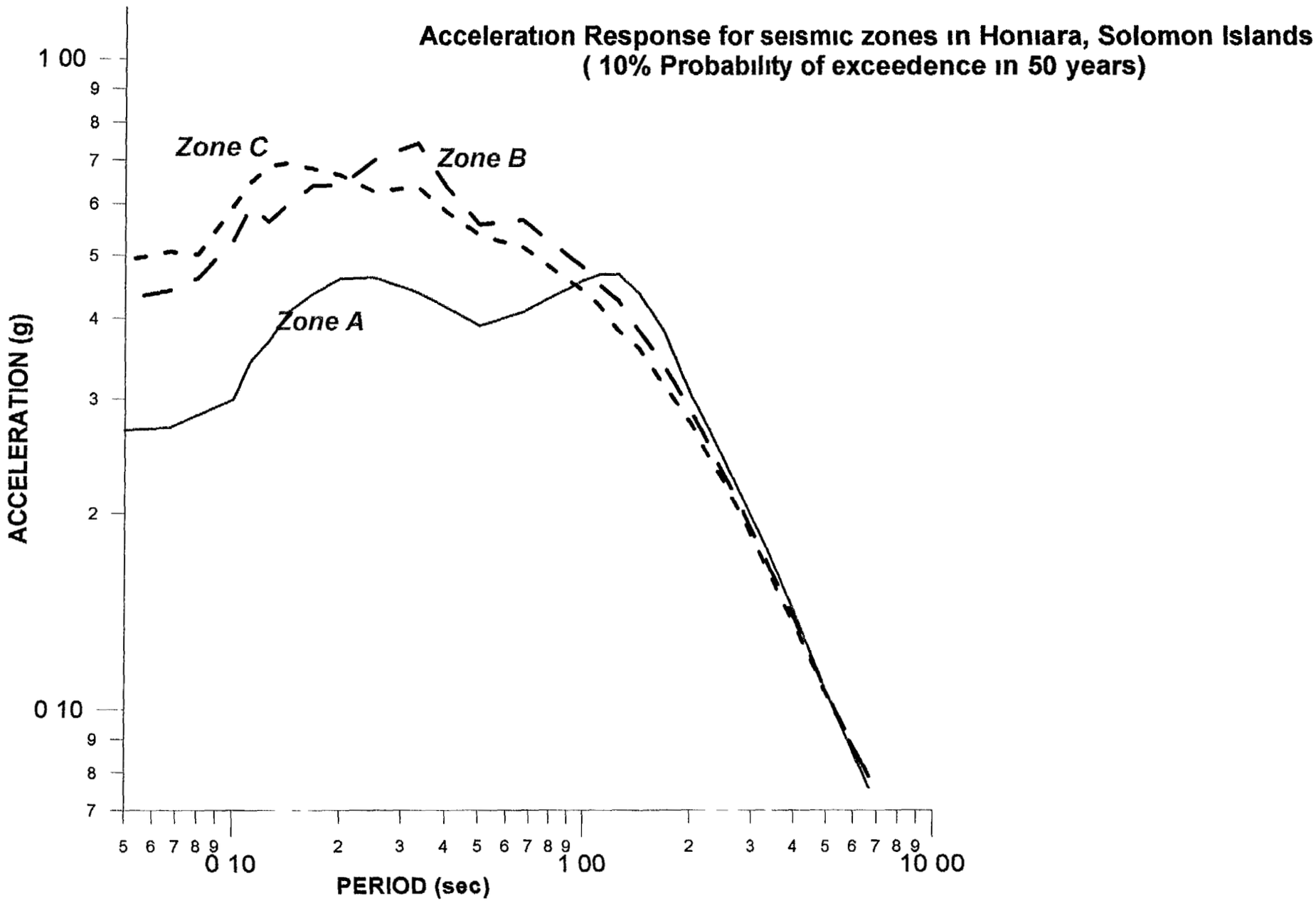
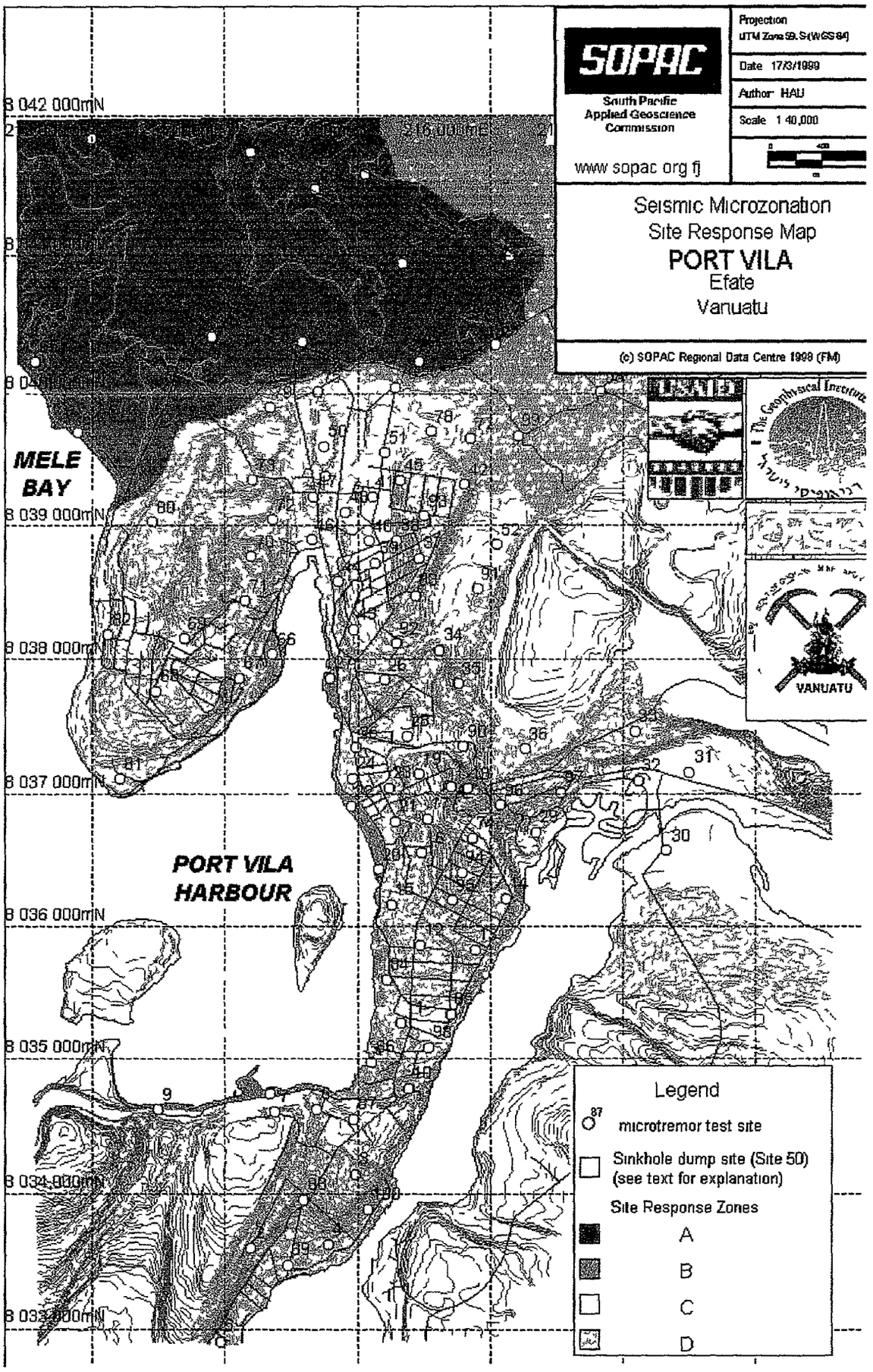
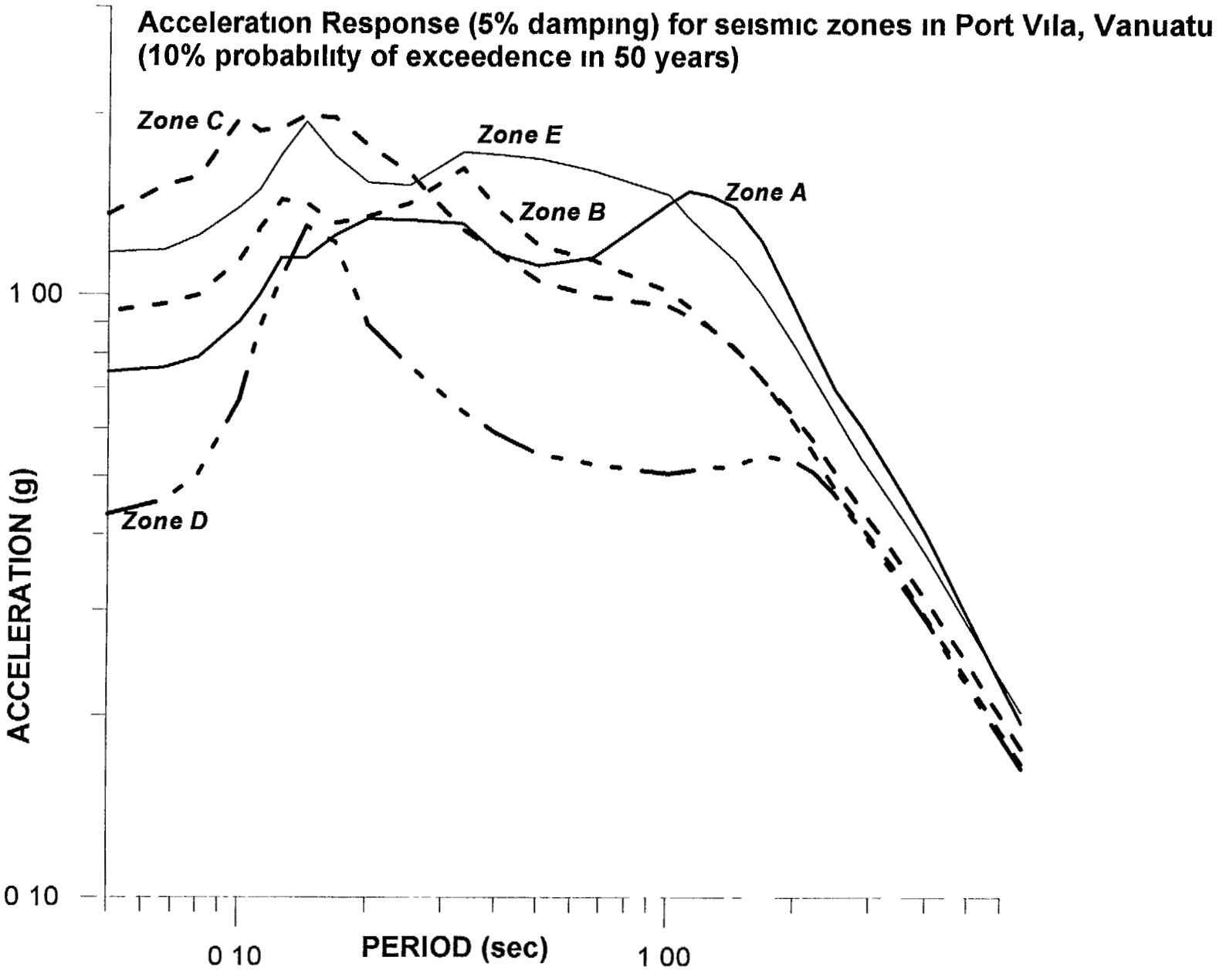
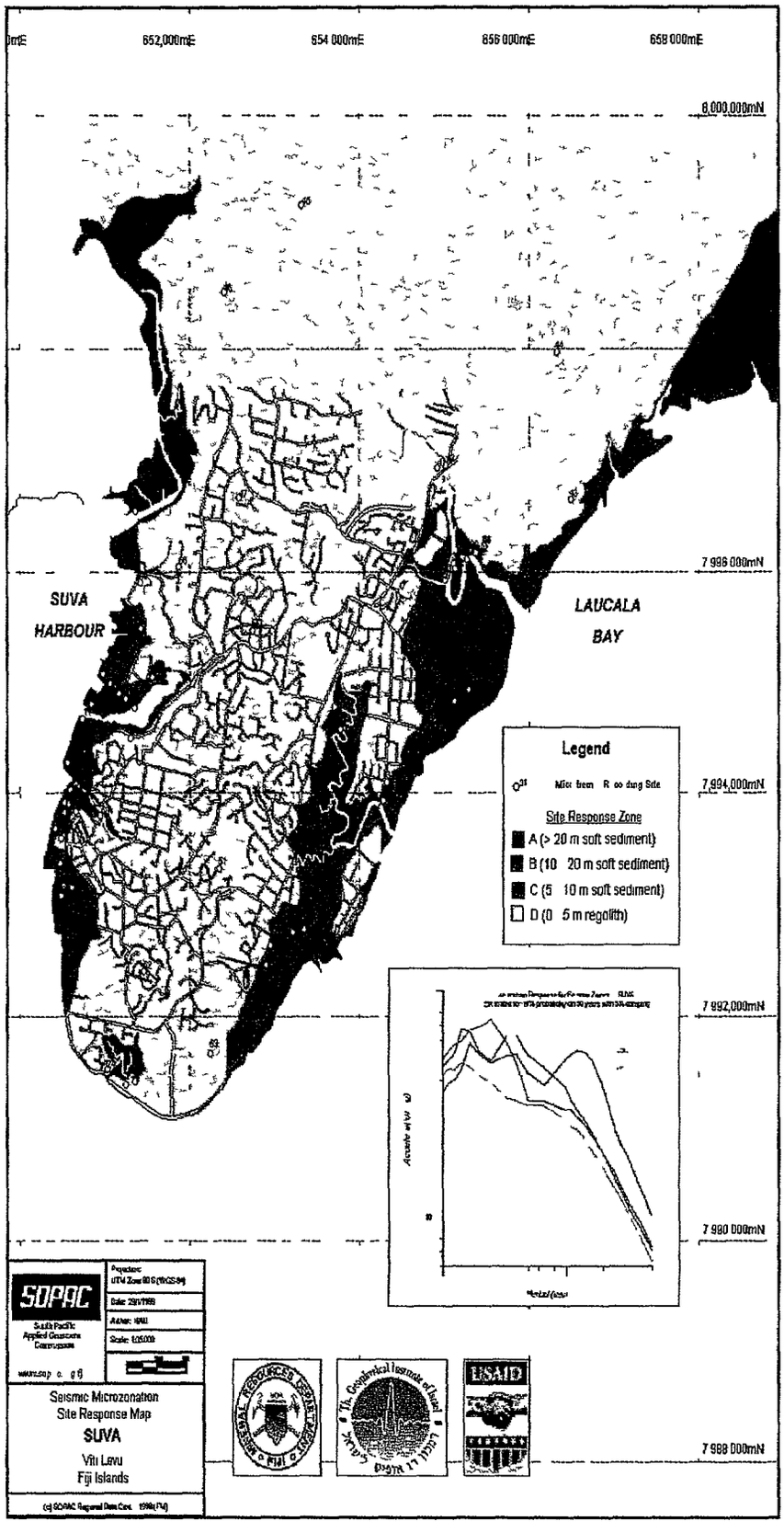
614 000mE
616,000mE

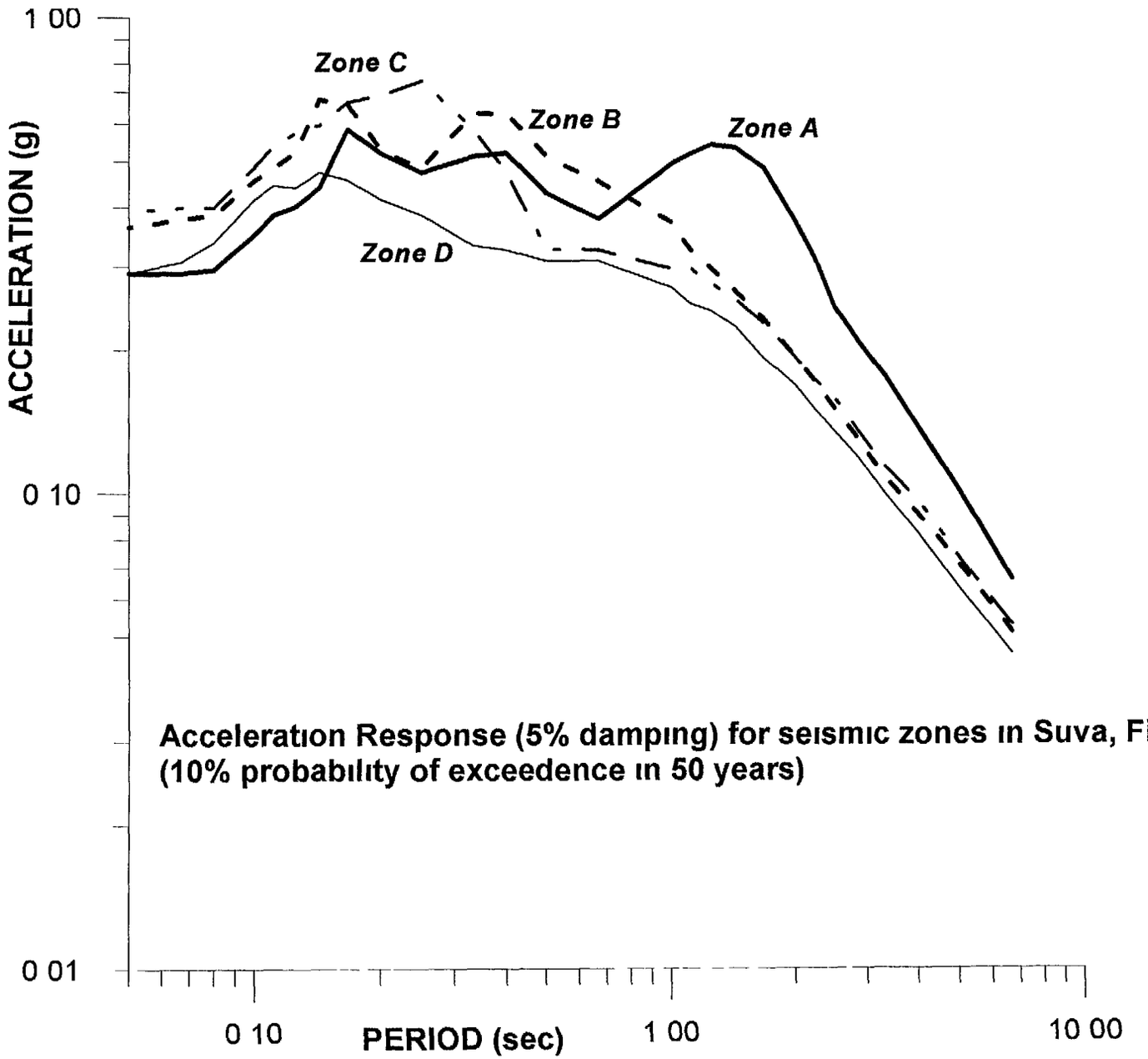

Acceleration Response for seismic zones in Honiara, Solomon Islands
( 10% Probability of exceedence in 50 years)
Zone C
Zone B
Zone A
ACCELERATION (g)
1 00
9
8
7
6
5
4
3
2
0 10
9
8
7
5 6 7 8 9
0 10
2 3 4 5 6 7 8 9
1 00
2 3 4 5 6 7 8 9
10 00
PERIOD (sec)


SOPAC
South Pacific Applied Geoscience Commission
www.sopac.org.fj
Projection
UTM Zone 59, S (WGS 84)
Date 17/3/1999
Author HAU
Scale 1:40,000
Seismic Microzonation
Site Response Map
PORT VILA
Efate
Vanuatu
(c) SOPAC Regional Data Centre 1999 (FM)
MELE BAY
PORT VILA HARBOUR
8 042 000mN
8 039 000mN
8 038 000mN
8 037 000mN
8 036 000mN
8 035 000mN
8 034 000mN
8 033 000mN
VANUATU
Legend
microtremor test site
Sinkhole dump site (Site 50)
(see text for explanation)
Site Response Zones
A
B
C
D

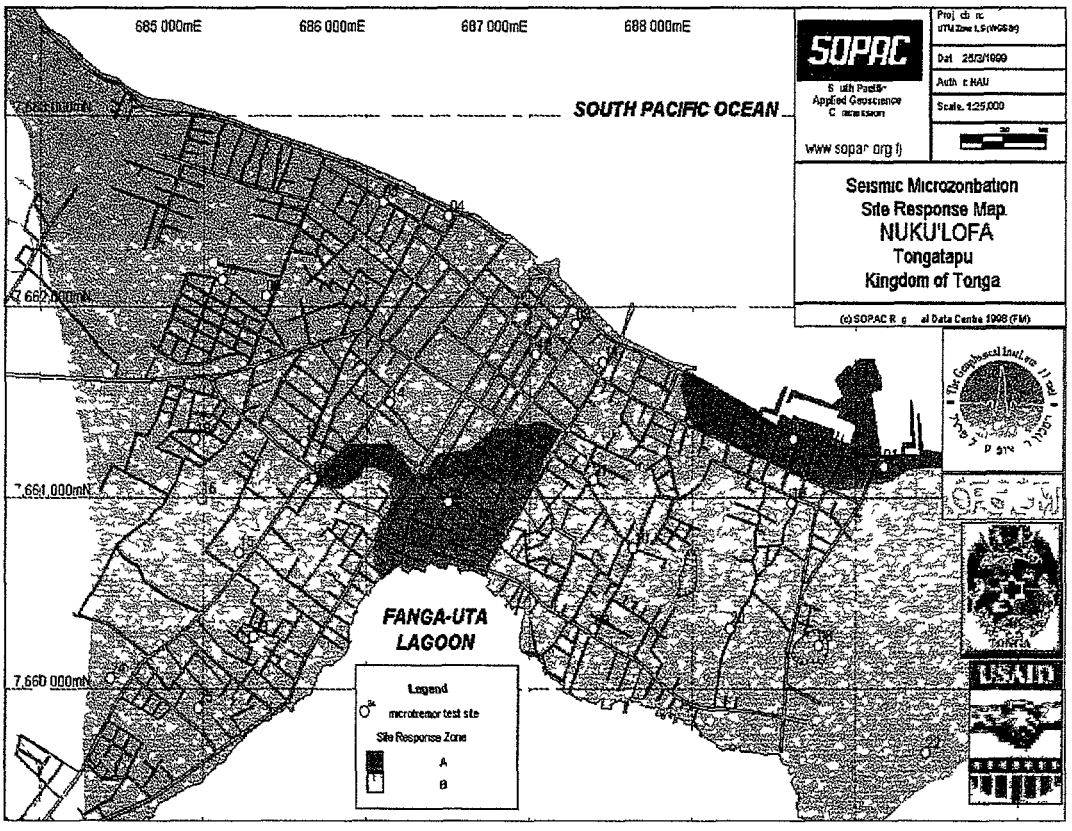
17

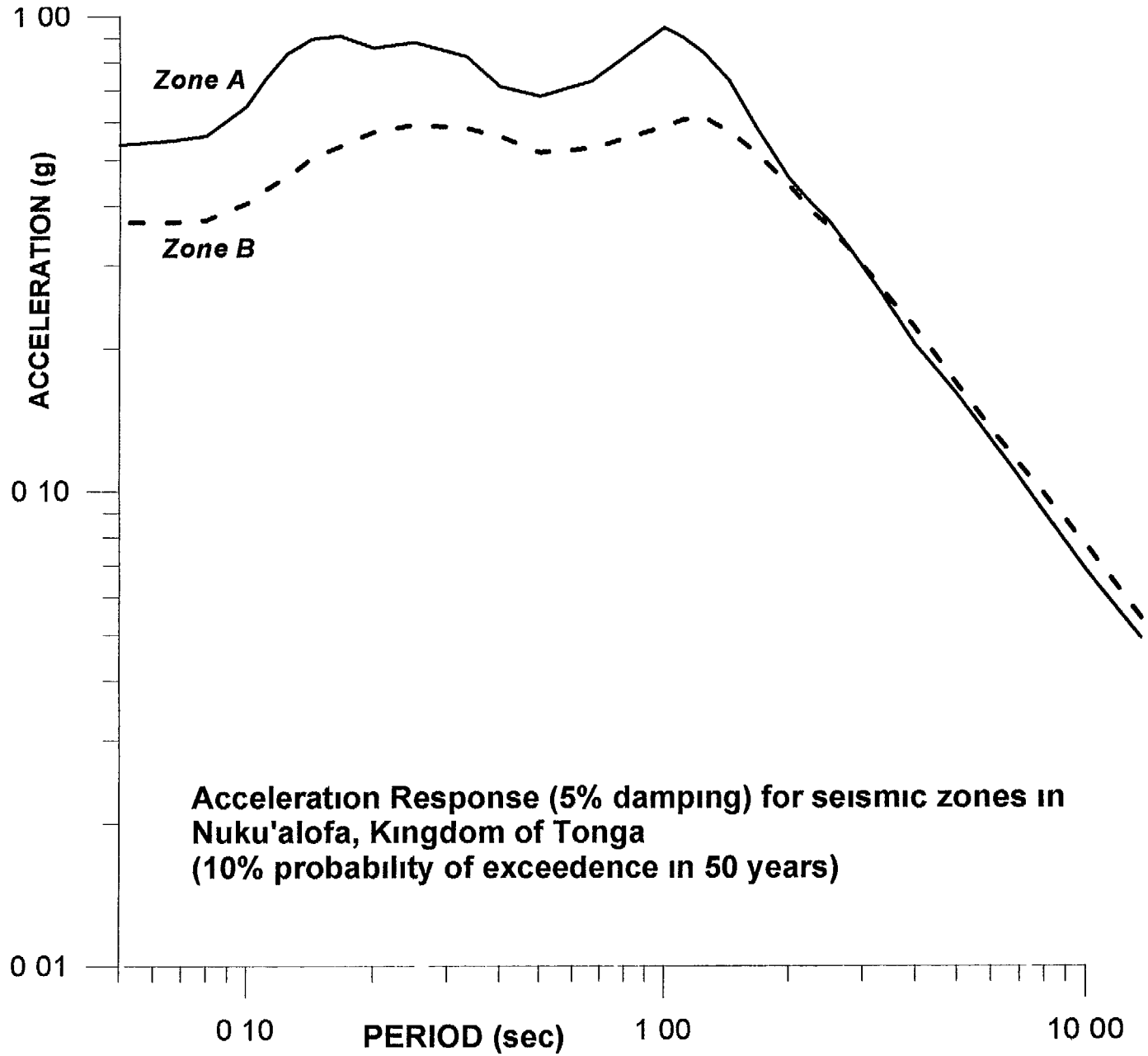

Acceleration Response (5% damping) for seismic zones in Port Vila, Vanuatu
(10% probability of exceedence in 50 years)
Zone C
Zone E
Zone A
Zone B
Zone D
1 00
0 10
ACCELERATION (g)
0 10
PERIOD (sec)
1 00


652,000mE
654 000mE
656 000mE
658 000mE
8,000,000mN
7 998 000mN
7,994,000mN
7 992,000mN
7 990 000mN
7 988 000mN
SUVA
HARBOUR
LAUCALA
BAY
Legend
Site Response Zone
A (> 20 m soft sediment)
B (10 20 m soft sediment)
C (5 10 m soft sediment)
D (0 5 m regolith)
SOPAC
South Pacific
Applied Geoscience
Commission
Seismic Microzonation
Site Response Map
SUVA
Viti Levu
Fiji Islands
USAID




Acceleration Response (5% damping) for seismic zones in Suva, Fiji Islands
(10% probability of exceedence in 50 years)


685 000mE
686 000mE
687 000mE
688 000mE
7,663 000mN
7,662 000mN
7,661 000mN
7,660 000mN
SOUTH PACIFIC OCEAN
FANGA-UTA LAGOON
Legend
microtremor test site
Site Response Zone
A
B
SOPAC
South Pacific Applied Geoscience Commission
www.sopac.org.fj
Date 25/3/1999
Author HAU
Scale 1:25,000
Seismic Microzonbation
Site Response Map
NUKU'LOFA
Tongatapu
Kingdom of Tonga
(c) SOPAC Regional Data Centre 1998 (FM)
USAID




Acceleration Response (5% damping) for seismic zones in Nuku'alofa, Kingdom of Tonga
(10% probability of exceedence in 50 years)

204

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# FINAL REPORT

*Submitted to.*

*The US Agency for International Cooperation – CDR Program*

## SEISMIC MICROZONING IN CAPITAL CITIES IN THE SOUTH PACIFIC

**Grant No.: TA-MOU-95-C13-024**

# APPENDICES

21

# APPENDIX A

# PRE-PRINTS

**Microzonation of the expected seismic site effects across Port Vila, Vanuatu**

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**Abstract**

The city of Port Vila, Vanuatu, is located in one of the most active seismic regions on earth Earthquakes are felt frequently and, due to very rapid plate convergence rates, return period of large earthquakes (M>6) in the New Hebrides Benioff zone can be less than 10 years Even though Port Vila does not lie on an identified seismic fault zone, strong motions by nearby earthquakes have to be expected due to the city's geographical location close to the plate boundary of New Hebrides convergence zone An accurate estimation of the seismic ground motion across the city is of prime importance for urban developments and mitigation of earthquake risk The seismic microzonation of the city has been carried out to provide a detailed map of the zones that exhibit site effects and where resonance for different type of building may occur The Nakamura technique has been used to estimate site amplification effects from single station noise recordings Interestingly, aside one site located on an old dump zone, the amplification factors at about the 100 sites surveyed in Port Vila remain below 3 with an average well below 2 in the 1 to 10 hertz frequency band These results suggest there is no thick sedimentary layer in the surveyed down town area and that they are in agreement with the mapping of limestone terraces throughout Port Vila area However, both the surface geology and results from seismic zonation indicate a thicker (up to several tens of meters) sedimentary cover around the Bauerfield airport and in the Mele terrace zone Low resonance frequencies (around and below 1 hz) and amplification factor of the order of 5 were observed over this large area, immediately outside Port Vila Any building development in this area should take these results into account

**Introduction**

The epicenters of earthquakes with moment magnitude of 5 or more for the period 1977-1997 (from the Harvard CMTS catalogue) in the Efate segment of the New Hebrides subduction zone in Vanuatu are shown in figure 1 Port Vila, due to its proximity to those seismic sources, is vulnerable to strong earthquakes Diagrams of cumulative coseismic slip versus time give for the NH subduction zone a maximum magnitude earthquake of 8 6 A mean return period of 480 years for this maximum magnitude has been estimated from a Gutenberg-Richter frequency magnitude relationship diagram (R Pillet, personal communication) Along the NH island arc, the average recurrence interval for a magnitude 8 earthquake is about 10 years

Evidently, proximity to high magnitude events is not the only controlling parameter of the earthquake damage Major variations in the damage rate observed during strong earthquake at adjacent locations with different geology and topographical conditions is a poignant demonstrator of the importance of understanding and assessing site response effects Some of the most dramatic examples of this phenomenon occurred during the 1985 Mexico City earthquake (e g , Singh et al , 1988), Armenian (Spitak) earthquake in 1988 (Borcherdt et al , 1989), the Loma Prieta earthquake of 1989 (e g Hough et al , 1990) , the Northridge earthquake in 1994 and during the recent Hyogo-ken Nanbu (Kobe) earthquake in 1995 A dramatic topographic effect is observed during the Northridge earthquake were ground accelerations as high as 1 8g have been recorded in Tarzanna near the epicenter

The geology of Efate island and in particular of the city of Port Vila is fairly simple Efate is a large Plio-Quaternary volcano-sedimentary island It is made of prevailingly volcanic eruptive rocks and ashes depots Its formation has also been controlled by important tectonic

uplifts and it is now bounded by large quaternary limestone and sedimentary terraces The city of Port Vila is located on raised limestone terraces of different ages, up to a high of 120 m The volcanic substratum does not outcrop in Port Vila area and is probably lying at great depth beneath the city Active faulting in Port Vila area, roughly in two conjugate directions, has played a major role to control the topography of the city in a blocklike (checker) scheme The numerous faults have also favored minor, local uplift of blocks Due to this rough topography, soil thicknesses are very variable within Port Vila area, but are on average, quite thin (few meters) Only at a very few places, significant thickness of soil can be observed Some of them are man made sedimentary fills Borehole data usually show, below the thin soil layer, a 20 to 30 meters thick layer of variably weathered limestone banks mixed with sand and gravel depots To the north of Port Vila, boarded to the west by the Mele bay, one can find a large collapsed zone filled with important (up to several tens of meters) thicknesses of light volcanic sediments This area, very closed to the city, has the potential for future economical developments, especially around the Bauerfield international airport located in the middle of this distinct geological and pedological unit (Quantin, 1980)

Hence, based on the mapped geology and topography of the city, different locations across Port Vila has the potential of amplifying seismic vibrations The main objective of this study was to detect site effects in Port Vila, estimate the local site response functions and provide a microzonation map of that phenomenon

The proper site response functions are best determined from the recorded ground motion during an actual event, preferably, by means of comparison with the recordings at a near-by reference site located on competent ground ( see for example, Rogers et al , 1984, Singh et al , 1988, Jarpe et al , 1989, Darrag and Shakal, 1991, Gutierrez and Singh, 1992) Many investigators, among them Tucker and King (1984), King and Tucker (1984), Jongmanns and Campilo (1993), Liu et al (1992) and Gagnepain-Beyneix et al (1995) evaluated site response functions from weak motions of earthquakes The implementation of these approaches is quite time consuming, especially for microzoning purposes, even in an active area like Efate island

A rather fast and inexpensive technique for assessing the site response is the application of microtremor (ambient seismic noise) measurement This technique has apparently worked well in some areas among them Japan (Ohta et al , 1978), the San Fernando Valley (Kagami et al , 1986), the Dushanbe Valley, Tadjikistan, (Zaslavsky, 1987), Mexico (Lermo et al 1988 and Gutierrez et al , 1992 ), Italy (e g , Rovelliet al , 1991, Hough et al ,1992, Malagnini et al , 1993), New York (Field et al , 1990, 1992), Australia (Gaull et al , 1995), and Israel (Zaslavsky et al , 1994, 1995) The use of microtremors in estimating site response is gaining popularity One of the most used techniques has been introduced Nakamura (1989) The technique relies on the interpretation of microtremors as Rayleigh waves propagating in single layer over a half-space Under these conditions the site response function, under linear conditions, is, as a first approximation, the spectral ratio between the horizontal and the vertical components of the seismic motion at the surface

$$H(w) = Sh(w)/Sv(w)$$

where Sh(w) and Sv(w) are the amplitude spectra of the horizontal and vertical component of motion, respectively Results obtained by implementing Nakamura's technique (see for example, Ohamachi et al ,1991, Lermo and Chavez-Garcia, 1993, 1994, Field et al , 1995, Shapira et al , 1994, Gitterman et al , 1995) are in support of the idea that seismic site effects can be estimated by using spectral ratios from only one three-component (3C) station

Although it is well known that soil sites can strongly affect seismic signals, it is commonly assumed that hard-rock sites do not However, Boore (1973), Davis and West (1973), Tucker et al , (1984), Bard and Tucker (1985), Geli et al (1988) and Chiu and Huang

(1992) among other, based on theoretical considerations as well as observations, have shown that the site topography can strongly affect the surface ground motions Investigation of the variation of S-wave motion at several typical sites on outcrops of basement rock on a ridge showed that incident motions are amplified by as a much as a factor of eight over a narrow frequency band For example, the extensive damage at Canal Beagle, a subdivision of Vina del Mar caused of the 3 March 1985 Chile earthquake, correlates well with the topographical amplification determined from aftershock records (Celebi, 1987)

In this study, the Nakamura method has been implemented for empirical evaluation of site effects in Port Vila that may result either from the subsurface geology and/or the topography In a few cases, low magnitude earthquakes were also recorded while measuring noise and were also used in the evaluation

**The Measurements and Analysis**

***The technique***

Microtremor recordings were made at 100 sites within Port Vila and Bauerfield airport areas The fieldwork has been carried out using 1 hz L4C Mark Products seismometers and a 12 bits PC based data acquisition system (see Shapira and Avirav, 1995, 1996) A 12 5 hz lowpass filter and an 100 hz sampling rate were selected for recording the data At each site, the ambient noise was recorded for 3 minutes every 10 minutes during one hour The recorded microtremors were analyzed by the GII-SRD program, using the Nakamura (1989) technique to recover the polarization characteristics of the wavefield That involves computing the ratio of the spectra of both horizontal components relative to the vertical component of ground motion For each site, average vertical and horizontal spectra are computed from several 20 seconds data samples The spectral ratios for both horizontal components are then computed Finally an average spectral ratio is computed

***Observations- Typical examples***

On figure 2 are plotted 25 individual site response functions (i e, spectral ratios of the horizontal over the vertical components) from sites throughout Port Vila 60% of the sites surveyed exhibit similar site responses It actually shows no amplification at frequencies up to 10 hz Around 10 hz in the spectrum, one can see some scattering due to small variations in soil layer thickness

If we adhere to the basic assumptions upon which the Nakamura method is based then, as a first approximation, the resonance frequency, f0 ,of the superficial layer and the amplification level A(f0), are given by the equations

$$f0 = V_1/4H$$

$$A(f0)= V_2*r_2/ V_1*r_1$$

Where $V_1$ and $V_2$ are the s-wave velocities in the upper layer and the bedrock, respectively The corresponding densities of the material are $r_1$ and $r_2$, and H is the thickness of the superficial layer Consequently, the capability to identify significant site effect is heavily depended on the impedance at its subsurface (practically $V_2/V_1$)

At this stage we should add that the Nakamura technique is basically associated with ambient noise measurements, however, as shown by Lachet and Bard (1994), Zaslavsky et al (1994), spectral ratios of incident S-waves from earthquakes yield similar results as those obtained from noise measurements

As demonstrated in the examples shown in Fig 2, there is no significant site effect among the investigated sites These observations are confirmed by analyzing the recordings of 3 earthquakes that happen to occur during the occupation of the sites The spectral ratios of

the S-wave recordings (Fig 3) suggest some resonance at lower frequencies that might be associated with deeper layer(s) of higher S-wave velocity Nevertheless, the amplification is still low with no significant influence on the seismic hazard at those investigated sites Figures 4 and 5 show the evaluated response functions of two areas of Port Vila with slight amplification, within a factor of 3, over a broad range of frequencies One (fig 4) is a compilation of the responses in reclaimed land located in the harbor area (Ardimani and Star wharf) and in the down-town area, at three sites along the sea front There is not a single distinguished pick of resonance but rather a broad dome-shaped zone of amplification centered at 4 hertz In both areas the surface of the reclaimed land is fairly small and the maximum thickness of the fill is of the order of 5 meters at the sea front area and up to about 10 meters at the wharf platforms Hence, for f0= 3-5 Hz And assuming a shear wave velocity of 100 m/s for the gravel (Fah et al, 1997) used to made up the platform over the bedrock (modern reef flat), we get estimated thicknesses of 8-5 meters that are compatible with the observed ones

The Tassiriki area around the bend between the two inland lagoons, shows a slightly different response (see Fig 5) This is a flat and sediment filled area and it is probably at the junction of majors faults, now inactive, that made up the troughs where the lagoons are located The maximum amplitude of the ratio is variable, between 2 and 3, and its position spreads between 5 and 7 hertz Assuming again a low shear wave velocity between 100 and 200 m/s, this yields a top layer thickness of about 10 meters

Figure 6 is an example of the response at a site of man made fill located along the main street to the airport at the northern limit of the city This location has been used for a long time as a dump site Its resonance frequency is centered around 2 5 hertz with an amplification factor of about 6 Assuming S wave velocity of the upper layer to be between 100 and 200 m/s, may suggest a layer thickness of 10 to 20 meters This figure is reasonable, yet not confirmed by other geological or geophysical information The observed amplification factor at this site is not representative of site responses in Port Vila It is located in a trough that was probably already partly filled with alluvium This is usually the case in many other throughs that have been surveyed during this project In general, the responses of sites located at the bottom of such throughs show a slightly higher site amplification of a factor of about 2 to 3 at frequencies between 5 and 10 hertz as compared to most sites across Port Vila

The area around Bauerfield airport, north of Port Vila is part of the larger Mele terrace The response functions obtained for that area (see Fig 7) are characterized by two picks, one at low frequencies around 1 hz, and one at higher frequencies between 8 and 9 hertz The pick at low frequencies is systematically observed at each site, but with a variation in position and amplitude, which is indicative of varying thickness of the superficial layer Assuming a constant shear wave velocity (100-200 m/sec) over the considered area, that implies a thickness variation between 20-100 meters The second pick centered at 8 2 hertz is not observed on all sites from the Bauerfield airport area It could be related to a sand layer which is observed in many places in this area up to the base of Mt Bernier that limits the Mele volcano-sedimentary terrace to the north

**Site response microzonation**

Based on these observations, the soil map (Quantin, 1980), the topographic map (ign,1965) and drillhole information provided by the Geology and Mines department of Vanuatu, we have prepared a zoning map of the Port Vila and Bauerfield airport areas (figures 8) We have also modeled the subsurface at some sites when the amplification site factor was above 2 The modeling process is based on matching the observed response functions with an analytical function that is calculated by assuming S-wave velocities, densities and thicknesses of the layers underlying the surface The computations associated with each model are made by using the program of Joyner (1977) The observed site response parameters and computed model parameters across Port Vila are presented in Table 2 In the modeling process, a very

good fit to the observed resonance frequencies is achieve while the amplification factor is recover within 10% accuracy

**Table 2 Site response observations and generalized estimations**

| Observed | | | | Estimated by modeling | |
|---|---|---|---|---|---|
| Site No | Sites name | resonance freq (Hz) | Amp factor | H (m) sediment thickness | V (m/s) shear wave velocity |
| 8 | Ardimani wharf | 4 | 3 | 15 | 0 2 |
| 29 | Tassiriki | 5-7 | 3 | 5-7 | 0 12 |
| 50 | Depotoire | 2 | 6 | 10 | 0 1 |
| 57 | Bauerfield | 1 2 | 4 | 25 | 0 12 |
| 74 | Ecole française | 9 | 3 5 | 2 5 | 0 1 |
| 78 | Olhen fresh wind | 7 | 4 | 3 5 | 0 1 |
| 82 | Malopoa | 8 | 3 2 | 3 8 | 0 11 |

Based on the analysis of the observed site responses, it is suggested that Port Vila and the Bauerfield airport areas be divided into a 4 zones system, each of them characterized by a predominant resonance frequency and a range of expected site amplification factor A site with no amplification factor ($ 1) would not be included in either zone, no matter the shape of the spectral ratio function To a first approximation, the relationship between the height of a building and its fundamental period of vibration can be expressed by the crude formula

**T = (nb storeys)/10**

Two groups of building are then considered for the map low rise (1 to 5 storeys) and high rise (more then 5 storeys) building If the natural period of the ground matches the period of the building, then resonance may occur and may increase the probability of damage to the building

The four zones on the map are as follows
**Zone 1** No site resonance limestone terraces with no or little topographic variations
**Zone 2** Low resonance frequencies (< 1 hz) thick sedimentary layer Found only in Bauerfield area Possible resonance for very high rise building (more then 10 storeys)
**Zone 3** Resonance frequency between 1 and 5 hertz Found in the reclaimed areas and in a transition zone between Bauerfield area and Port Vila Possible resonance for medium to high rise building (5 to 10 storeys)
**Zone 4** Resonance frequency between 5 and 10 hertz Found in some areas with shallow sediments (up to few meters) over limestone basement or areas with complex topography (cliff, narrow graben, ) Possible resonance for low rise building (1 to 5 storeys, most frequently found in Port Vila area)

**Discussion**
This extensive study was aimed mainly for identifying locations within Port Vila, Vanuatu that may exhibit unusual site effects during strong earthquakes We have applied the Nakamura method over 100 sites across Port Vila and obtained rough estimations of the resonance frequencies and amplifications of the superficial layers The Nakamura (1989) approach, based on seismic noise measurements, has gained great popularity and is used by many across the globe However, it is by now well known that this approach may fail at locations where amplification effects are only marginal Even when a strong amplification is observed, the

amplification factor is often not accurately determined and should be substantiated with additional geological and/or geophysical information

Except of few areas within Port Vila, that exhibit amplification effect of engineering significance, most of the city area seems not to be vulnerable to site effects which may result either from soft sediments overlying hard rocks or from the topography Despite the limitations inherent in the measurements and their interpretations, we may fairly assume that significant amplifications (let us say with factors greater than 2), if exist, would have been detected For example, the map in the down town area, shows no resonance pattern associated with areas closed to the coast, where eventually soft materials can accumulated However this is perhaps not true along the second lagoon outside the map where strong ground shaking are reported during earthquake We also did not often observed significant effects due to the topography in the site responses, up to 10 hertz The only sites where such large effects have been observed are located on the highest points in the city Above 10 hertz, the complexity of the spectral ratio at some sites located on rocks could also indicate topographic effects However building cannot be effected very much by resonance in this high frequency band

Earthquakes are felt frequently in Port Vila Surprisingly, there are very few cases of reported damage to buildings (Louat and Baldassari, 1989) over approximately a 100 years period As an example, the July 15, 1981, Ms 7 earthquake occurred at about 80 km, northwest of Port Vila and did generate much damage There is also no reported dramatic site effect across Port Vila but there are few places where earthquake are more strongly felt than elsewhere These locations are coincident on the map with zones characterized by a resonance frequency One location is along the road to Mele and is within the "Bauerfield zone" with resonances around or below 1 hertz This is the present location of the glass depot PAF They have reportedly noted anomalous glass breaking during earthquakes Other places that experienced stronger shaking spread along the shore of the second lagoon, starting from the Tassiriki area (narrow zone that connect the two inland lagoons) which is characterized by a resonance frequency between 5 and 10 hertz, affecting mostly low rise buildings It is clear, in both cases, that the strong shaking experienced at these locations were ground motion amplification due to significant soil thickness

In conclusion, sites in Port Vila usually show no significant site effects This is due to the poor sedimentary cover found on recent volcanic structures located on modern island arcs like the New Hebrides In most places in the city, large thicknesses of uplifted limestone terraces are found on top of the volcanic rocks and ashes depots which yields no site effect Site amplification factors can, in some places, be increased by both topographical effects and very localized soil thickness controlled by active faulting

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**Figure captions**

Figure 1 Earthquake epicenters in the Efate island region Large dots are epicenters from the Harward CMTS catalog Small dot are epicenters from the ORSTOM local network catalog

Figure 2 Spectral ratios of sites throughout Port Vila with no resonance effect

Figure 3 Comparison of spectral ratios at three sites computed with microtremor (black curves) and S wave coda (grey curves) The grey box on the seismogram shows the time window of the signal used to compute the spectral ratio

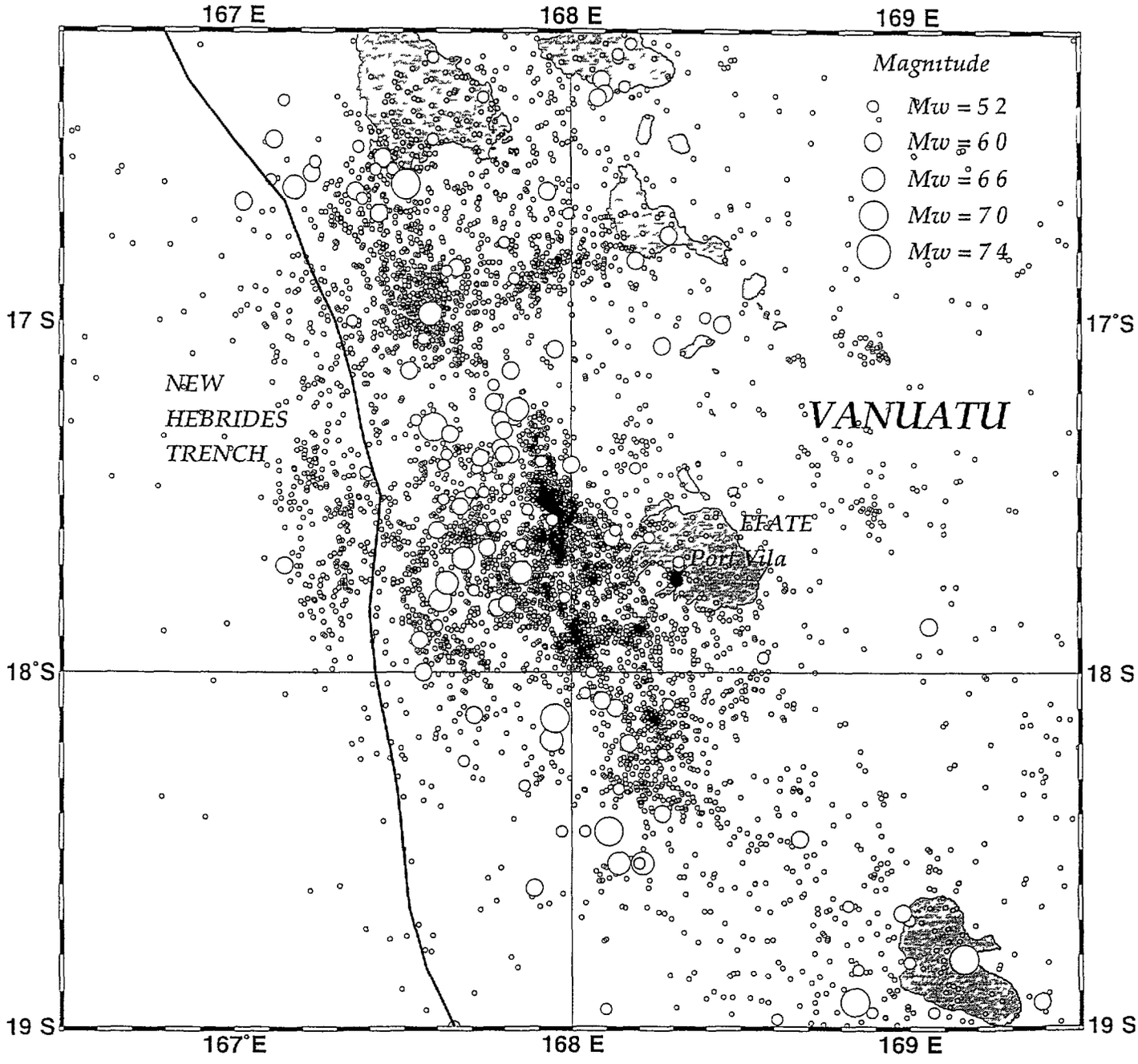
figure 4 Spectral ratio of sites located on reclaimed areas

figure 5 Spectral ratio of sites located in the Tassiriki area

figure 6 Spectral ratio of the site nb 50 located on an old dump zone (Le depotoire)

figure 7 Spectral ratios of sites located on Mele terrace, around Bauerfield airport

figure 8 Microzonation map of Port Vila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168 E
169 E
17 S
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Magnitude
Mw = 5 2
Mw = 6 0
Mw = 6 6
Mw = 7 0
Mw = 7 4
NEW
HEBRIDES
TRENCH
VANUATU
EFATE
Port Vila

Fig 2

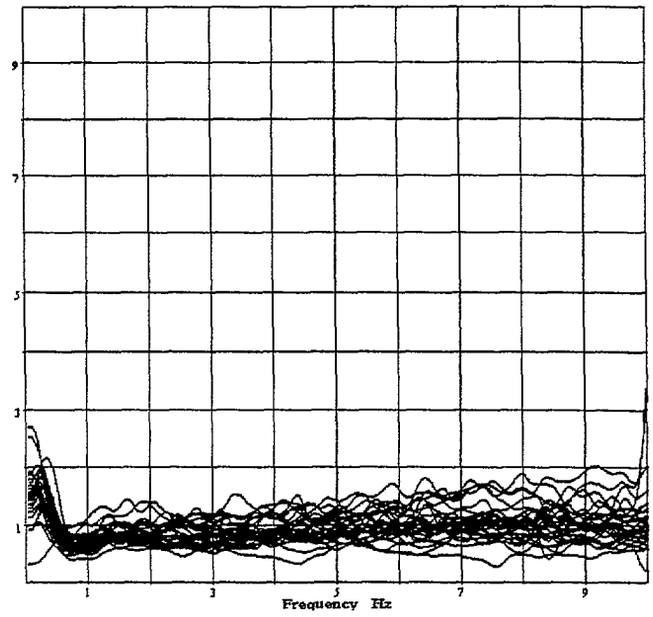
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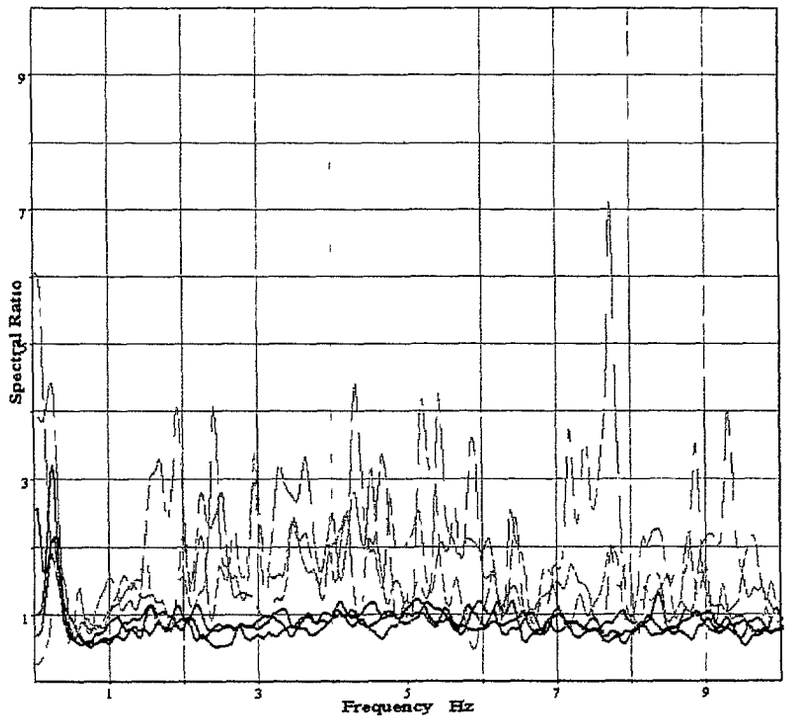
Fig 3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Spectral Ratio
1
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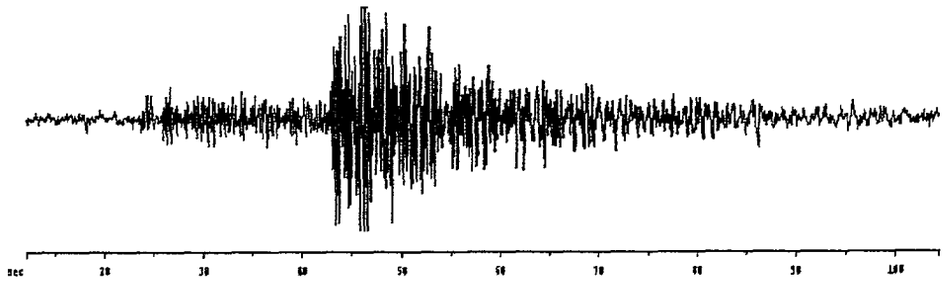

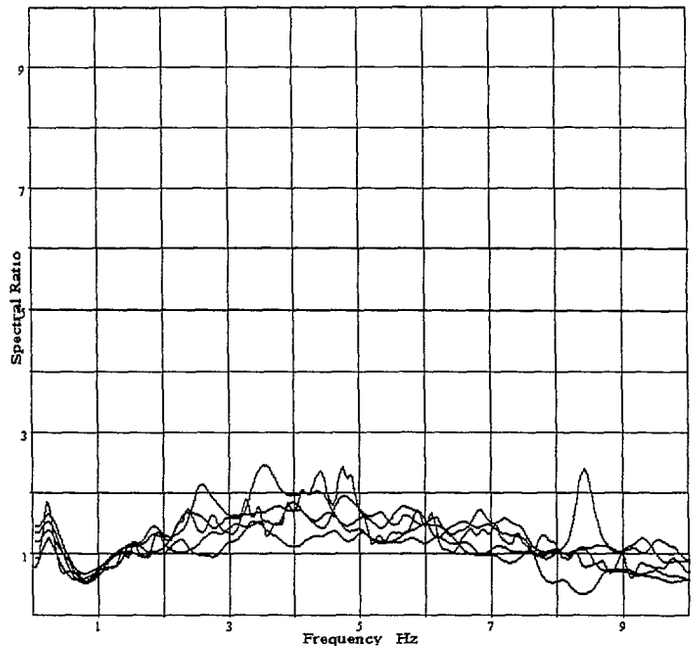
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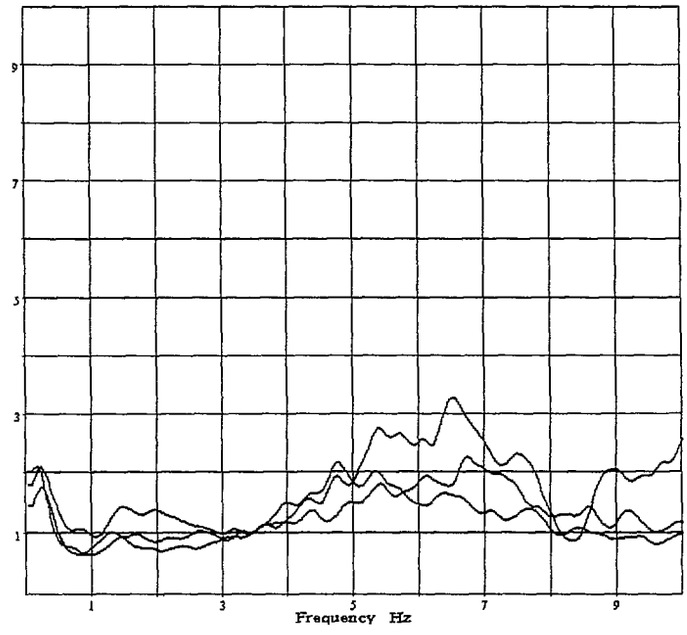
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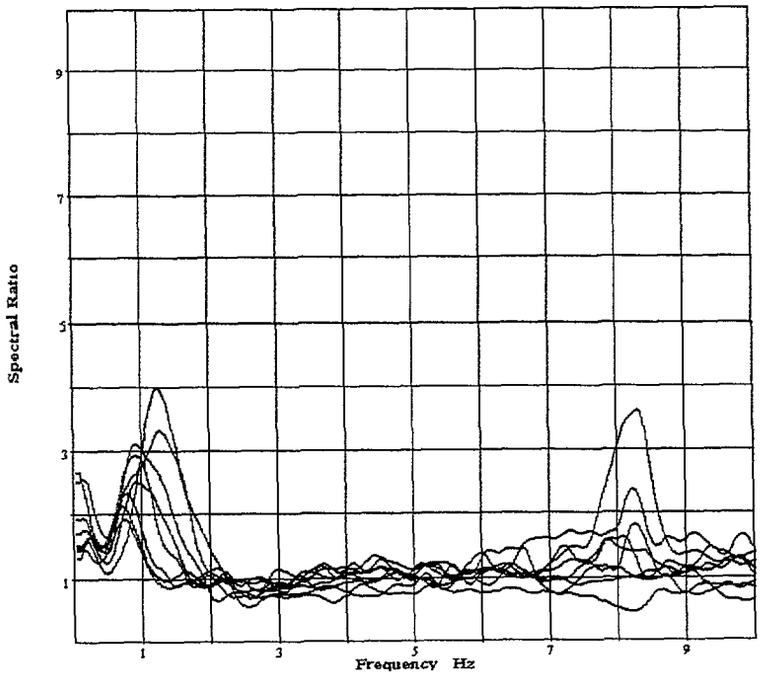
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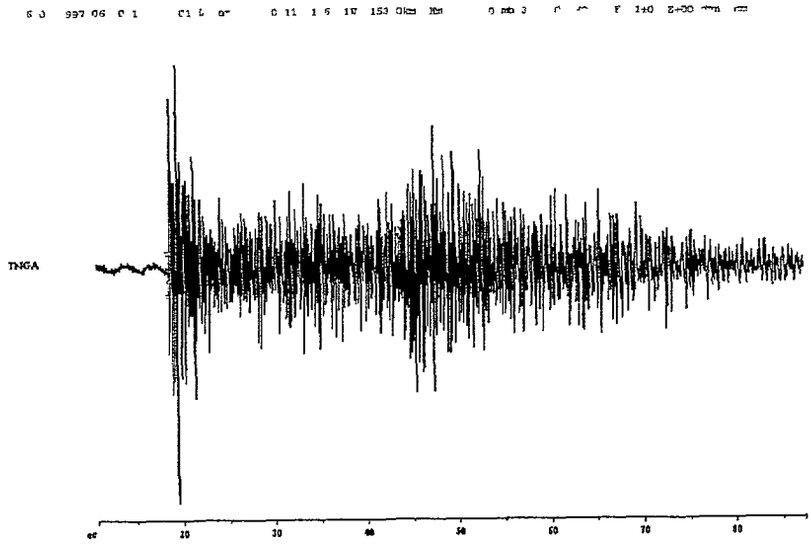
TNGA
20
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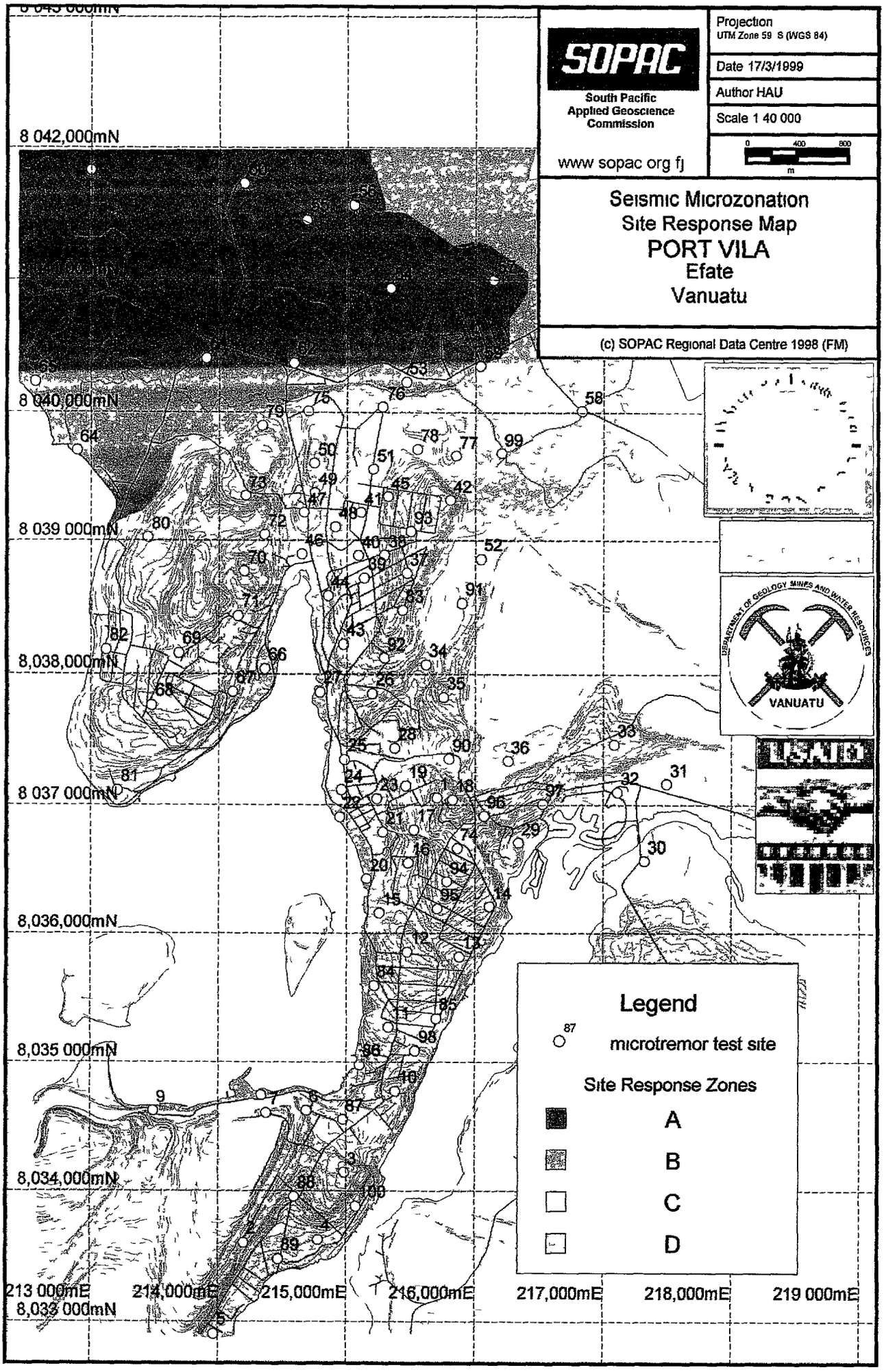
SOPAC
South Pacific Applied Geoscience Commission
www sopac org fj
Projection
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Date 17/3/1999
Author HAU
Scale 1 40 000
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Seismic Microzonation
Site Response Map
PORT VILA
Efate
Vanuatu
(c) SOPAC Regional Data Centre 1998 (FM)
DEPARTMENT OF GEOLOGY MINES AND WATER RESOURCES
VANUATU
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Legend
87
microtremor test site
Site Response Zones
A
B
C
D

36

# Frequency-Magnitude Relationships for seismic areas around the capital cities of Solomon, Vanuatu, Tonga and Fiji Islands

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**Abstract**

We studied the relationships between the frequency of occurrence and the magnitudes in seismogenic areas that will affect four capital cities in the South Pacific, namely Honiara in Solomon Islands, Port Vila in Vanuatu, Suva in Fiji and Nuku'alofa in Tonga We used the NEIS catalogues for the period 1973-1997, for magnitudes greater than about 5, in the proximity to the city under investigation The definitions of the geographic boundaries of the seismogenic zones are based on the classical concepts of the distribution of the tectonic plates, the overwhelming number of studies that describe the seismotectonics in those active regions and on the observed seismicity and studies of the local people Completeness of the catalogue is assumed because of the high seismicity in these areas, despite the relatively short time span We have used a hybrid process combining least squares fitting and Newtonian search process to find the best fit of the statistical parameters The characteristic b value is 1 27, and seems to be irrespective of the depth and/or region

## Introduction

One of the ways for characterizing the seismicity of a region is through the study of its magnitude distribution in the time domains Due to the lack of precise

models for describing the temporal distribution of earthquakes, in most of the seismically active areas on our globe, the classical frequency-magnitude relationship suggested by Gutenberg and Richter (1944) is still the most commonly used, especially in association with probabilistic earthquake hazard assessments We studied the relationships between the frequency of occurrence and the magnitudes in seismogenic areas that will affect four capital cities in the South Pacific, namely Honiara in Solomon Islands, Port Vila in Vanuatu Islands, Suva in Fiji Islands, and Nuku'alofa in Tonga Islands This project itself is one step in a comprehensive study of the assessment of earthquake hazard in those cities

The earthquake data upon which this study is based, are retrieved from the earthquake catalogues of the US Geological Survey, the National Earthquake information Service (NEIS), for the period 1973-1997, and for magnitudes greater than 4 The maps shown in Figs 1A to 1D depict the locations of the earthquakes used in this study and also mark the different seismogenic zones The definitions of the geographic boundaries of those seismogenic zones are based on the classical concepts of the distribution of the tectonic plates, the overwhelming number of studies that describe the seismotectonics in those active regions and on the observed seismicity and studies of the local people (several out of many, Curtis, 1971, Zhang and Lay, 1981, Papazachos et al , 1997) An important parameter for defining a seismogenic zone was the proximity to the city under investigation Since this study is aimed at providing parameters for seismic hazard assessments, we ignored the seismic activity occurring in areas that are too far away from those cities

**Frequency-magnitude relationship**

There are a number of studies dealing with estimating the parameters $a$ and $b$ in the "Gutenberg – Richter" relationship (Eq 1) for deep subduction zones in the south Pacific

$$LogN = a - bM \qquad M_{min} \leq M \leq M_{max} \qquad (1)$$

where $M$ is the magnitude and $N$ is the frequency of occurrence

For example, Epstein and Lomnitz (1966) studied the variation of the *b*-value as a function of depth In their study, the earthquakes occurring at depths of 0-125 km show *b*=1 18, deeper events (126-250 km) have *b*=1 39 and those at depths greater than 250 km yield *b*=0 86 Curtis (1973) presents similar results, for earthquakes occurring from 1961 to 1970 Acharya (1971) compared b-value estimations for different regions in the south Pacific, for the period 1961 to 1966 His results show *b*-values of 0 81-0 85 for the Tonga – Fiji trench at all depth In the New Hebrides (Vanuatu), the *b*-value decreases with depth from 0 81 (0-70 km) to 0 71 (70-300 km) and to 0 48 for the events deeper than 300 km A similar trend is observed in the Solomon Islands – New Guinea subduction zone, i e , *b*=0 9 for the shallow events (0-70 km), *b*=0 78 for the intermediate depth events (70-300 km) and *b*=0 44 for the deep events (> 300 km)

As demonstrated in those examples, the empirical estimations of the seismicity parameters across subduction zones in the south Pacific vary significantly We may attribute the differences in the statistical results to two major sources (A) differences in the definition of the size and location of the seismogenic zones, (B) limitations of the data in the used earthquake catalogues (e g inhomogeneity and incompleteness)

In the current study we used the NEIS catalogues for the period 1973-1997 With the wealth of operating seismic stations and networks around the globe we may fairly assume that all earthquakes with magnitudes 5 0 and greater which have occurred in the seismogenic zones described above, are included in the NEIC catalogues We refer to a magnitude 5 0 earthquake as the lowest magnitude that may cause significant damage to the capital cities under study We may also assume completeness of the catalogue because of the high seismicity in these areas (possibly the highest on our globe), despite the relatively short time span, and thus it is sufficient to enable reliable assessments of the seismicity parameters

It is well known and commonly accepted that Eq (1) may describe the frequency-magnitude relationship for discrete magnitude values For the cumulative frequency – magnitude relationship we adhered to Wiechert (1980), i e ,

$$N(M) = \alpha \frac{e^{-\beta(M-M_{min})} - e^{-\beta(M_{max}-M_{min})}}{1-e^{-\beta(M_{max}-M_{min})}} \qquad (2)$$

In both equations (1) and (2) $M_{min}$ is the lower magnitude threshold for which the earthquake catalogue is considered complete (4 8), $M_{max}$ is the maximum magnitude expected to occur in the investigated area, $\beta = b \ln 10 = 2\ 3b$, and $\alpha$ is the accumulative annual number of earthquakes Here we empirically estimated that $M_{min} = 4\ 8$ (Fig 2), and assumed that $M_{max}$=8 5 which is slightly higher than the largest $M_W$=8 2 earthquake that occurred in the Tonga trench in June 1977 (Zhang and Lay, 1989)

**Results and Discussion**

We have used a hybrid process combining least squares fitting of Eq 1 and Newtonian search process for Eq 2 to find the best fit for α, β and *b* The results of this statistical analysis are displayed in Figs 2 and 3 and summarized in Tables 1 and 2 Below we describe various groupings of the regions and zones that were executed in order to check any regional or depth dependence In the first case each zone was divided into a series of depth intervals or sub-zones For each single sub-zone we checked the dependence of the *b*-value on the tectonic region and depth (Table 1), assuming that each depth interval has its own characteristic *b*-value The variations of the *b*-values are in a limited interval of 1 2 to 1 5 (Table 1, Fig 2A,B), with no clear depth dependence, except the zones that exhibit subduction tectonics with a high activity rate, i e depth interval 450 to 700 km east of Fiji Islands The uncertainty factor $\sigma$ is calculated from Eq 3

$$\log_{10} \sigma = \sqrt{\frac{1}{N-1} \sum_{N} [\log_{10} \alpha(obs) - \log_{10} \alpha(theor)]^2} \qquad (3)$$

where $N$ is the number of observations The criterion for an accepted *b*-value was obtaining a minimum in $\sigma$ values The $\sigma$ values are relatively small to moderate, with values of about 1 2 to 1 4 Consequently these results can justify the grouping of the observations in the sub-zones Table 1 lists also the grouping of all the earthquakes in a given region regardless of the depth or the zone division, yielding

similar $b$-values or uncertainty factors to the above mentioned (Fig 2C) As was shown earlier we can justify grouping of the observations of a given region

The second step was to test a series of groups based on regions or zones In this case we assume that a given region, i e the region of Islands, is characterized by a constant $b$-value throughout the different depths but we let $\alpha$ values to vary These groupings clearly show that the $b$-values vary in a rather limited interval of 1 2 to 1 4 (middle $b$, $\alpha$, and $\sigma$ columns in Table 2, Fig 3A,B), despite the different tectonic regions The uncertainty factor $\sigma$ also shows small variations mainly in the interval of 1 2 to 1 5 The last check was to group all the south Pacific regions, assuming an overall common $b$-value Except 3 sets specific by their depths, which were excluded, that probably represent subduction tectonic with high activity rate, the $b$-value of 1 27 determined for all the south Pacific regions in this study appears to be satisfactory, i e low $\sigma$ values for most studied zones (B, A, and $\Sigma$ columns in Table 2, Fig 3C,D) The cases with insufficient data (In D in Table 2) were not used for the $b$-value determination

The various grouping and tests we have conducted are pointing to a common result that $b$-values and uncertainty factors remain relatively similar (Tables 1,2) Furthermore, those values do not exhibit depth dependence Our results are somewhat different from results of earlier studies (i e Epstein and Lomnitz, 1966, Acharya, 1971, Curtis, 1973), which are based on relatively short time span Thus assuming completeness of the dataset to $M_{min} = 4\ 8$ based on 25 years of earthquake monitoring, we conclude that an overall south Pacific $b$-value of 1 27 is a satisfactory one

**Acknowledgements**

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**Table captions**

| Region | Zone | Depth km | $b$ | $\alpha$ | $\sigma$ |
|---|---|---|---|---|---|
| | | | | | |
| Fiji | 1 | 33-70 | 1 41 | 1 14 | 1 30 |
| | 2 | 0-33 | 1 42 | 1 11 | 1 38 |
| | | 33-70 | 1 31 | 1 58 | 1 22 |
| | 3 | 33-70 | 1 29 | 4 22 | 1 15 |
| | 4 | 33-70 | 1 07 | 0 72 | 1 22 |
| | | 70-150 | 1 69 | 0 68 | 1 18 |
| | | 150-450 | 1 19 | 7 67 | 1 10 |
| | | 450-700 | 1 82 | 90 75 | 1 20 |
| Solomon | 1 | 0-33 | 1 31 | 10 55 | 1 30 |
| | | 33-70 | 1 25 | 15 01 | 1 14 |
| | | 70-150 | 1 27 | 5 92 | 1 07 |
| Tonga | 1 | 0-33 | 1 13 | 11 54 | 1 11 |
| | | 33-70 | 1 49 | 64 71 | 1 23 |
| | | 70-150 | 1 34 | 14 16 | 1 14 |
| | | 150-450 | 1 31 | 19 68 | 1 15 |
| | | 450-700 | 1 39 | 0 99 | 1 16 |
| | 2 | 33-70 | 1 09 | 0 91 | 1 21 |
| | | 150-450 | 1 34 | 7 82 | 1 13 |
| | | 450-700 | 1 85 | 103 65 | 1 20 |
| Vanuatu | 1 | 0-33 | 1 11 | 1 93 | 1 05 |
| | | 33-70 | 1 26 | 8 20 | 1 45 |
| | | 70-150 | 1 52 | 1 64 | 1 15 |
| | 2 | 0-33 | 1 36 | 9 16 | 1 28 |
| | | 33-70 | 1 60 | 21 03 | 1 37 |
| | | 70-150 | 1 34 | 10 09 | 1 13 |
| | | 150-300 | 1 31 | 5 15 | 1 15 |
| | 3 | 0-33 | 1 55 | 9 32 | 1 28 |
| | | 33-70 | 1 55 | 7 44 | 1 34 |
| | | 70-150 | 1 25 | 1 13 | 1 06 |
| | | 150-300 | 1 33 | 3 04 | 1 14 |
| | 4 | 0-33 | 1 29 | 10 22 | 1 18 |
| | | 33-70 | 1 41 | 23 80 | 1 23 |
| | | 70-150 | 1 34 | 12 35 | 1 12 |
| | | 150-300 | 1 19 | 6 92 | 1 08 |
| | | | | | |
| Fiji | ALL | ALL | 1 76 | 119 38 | 1 22 |
| | 1 | ALL | 1 42 | 1 96 | 1 41 |
| | 2 | ALL | 1 52 | 2 98 | 1 33 |
| | 3 | ALL | 1 34 | 6 40 | 1 29 |
| | 4 | ALL | 1 72 | 98 18 | 1 16 |
| Solomon | ALL | ALL | 1 34 | 34 25 | 1 28 |
| Tonga | ALL | ALL | 1 57 | 176 85 | 1 16 |
| | 1 | ALL | 1 46 | 122 81 | 1 21 |

| Region | Zone | Depth km | $b$ | $\alpha$ | $\sigma$ |
|---|---|---|---|---|---|
| | | | | | |
| Tonga | 2 | ALL | 1 88 | 125 87 | 1 28 |
| Vanuatu | ALL | ALL | 1 53 | 158 19 | 1 29 |
| | 1 | ALL | 1 36 | 13 52 | 1 39 |
| | 2 | ALL | 1 44 | 45 52 | 1 23 |
| | 3 | ALL | 1 65 | 26 77 | 1 30 |
| | 4 | ALL | 1 34 | 50 44 | 1 21 |

Table 1 - Separation of the 4 seismic regions into sub-zones Various groupings into one set are presented at the lower part of the table ALL refers to either all depths for a given zone or all zones for a given region

| Region | Zone | Depth km | $b$ | $\alpha$ | $\sigma$ | B | A | $\Sigma$ |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| Fiji | 1 | 0-33 | In D | | | 1 27 | 0 87 | 1 59 |
| | | 33-70 | 1 43 | 1 16 | 1 32 | 1 27 | 0 99 | 1 34 |
| | 2 | 0-33 | 1 43 | 1 12 | 1 41 | 1 27 | 0 96 | 1 43 |
| | | 33-70 | 1 43 | 1 82 | 1 26 | 1 27 | 1 50 | 1 24 |
| | 3 | 0-33 | In D | | | 1 27 | 1 77 | 1 46 |
| | | 33-70 | 1 43 | 5 07 | 1 21 | 1 27 | 4 12 | 1 16 |
| | 4 | 0-33 | In D | | | 1 27 | 0 26 | 1 01 |
| | | 33-70 | 1 43 | 1 08 | 1 47 | 1 27 | 0 90 | 1 32 |
| | | 70-150 | 1 43 | 0 56 | 1 26 | 1 27 | 0 50 | 1 35 |
| | | 150-450 | 1 43 | 11 89 | 1 38 | 1 27 | 8 89 | 1 15 |
| | | 450-700 | 1 43 | 43 33 | 1 69 | | | |
| Solomon | 1 | 0-33 | 1 27 | 9 76 | 1 31 | 1 27 | 9 76 | 1 31 |
| | | 33-70 | 1 27 | 15 64 | 1 15 | 1 27 | 15 64 | 1 15 |
| | | 70-150 | 1 27 | 5 92 | 1 08 | 1 27 | 5 92 | 1 08 |
| | | 150-300 | In D | | | 1 27 | 0 22 | 1 38 |
| Tonga | 1 | 0-33 | 1 41 | 24 22 | 1 42 | 1 27 | 14 09 | 1 49 |
| | | 33-70 | 1 41 | 54 67 | 1 28 | 1 27 | 40 71 | 1 45 |
| | | 70-150 | 1 41 | 16 14 | 1 18 | 1 27 | 12 42 | 1 18 |
| | | 150-450 | 1 41 | 23 78 | 1 21 | 1 27 | 18 24 | 1 17 |
| | | 450-700 | 1 41 | 1 01 | 1 18 | 1 27 | 0 89 | 1 20 |
| | 2 | 0-33 | In D | | | 1 27 | 0 31 | 1 25 |
| | | 33-70 | 1 41 | 1 32 | 1 47 | 1 27 | 1 12 | 1 31 |
| | | 70-150 | In D | | | 1 27 | 0 41 | 1 56 |
| | | 150-450 | 1 41 | 8 69 | 1 16 | 1 27 | 7 03 | 1 16 |
| | | 450-700 | 1 41 | 45 01 | 1 79 | | | |
| Vanuatu | 1 | 0-33 | 1 35 | 2 48 | 1 16 | 1 27 | 2 74 | 1 46 |
| | | 33-70 | 1 35 | 9 51 | 1 50 | 1 27 | 8 34 | 1 47 |
| | | 70-150 | 1 35 | 1 43 | 1 19 | 1 27 | 1 70 | 1 31 |
| | | 150-300 | In D | | | 1 27 | 0 07 | 1 24 |
| | 2 | 0-33 | 1 35 | 9 03 | 1 30 | 1 27 | 8 14 | 1 35 |
| | | 33-70 | 1 35 | 15 32 | 1 48 | 1 27 | 13 22 | 1 74 |
| | | 70-150 | 1 35 | 10 32 | 1 13 | 1 27 | 9 13 | 1 32 |
| | 2 | 150-300 | 1 35 | 5 50 | 1 16 | 1 27 | 4 83 | 1 16 |
| | 3 | 0-33 | 1 35 | 7 40 | 1 36 | 1 27 | 7 35 | 1 45 |
| | | 33-70 | 1 35 | 5 52 | 1 45 | 1 27 | 4 90 | 1 53 |
| | | 70-150 | 1 35 | 1 22 | 1 09 | 1 27 | 1 21 | 1 24 |
| | | 150-300 | 1 35 | 3 12 | 1 15 | 1 27 | 3 01 | 1 21 |
| | 4 | 0-33 | 1 35 | 11 67 | 1 19 | 1 27 | 8 19 | 1 45 |
| | | 33-70 | 1 35 | 20 98 | 1 26 | 1 27 | 17 53 | 1 31 |
| | | 70-150 | 1 35 | 12 58 | 1 13 | 1 27 | 11 78 | 1 29 |
| | | 150-300 | 1 35 | 9 22 | 1 24 | 1 27 | 7 99 | 1 14 |

Table 2 - The 4 seismic regions (see Fig 1) are treated as one unit in each case (middle $b$, $\alpha$, and $\sigma$ columns) B, A and $\Sigma$ (left columns) are equivalent to $b$, $\alpha$ and $\sigma$, respectively, but for all the south Pacific regions together In D - Insufficient data

45

**Figure captions**

Figure 1 - Observed seismicity, based on NEIS, in the vicinity of the capitals (solid square) (A) Suva in Fiji Islands, (B) Honihara in Solomon Islands, (C) Nukua'lufa in Tonga Islands, (D) Port Vila in Vanuatu Islands Numbers refer to zone division (see also Tables 1,2)

Figure 2 - Frequency-magnitude relationship for each of the regions in Fig 1 and Table 1 Numbers in parenthesis refer to the zone (A) Regions of Fiji and Solomon Islands, (B) Regions of Tonga and Vanuatu Islands, (C) Grouping of the zones or all of the earthquakes for a given region

Figure 3 - Frequency-magnitude relationship for each of the regions in Fig 1 and Table 2, assuming constant *b*-value for a given region Numbers in parenthesis refer to the zone (A) Regions of Fiji and Solomon Islands, (B) Regions of Tonga and Vanuatu Islands, (C) Grouping of all the zones in the south Pacific ($b$=1 27) - regions of Fiji and Solomon Islands, (D) as C but for Tonga and Vanuatu Islands

# Fiji Events 1/1973-12/1997

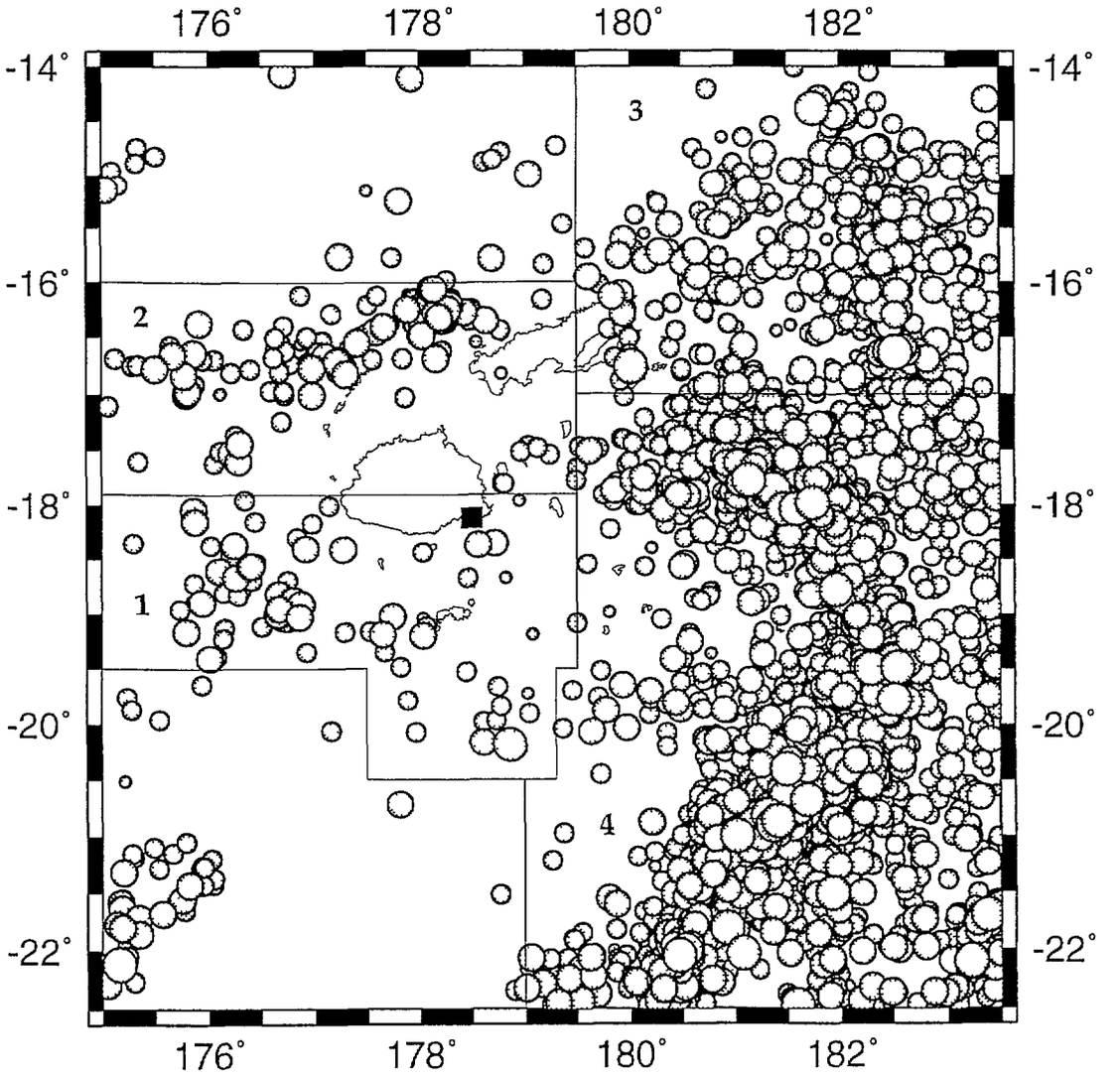



Fig. 1 A

# Solomon Events 1/1973-12/1997

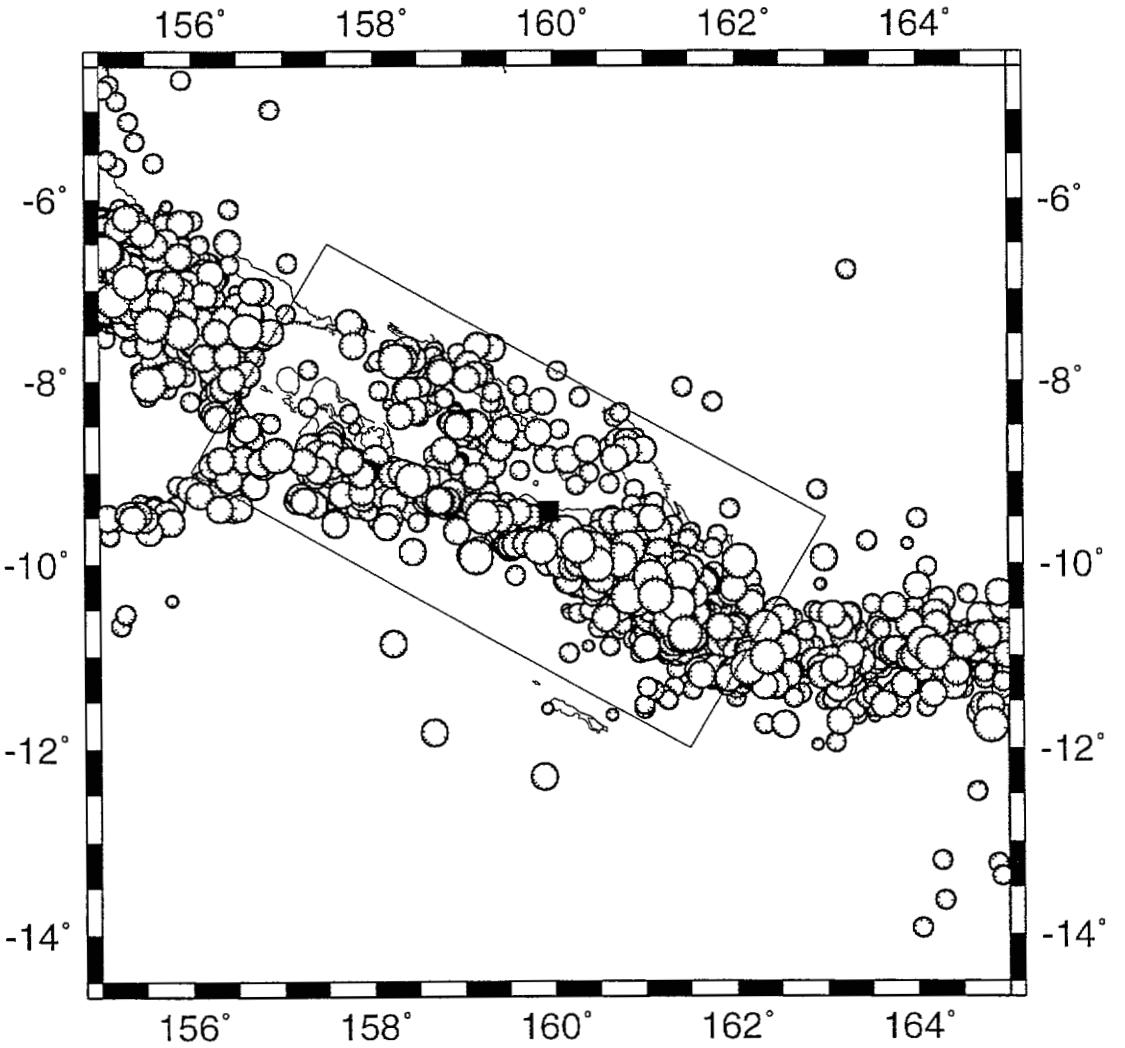



Fig. 1B

# Tonga Events 1/1973-12/1997

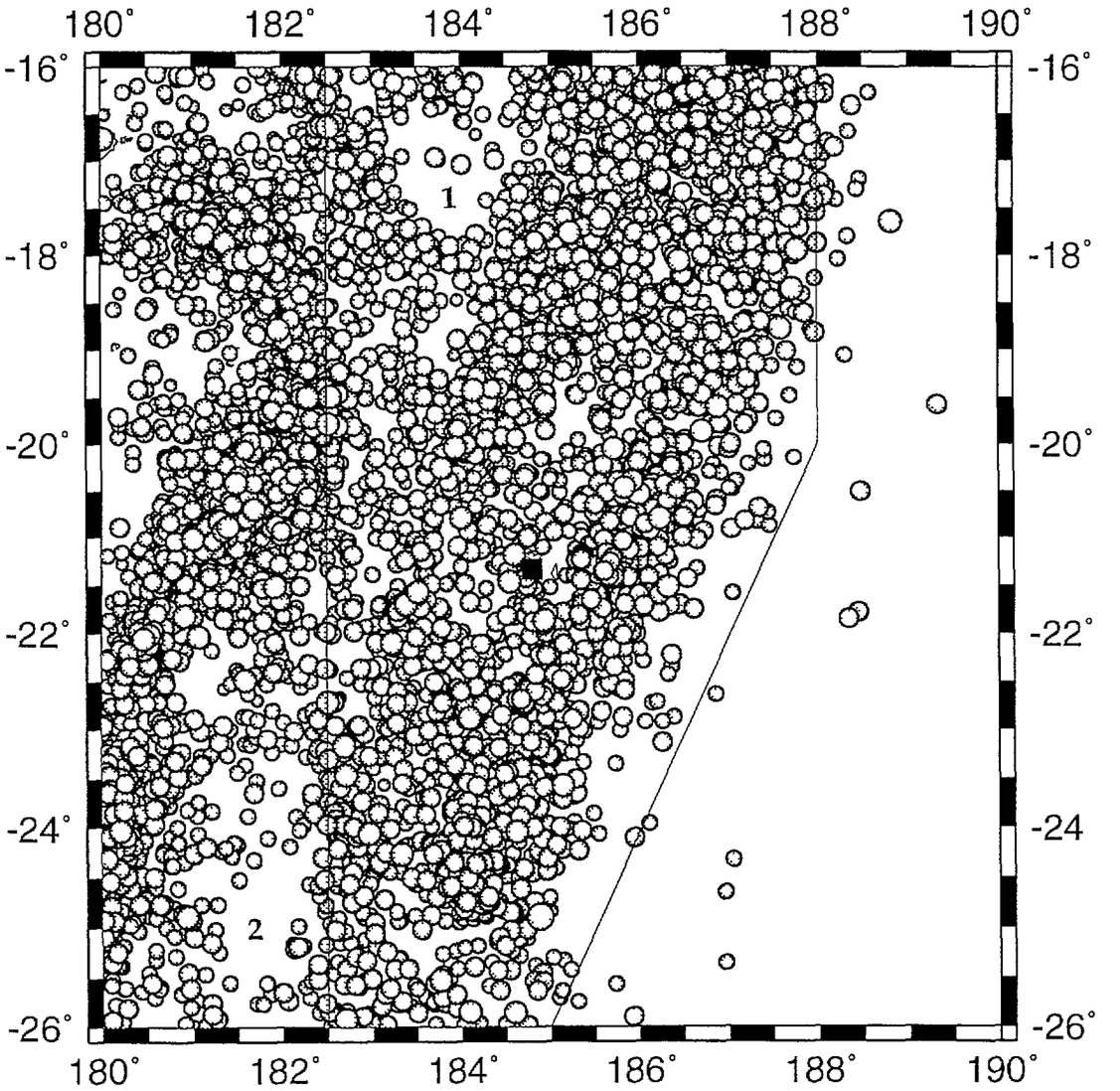



Fig. 1C

# Vanuatu Events 1/1973-12/1997

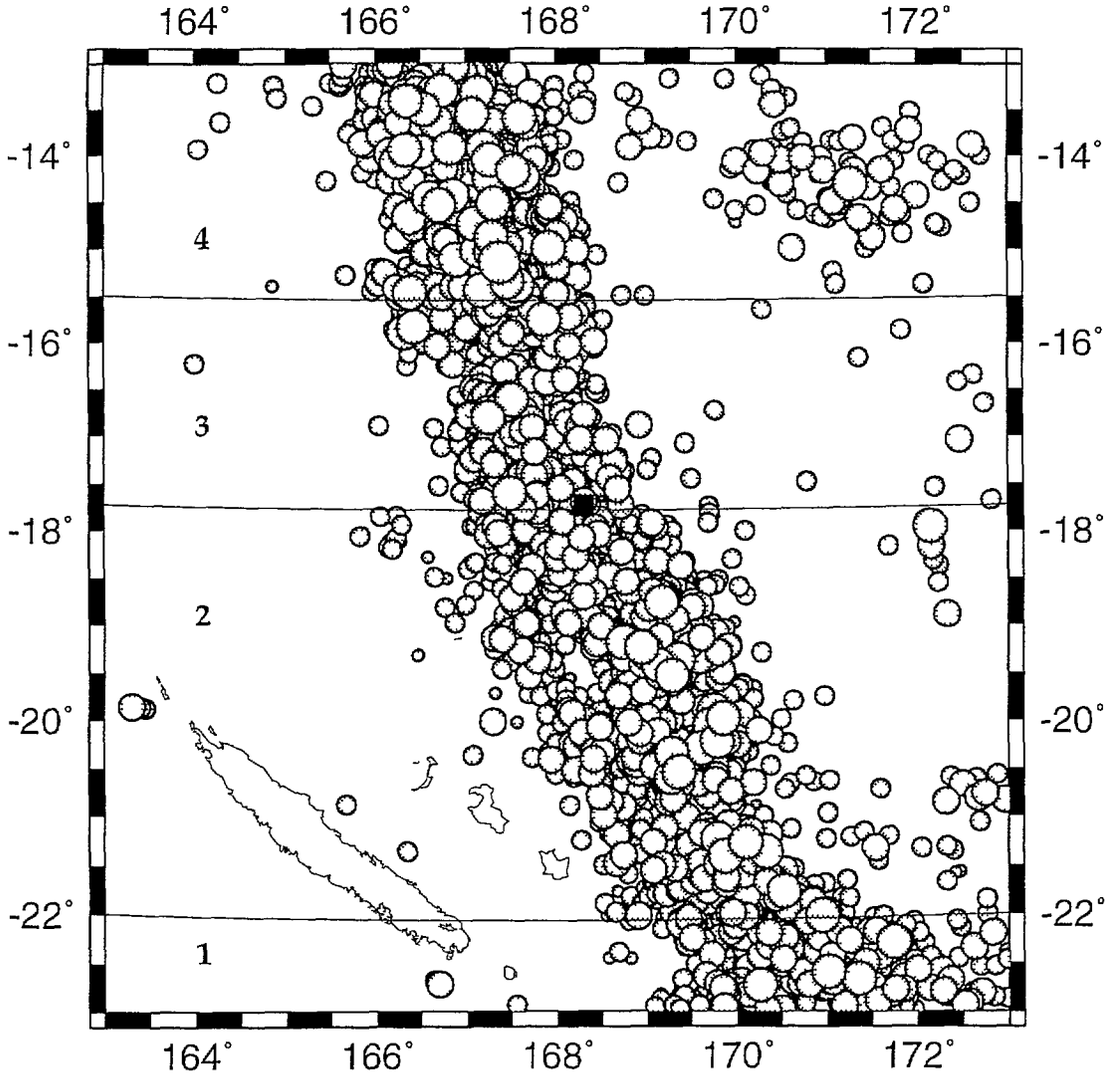



Fig 1D

Fig. 2A

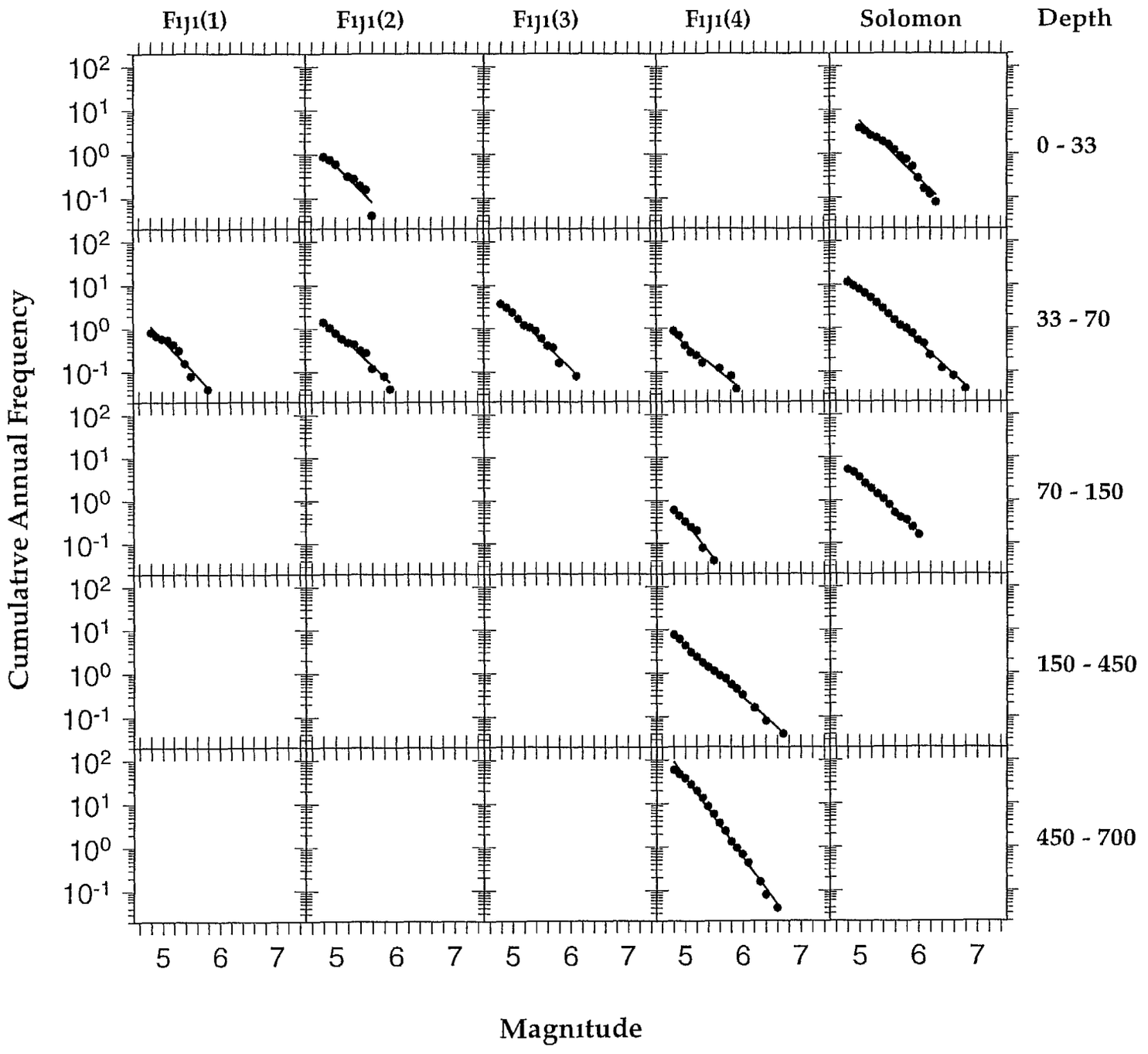

Fiji(1)
Fiji(2)
Fiji(3)
Fiji(4)
Solomon
Depth
0 - 33
33 - 70
70 - 150
150 - 450
450 - 700
Cumulative Annual Frequency
$10^2$
$10^1$
$10^0$
$10^{-1}$
5 6 7
Magnitude

Fig. 8a

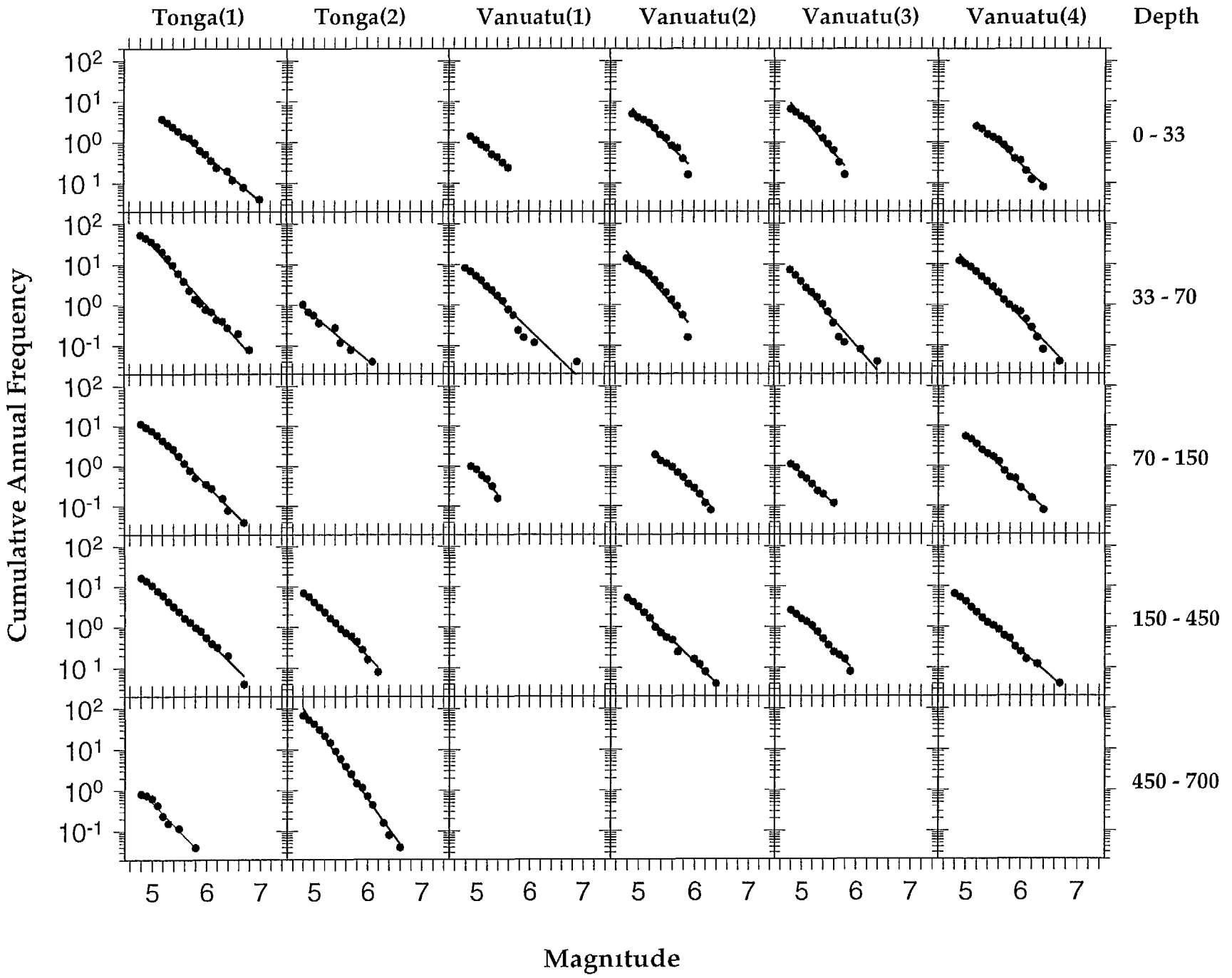

Tonga(1)
Tonga(2)
Vanuatu(1)
Vanuatu(2)
Vanuatu(3)
Vanuatu(4)
Depth
0 - 33
33 - 70
70 - 150
150 - 450
450 - 700
Cumulative Annual Frequency
Magnitude

Fig. 2C

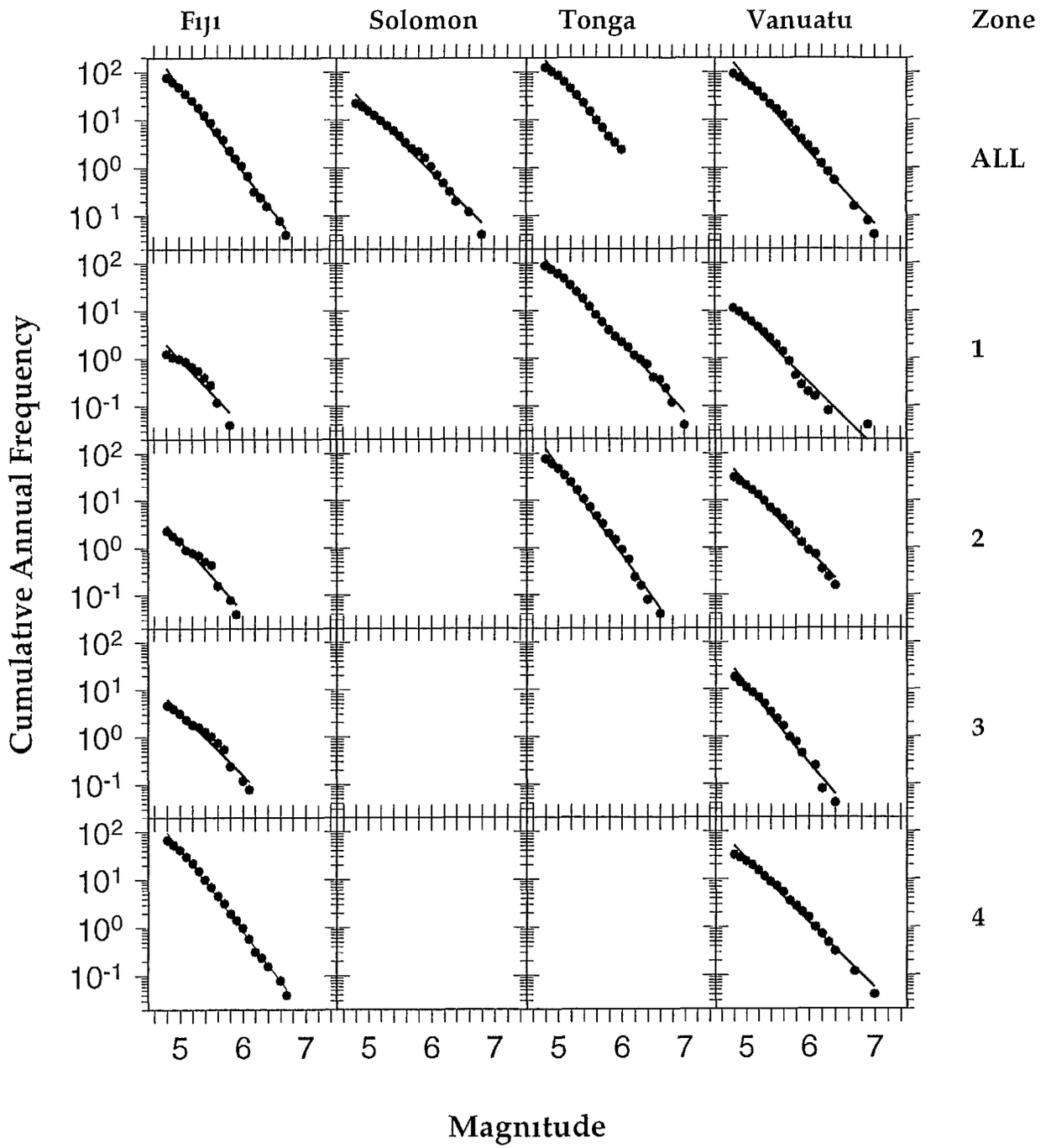

Fiji
Solomon
Tonga
Vanuatu
Zone
ALL
1
2
3
4
Cumulative Annual Frequency
$10^2$
$10^1$
$10^0$
$10^{-1}$
5
6
7
Magnitude

Fig. 2A

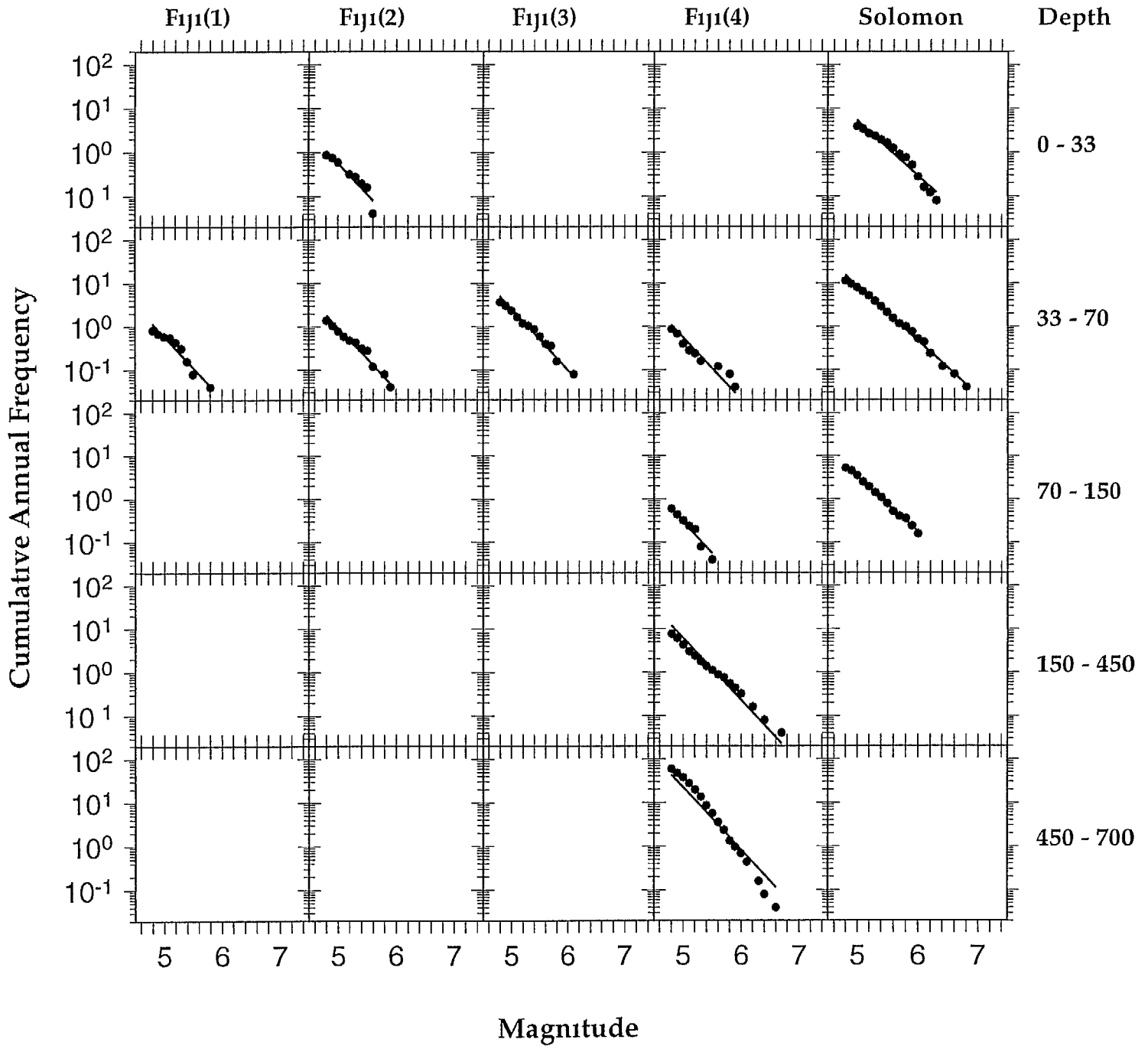

Fiji(1)
Fiji(2)
Fiji(3)
Fiji(4)
Solomon
Depth
0 - 33
33 - 70
70 - 150
150 - 450
450 - 700
Cumulative Annual Frequency
Magnitude

Fig. 33

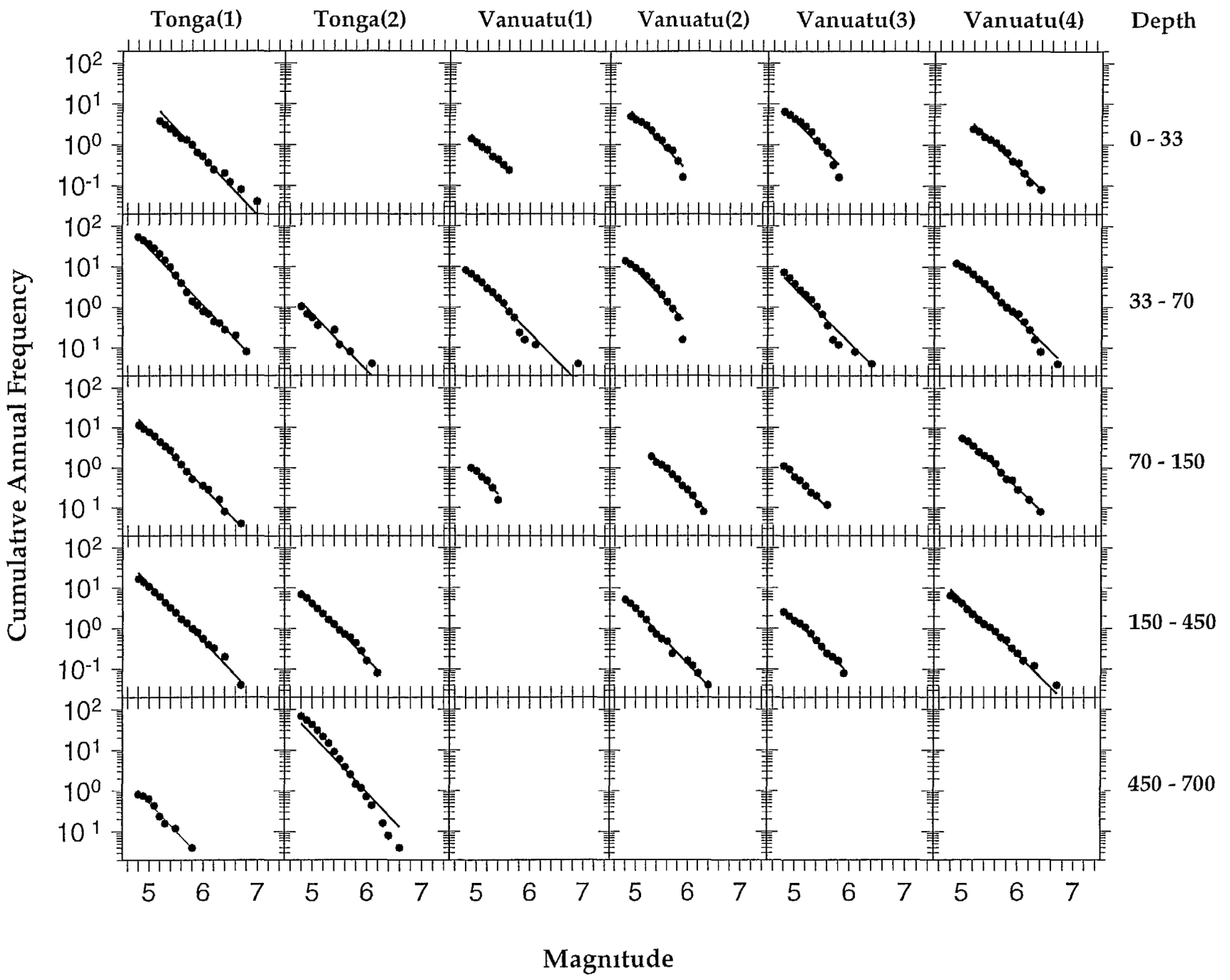

Tonga(1)
Tonga(2)
Vanuatu(1)
Vanuatu(2)
Vanuatu(3)
Vanuatu(4)
Depth
0 - 33
33 - 70
70 - 150
150 - 450
450 - 700
Cumulative Annual Frequency
Magnitude

Fig. 3 C

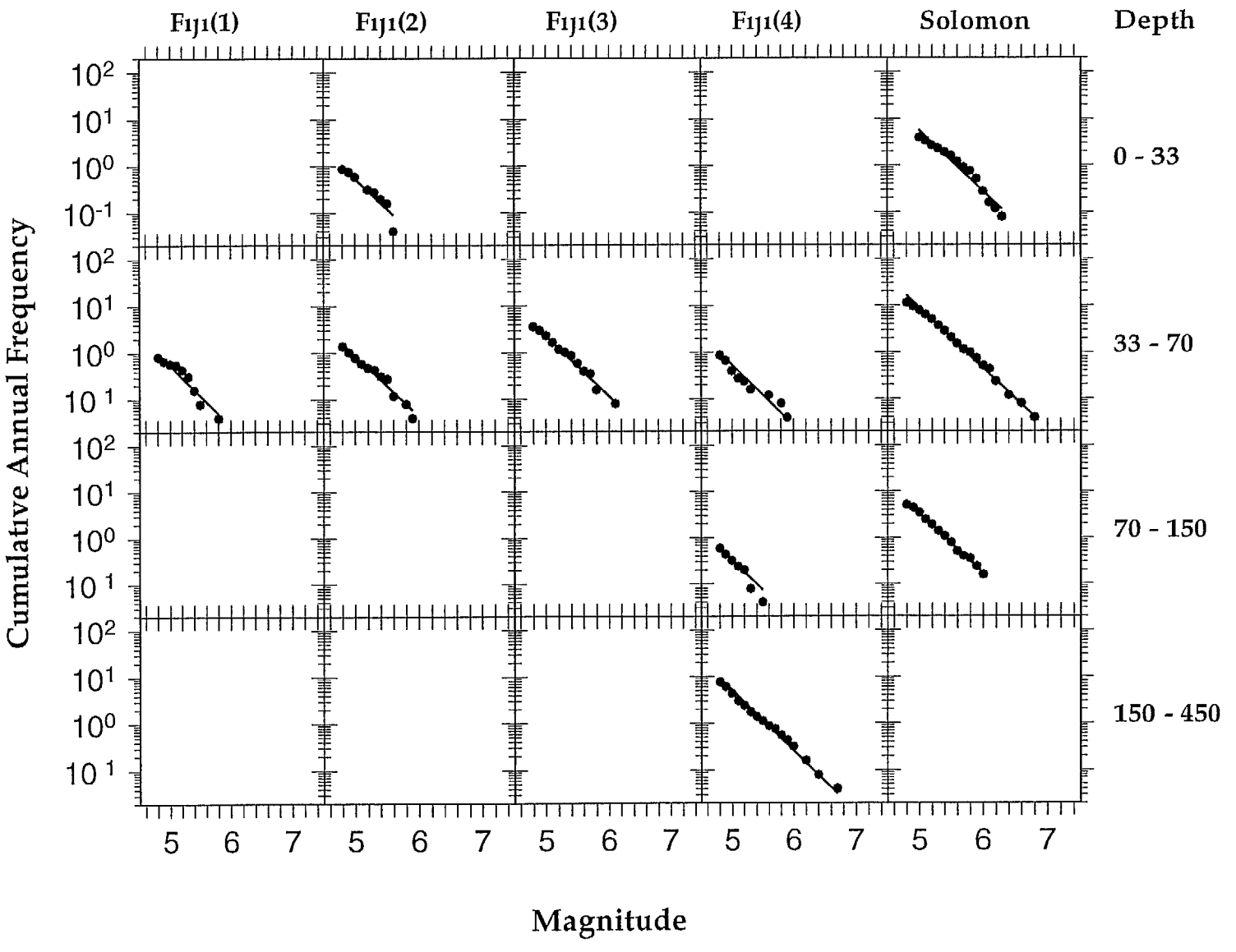
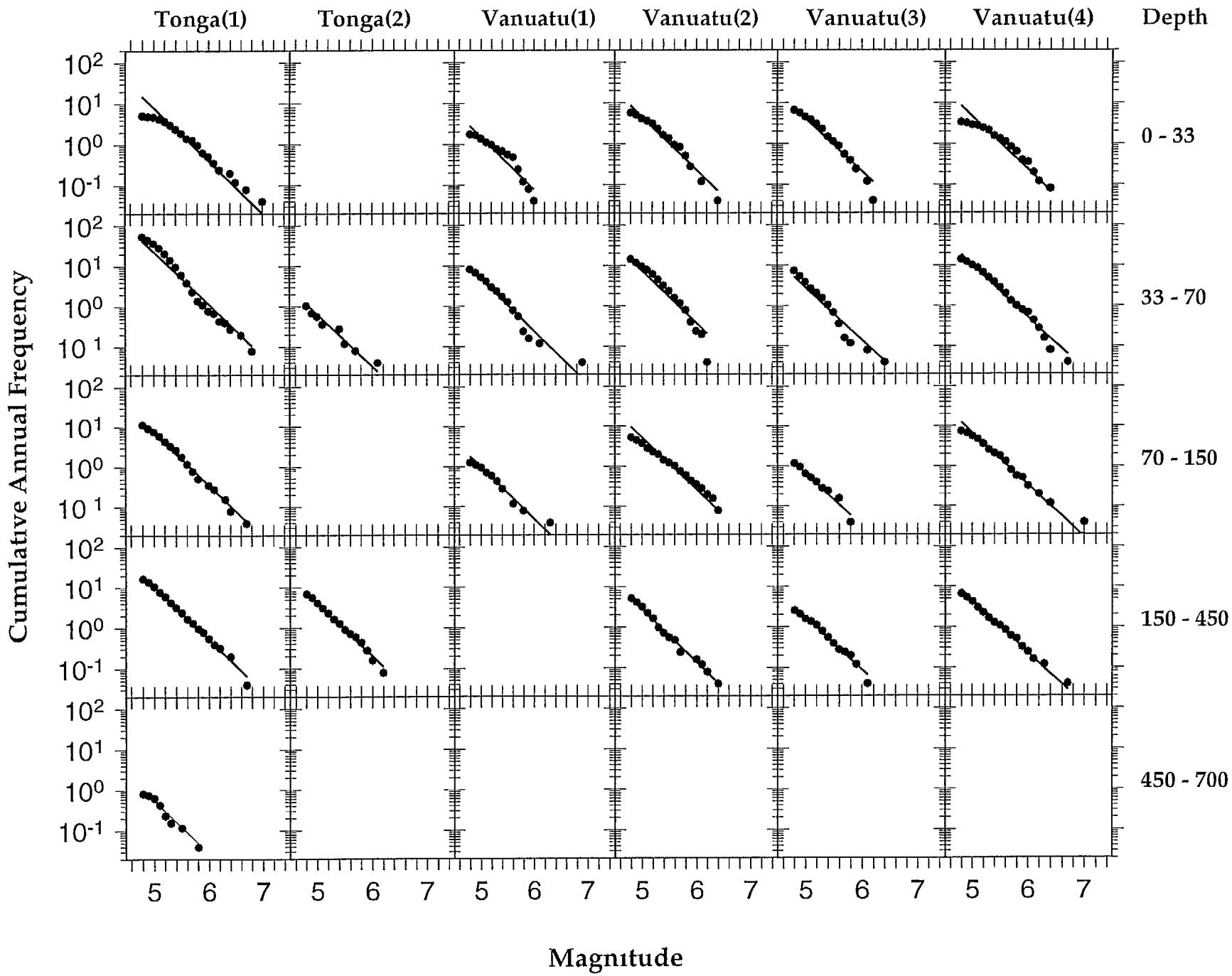

Fiji(1)
Fiji(2)
Fiji(3)
Fiji(4)
Solomon
Depth
0 - 33
33 - 70
70 - 150
150 - 450
Cumulative Annual Frequency
Magnitude

Fig. 3 (1)


Tonga(1)
Tonga(2)
Vanuatu(1)
Vanuatu(2)
Vanuatu(3)
Vanuatu(4)
Depth
0 - 33
33 - 70
70 - 150
150 - 450
450 - 700
Cumulative Annual Frequency
Magnitude

**Letter to the Editor**

# ON LOCAL MAGNITUDE DETERMINATIONS IN THE SOUTH PACIFIC REGION

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ABSTRACT

Local magnitudes are often based on empirical attenuation functions of the seismic parameters measured on the seismograms (e g , max amplitudes, coda duration, spectral level, etc) There are, however, exceptions such as in the case of Tonga, where such procedures are not practical due to the lack of data In this study we tried to define the local magnitude in terms of the estimated seismic moment, where seismic moment estimations are based on short period recordings We termed the new scale as Mm and equalized it in the range 4 0 < Mm < 5 2 to the body wave magnitudes, $m_b$, which are determined by NEIC The Mm scale is based on data from the Tonga region, but it might be applicable to other subduction zones in the South Pacific The same measurement procedures and equations are used to determine the magnitudes of a sample of earthquakes monitored in Vanuatu and in the Solomon Islands and are in agreement with $m_b$ determinations of NEIC

Key words Tonga, Local magnitude scale, Attenuation, South Pacific

The three component short period station TNG operated by the Ministry of Lands, Survey and Natural Resources of the Kingdom of Tonga, serves as a classic case where a local magnitude scale has to be defined with no sufficiently accurate reference system to provide a wide range of magnitudes for earthquakes at different focal depths and distances from the recording site The scarcity of seismic stations in and around the Tonga islands strongly limits the detection of low magnitude events and accuracy in determining the hypocenter locations The well established magnitude scales mb and Ms cannot be computed for too close events and the other classic ML scales (based on amplitude or coda duration measurements) require the establishment of an attenuation function which is applicable to the region

In this study we have focused our efforts on defining a local magnitude scale associated with estimations of the seismic moment, Mo, of the recorded events This choice is strongly associated with the fact that other ML formulae are basically empirical and require a database that is much larger than is currently available

The seismic moment of an earthquake (Brune, 1970) is

$$M_0 = 4\rho \ \pi \ \Psi(R,h) \ \beta^3 \ \Omega \ / \ (cFk) \qquad (1)$$

where $\rho$=2 7 gr/cc, $\beta \cong$3 6 km/s, c=2 (surface reflection), $\Psi$(R,h) is an empirical correction for the distance, R, and focal depth, h $\Omega$ is the low frequency displacement spectral level of the S waves measured at the station F is a correction associated with the radiation pattern of the S waves, F=0 18 when determining $\Omega$ from the vertical component and F=0 61 when $\Omega$ is determined from the horizontal component k is a free parameter used by Shapira and Hofstetter (1993) to correct for use of horizontal (k=1) or vertical (k=1 5) seismometers

As stated above, the function $\Psi$(R,h) has to be derived empirically (see e g Shapira and Hoftetter, 1993), a task which is difficult to perform when there is only one station which recorded the events At this stage we apply two basic assumptions

(1) The magnitude - Mo relationship suggested by Kanamori (1977), Hanks and Kanamori (1979), Bakun (1984) and many others is

$$M = \frac{2}{3}\log(M_0) \ - \ 10\,7 \qquad or \qquad \log(M_0) = 15 \ M + \ 16\,0 \qquad (2)$$

We assume that these equations are also applicable to the South Pacific region

(2) In the magnitude range 4 0-5 5, M=mb (see examples in Bath, 1981)

As shown in the following, some of the events recorded by TNG are also reported by NEIC who provide an estimate of mb Substituting mb for M in equation (2) and using equation (1), we obtain a simple relationship of the form

$$\Psi(R,h) = \log\Omega \ - \ 15 m_b \ + \ Const \qquad (3)$$

where the constant is a product of the constants in eqs (1) and (2)

As in many studies of attenuation functions of seismological parameters and, after examining different alternatives, it is assumed that

$$\Psi(R,h) = a1 \ \log D \ + \ a2 \ D \qquad (4)$$

where $D = \sqrt{(R^2 + h^2)}$

The TNG station (21 133°S 175 197°W) is equipped with 3 component short period seismometers The recorded motions are filtered in the band-pass of 0 2-12 5 Hz before being digitally recorded on the PC-SDA (PC based seismic data acquisition system, Shapira and Avirav, 1995) The response function of a seismic channel is presented in Fig 1

The station was installed in September 1996 However, due to power supply problems and other maintenance difficulties, its operation was interrupted for relatively long periods Nevertheless, within several months of routine operation, the station has recorded several hundreds of local and regional events, many of which, unfortunately, can not be located Foci of located earthquakes are shown on the map in Fig 2 Until June 1997, there were only 29 events which were recorded jointly by TNG and by other stations worldwide and, thus, were analyzed and reported by the US National Earthquake Information Center, NEIC Table 1 presents a list of these events where the epicentral distances depths and mb magnitudes are determined by NEIC and the low frequency displacement spectral levels, Ω, were computed and measured using the interactive GII-SDP software package developed by Malitzky and Shapira of the Geophysical Institute of Israel

Following the procedure described above, we obtained an empirical attenuation

$$\Psi(R,h) = D \text{ , (i e a1=1 0, a2=0 0)}$$

In fact, the best fit is observed for a1=1 02 and a2=0 0001, with a standard deviation of 0 21 (observed mb minus calculated magnitudes Mm)

Introducing Eq (4) to Eq (1), we obtain a "new" magnitude scale Mm which differs from the Moment magnitude scale Mw by the fact that it is based only on SHORT-PERIOD recordings at local and regional distances (up to 10°km) The correlation between the Mm and mb magnitude determinations is shown in Fig 3

The definition of the Mm scale, to serve as a local magnitude scale in the region of the South Pacific islands, is prompted by basic physical considerations or, in other words, it is linearly correlated with that part of the (log) seismic moment which is measurable by short period seismometers Evidently, when the corner frequency in the displacement spectrum of the event is lower than that of the band-pass of the seismometric system (about 0 3 Hz), the Mm values would not be an appropriate measure of the earthquake strength Under these conditions and according to Lee and Stewart (1981), we should expect that Mm will become saturated and lose linearity with log(Mo) at magnitudes about 5 5 and higher, i e , for estimating the magnitudes of strong earthquakes we may apply the same formulation but have to use recordings from broad band or strong motion seismometers

We are fully aware of the fact that the data base upon which we derived the regional attenuation function is limited in quantity and sometimes also in quality It should be noted that there is an inherent uncertainty in mb determinations As observed worldwide (see, for example, Bath, 1973 and Shapira and Kulhanek, 1978),

mb determinations of a given event may vary within ±0 3 and more In addition, many of the earthquakes used are located by NEIC with only a few stations (especially the low magnitude earthquakes) where there might be significant uncertainties associated with estimating the hypocentral distances Despite these difficulties, we have obtained the expected attenuation ( $R^{-1}$ ) which corresponds to the geometrical spreading of body waves (S waves in this particular case) Anelastic attenuation, if it exists, could not be resolved from the available data

The main practical significance of this study is the fact that it allows magnitude determinations of many seismic events which are not otherwise possible Encouraged by these results, it is interesting to test whether the procedure presented here is applicable to other subduction areas within the South Pacific Sporadic operations of the PC-SDA system in Port Vila (Vanuatu) provided recordings only of earthquakes also reported by NEIC Hundreds of events recorded by the PC-SDA system are not reported in international bulletins Mm versus mb determinations of these events are also shown in Fig 3 and demonstrate the applicability of the developed procedure to other areas in the South Pacific This new Mm scale may be used as a uniform local magnitude scale to that region

ACKNOWLEDGEMENTS

This study has been facilitated and sponsord by the US International Agency for Development under Grant No TA-MOU-95-C13-024

We thank our colleagues in the Ministry of Lands, Survey and Natural Resources of the Kingdom of Tonga and in the South Pacific Applied Geosciences Commission (SOPAC) for helping us maintain the station Thanks are due to Dr M Rengeir of ORSTOM (Vanuatu) and Mr Morris of the Dept of Geology, Mines and Water Resources, for operating the PC-SDA and providing us data from Vanuatu Special thanks to Dr G Shorten of SOPAC for coordinating the measurements and the workshops during which the data were analyzed

All the software used in the analysis was developed by Ms A Malitzky of GII, Israel, for which we are most grateful

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62

**Table 1 Events used in the Magnitude Analysis**
Mm is the new scale, while mb is the magnitude determined by NEIC

| DATE | ORIGIN TIME | LAT. | LONG | H | | |
|---|---|---|---|---|---|---|
| **Tonga Events** | | | | | | |
| 1996/10/31 | 14 04 11 4 | 18 07S | 178 17W | 496 | 4 3Mm | 4 7mb |
| 1996/11/03 | 21 44 51 9 | 22 29S | 179 27W | 300 | 4 3Mm | 4 1mb |
| 1996/11/06 | 09 23 40 9 | 17 85S | 175 15W | 150 | 5 0Mm | 5 0mb |
| 1996/11/08 | 09 22 37 9 | 20 32S | 176 67W | 202 | 4 3Mm | 4 5mb |
| 1996/11/08 | 14 00 46 6 | 22 26S | 179 22W | 458 | 4 4Mm | 5 2mb |
| 1996/11/11 | 16 02 34 2 | 19 46S | 175 59W | 200 | 3 6Mm | 3 6mb |
| 1996/11/16 | 14 43 05 2 | 19 03S | 177 57W | 491 | 4 1Mm | 4 3mb |
| 1996/12/03 | 12 15 55 4 | 19 56S | 176 04W | 142 | 3 9Mm | 4 3mb |
| 1996/12/03 | 12 56 57 6 | 18 35S | 172 27W | 32 | 5 4Mm | 6 0mb |
| 1996/12/08 | 04 08 54 0 | 20 26S | 174 52W | 14 | 4 3Mm | 4 5mb |
| 1996/12/08 | 17 13 18 0 | 20 07S | 177 83W | 513 | 4 4Mm | 4 6mb |
| 1996/12/15 | 15 38 50 5 | 23 29S | 176 10W | 248 | 4 6Mm | 4 9mb |
| 1996/12/16 | 17 01 14 8 | 18 88S | 179 32W | 576 | 4 6Mm | 4 9mb |
| 1996/12/16 | 18 53 06 7 | 23 39S | 179 74W | 457 | 4 5Mm | 4 6mb |
| 1997/02/13 | 12 18 50 3 | 18 07S | 178 41W | 542 | 4 5Mm | 4 4mb |
| 1997/02/14 | 13 39 13 7 | 22 00S | 179 51W | 600 | 4 1Mm | 4 2mb |
| 1997/02/15 | 22 54 15 3 | 21 90S | 175 14W | 17 | 3 8Mm | 4 2mb |
| 1997/02/18 | 05 13 21 7 | 21 30S | 175 99W | 55 | 4 2Mm | 4 4mb |
| 1997/04/09 | 18 52 38 9 | 20 29S | 177 69W | 339 | 4 4Mm | 4 7mb |
| 1997/04/13 | 08 48 34 6 | 22 19S | 176 24W | 111 | 4 7Mm | 4 7mb |
| 1997/04/13 | 15 17 31 7 | 19 73S | 175 30W | 141 | 4 4Mm | 4 8mb |
| 1997/04/14 | 06 58 32 2 | 21 48S | 178 59W | 272 | 3 9Mm | 3 9mb |
| 1997/04/15 | 14 43 36 2 | 20 47S | 177 62W | 439 | 3 8Mm | 3 6mb |
| 1997/04/20 | 16 20 48 1 | 20 20S | 178 22W | 481 | 4 1Mm | 4 2mb |
| 1997/04/20 | 18 45 23 0 | 19 73S | 177 68W | 355 | 5 1Mm | 5 1mb |
| 1997/04/24 | 01 45 04 4 | 20 36S | 178 20W | 304 | 4 3Mm | 4 4mb |
| 1997/04/25 | 07 31 09 0 | 19 47S | 174 11W | 127 | 4 1Mm | 4 3mb |
| 1997/04/27 | 07 16 31 5 | 20 46S | 177 80W | 511 | 4 2Mm | 4 7mb |
| 1997/04/28 | 05 32 56 0 | 20 67S | 178 20W | 504 | 4 1Mm | 4 7mb |
| 1997/05/01 | 03 25 59 1 | 21 75S | 176 93W | 99 | 4 3Mm | 4 5mb |
| 1997/05/04 | 05 30 09 2 | 19 99S | 178 00W | 450 | 4 0Mm | 4 0mb |
| 1997/05/05 | 01 21 16 0 | 19 72S | 177 29W | 400 | 4 3Mm | 4 2mb |
| 1997/05/06 | 06 55 10 3 | 22 27S | 179 43W | 506 | 4 3Mm | 4 6mb |
| 1997/05/06 | 07 30 18 5 | 20 76S | 175 85W | 40 | 3 8Mm | 3 5mb |
| 1997/05/06 | 15 12 48 7 | 21 91S | 175 59W | 33 | 4 2Mm | 4 2mb |
| 1997/05/08 | 01 33 37 4 | 19 32S | 175 35W | 81 | 4 2Mm | 4 4mb |
| 1997/05/08 | 05 56 13 1 | 19 43S | 175 83W | 178 | 4 9Mm | 5 1mb |
| 1997/05/11 | 15 29 50 4 | 22 00S | 175 62W | 12 | 4 5Mm | 4 6mb |
| 1997/07/16 | 02 10 18 8 | 21 40S | 175 81W | 18 | 4 5Mm | 4 6mb |
| 1997/07/17 | 07 01 35 2 | 22 80S | 175 29W | 15 | 4 8Mm | 4 9mb |
| 1997/07/22 | 14 28 09 8 | 22 86S | 175 39W | 136 | 4 7Mm | 5 0mb |

| DATE | ORIGIN TIME | LAT. | LONG. | H | | |
|---|---|---|---|---|---|---|
| 1997/07/23 | 08 33 58 3 | 22 92S | 175 34W | 88 | 4 6Mm | 4 6mb |
| 1997/08/05 | 08 13 10 3 | 21 06S | 176 45W | 244 | 4 3Mm | 4 2mb |
| 1997/08/05 | 20 45 35 8 | 21 24S | 174 57W | 21 | 4 7Mm | 4 9mb |
| 1997/08/16 | 10 01 14 9 | 21 14S | 174 07W | 82 | 4 2Mm | 4 3mb |
| 1997/08/17 | 17 43 57 1 | 20 50S | 176 11W | 179 | 3 9Mm | 4 0mb |
| 1997/09/06 | 06 50 15 5 | 20 11S | 176 51W | 153 | 3 7Mm | 3 6mb |
| 1997/09/08 | 23 49 34 9 | 20 73S | 174 50W | 62 | 5 0Mm | 5 0mb |
| 1997/09/09 | 06 38 22 5 | 22 61S | 174 65W | 124 | 4 1Mm | 4 5mb |
| 1997/09/13 | 17 28 56 0 | 21 37S | 174 58W | 33 | 4 5Mm | 4 6mb |
| 1997/09/24 | 15 16 30 6 | 21 09S | 174 33W | 50 | 4 8Mm | 4 8mb |
| 1997/09/27 | 15 59 01 9 | 19 39S | 173 73W | 33 | 4 2Mm | 4 5mb |
| **Vanuatu events** | | | | | | |
| 1997/01/16 | 02 44 37 5 | 16 03S | 167 28E | 129 | 4 6Mm | 4 5mb |
| 1997/01/20 | 05 38 18 2 | 19 27S | 167 59E | 25 | 4 4Mm | 4 3mb |
| 1997/01/20 | 20 58 14 6 | 18 92S | 169 45E | 122 | 4 6Mm | 4 7mb |
| 1997/01/25 | 11 04 48 6 | 16 09S | 167 95E | 155 | 4 9Mm | 4 9mb |
| 1997/01/27 | 01 12 38 2 | 17 91S | 167 38E | 200 | 4 8Mm | 4 3mb |

64

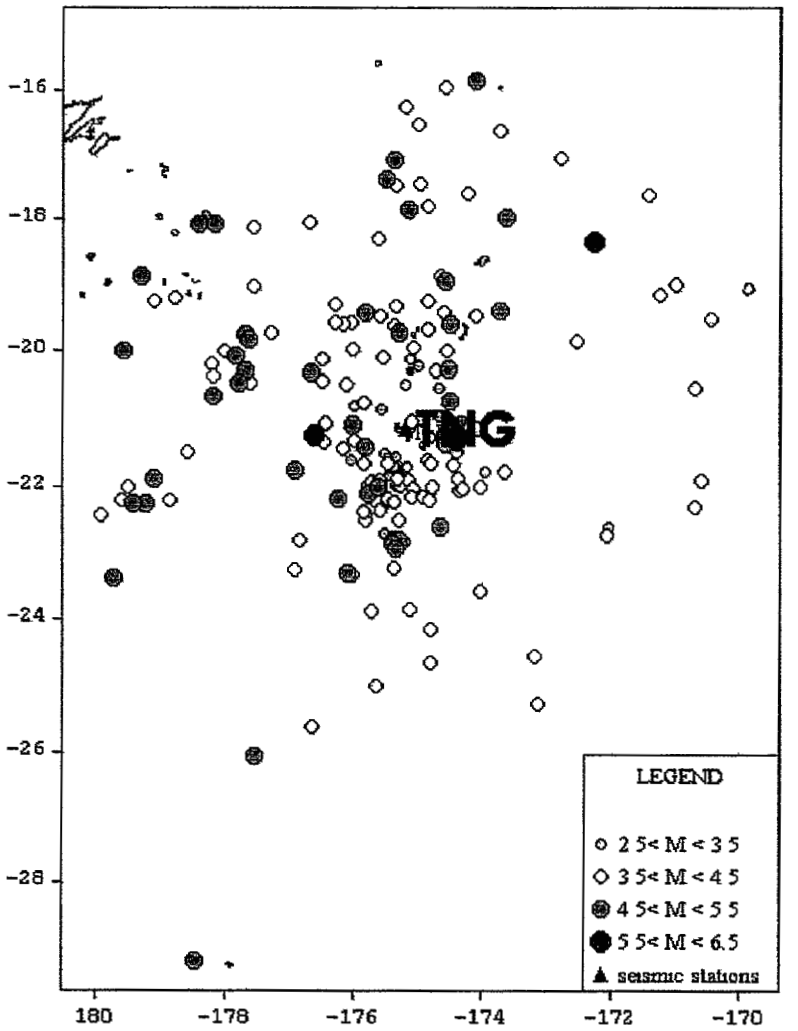
## FIGURE CAPTIONS

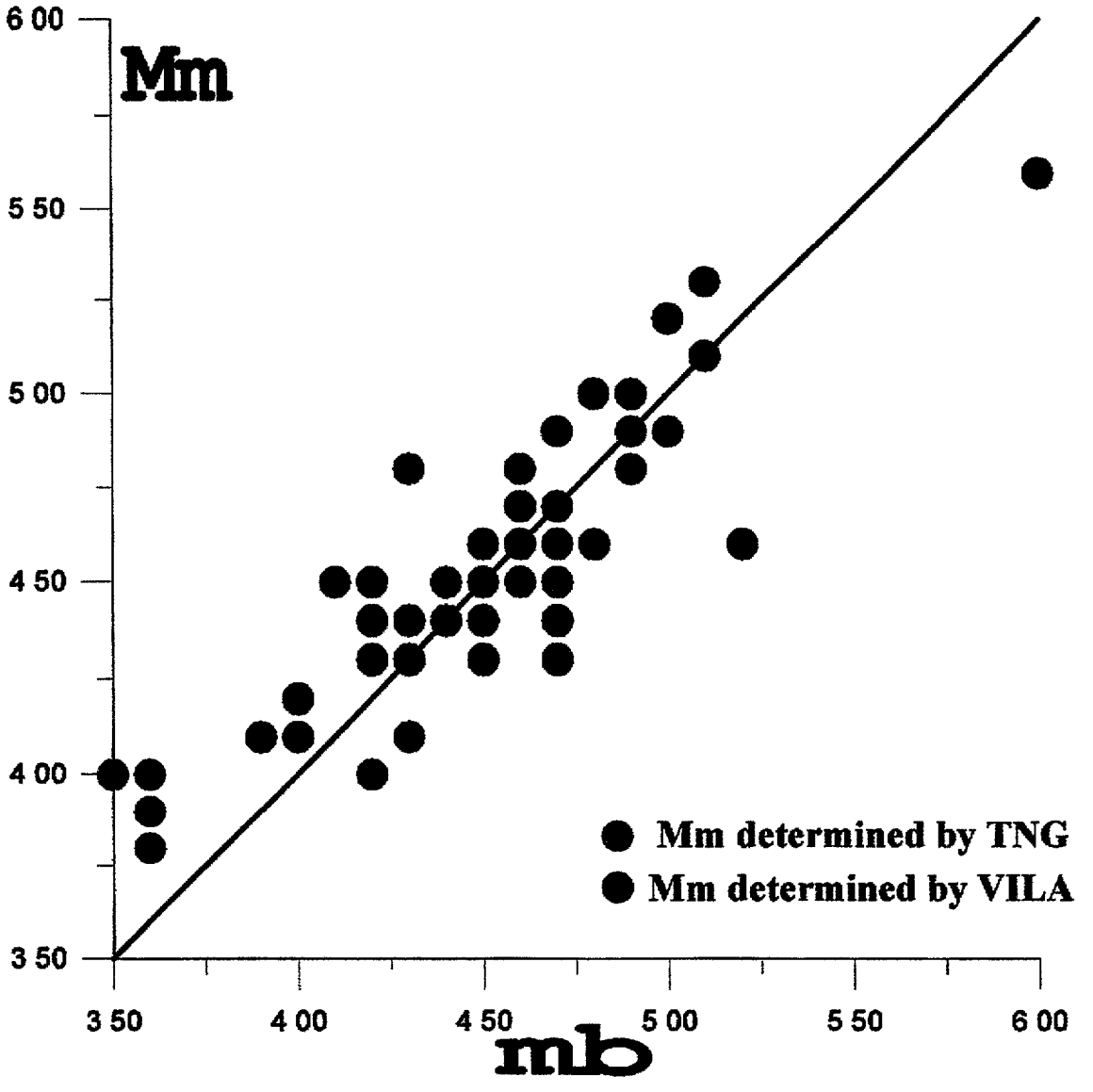
Fig 1 A typical transfer function of a seismic channel

Fig 2 Location map of the foci of earthquakes located by the TNG station

Fig 3 The correlation between Mm and mb magnitudes

65


-16
-18
-20
-22
-24
-26
-28
180
-178
-176
-174
-172
-170
TNG
LEGEND
2.5< M < 3.5
3.5< M < 4.5
4.5< M < 5.5
5.5< M < 6.5
seismic stations


Mm
6 00
5 50
5 00
4 50
4 00
3 50
3 50
4 00
4 50
5 00
5 50
6 00
mb
Mm determined by TNG
Mm determined by VILA

# APPENDIX B

# FINANCIAL REPORT

**AID Grant No TA-MOU-95-C13-024**

# ACTUAL DISBURSEMENTS REPORT
## *FINAL REPORT*

Grantee The Geophysical Institute of Israel
Grant Number AID Grant No TA-MOU-95-C13-024
Period covered by this report from January 1999 to May 1999

| BUDGET LINE ITEM | BUDGET | | DISBURSEMENTS THIS PERIOD | | CUMMULATIVE DISBURSEMENT | BALANCE |
|---|---|---|---|---|---|---|
| | PRIME | SUB | PRIME | SUB | | |
| Salaries | | 21,500 | | | 21,304 | 196 |
| Materials and Supplies | 3,000 | 3,750 | | | 3,000<br>3,750 | |
| Travel and Transport | 64,100 | 45,400 | 8,548 | | 63,108<br>45,346 | 992<br>54 |
| Equipment | | 61,500 | | | 61,500 | |
| Other indirect costs | | 750 | | | 750 | |
| **TOTAL EXPENSES** | **67,100** | **132,900** | **8,548** | | **198,758** | **1,242** |

Comments

1 Please attach a separate Request For Payment Form for each grantee!

Note All amounts in U S Dollars ($)

The undersigned hereby certifies (A) that payment of the sum claimed is proper and due and that appropriate refund to AID will be made promptly upon request in the event of disallowance of costs not reimbursable under the terms of the agreement, (B) that information on the fiscal report is correct and such detailed supporting information as AID may reasonably require will be furnished promptly to AID on request, (C) that all requirements called for under the agreement to date of this certification have been met

BY Y. Rotstein

Dr Yair Rotstein

TITLE General Manager

DATE May 18, 1999

THE GEOPHYSICAL INSTITUTE OF ISRAEL

19/5/99
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69