ANALYSIS OF EARTHQUAKE HAZARD IN PAPUA NEW GUINEA

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Declaration of the Candidate

This thesis contains no material that has been accepted for the award of any other degree or diploma in any university or institution. To the candidate's best knowledge, the thesis contains no material previously published or written by another person, except where due references have been made. The core theme of the thesis is earthquake hazard with discussions of related tectonics and seismicity, specifically that for Papua New Guinea and the region encompassing 0-12° South and 130-163° East. The ideas developed and writing up of the thesis and related papers were my own responsibility, working within the School of Geosciences under the supervision of Professor Jim Cull, and Dr. Gary Gibson of the Seismology Research Centre, Environmental Systems & Services - Melbourne.

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Abstract

Earthquake activity in Papua New Guinea (PNG) is amongst the most intense in the world. The activity is a result of the existence and interaction of lithospheric tectonic plates in the region. Within the collision zone of the major India-Australian and Pacific Plates, there exist numerous minor plates or buffer plates. Included are the well-recognised Solomon Plate that lies to the southeast, the South Bismarck Plate that lies in the centre and the North Bismarck Plate to the northwest. Further northwest and to the west of the Pacific Plate is the Caroline Plate, north of Papua Province in Indonesia. The eastern border of this plate with the Pacific or the North Bismarck Plate in PNG is not clearly defined by seismicity, which is not continuous and scattered, but shows a clear bathymetry depression indicative of a trench and thus a boundary.

In the southeast and dominating the east of the India-Australia Plate in the Solomon Islands and Bougainville Island is the Ontong Java Plateau (OJP) in the plate boundary front of the Pacific Plate. The largest in thickness and size oceanic plateau on the planet, exists as the eastern front and border of the Pacific Plate with the buffer plates existing within the collision zone with the India-Australia Plate. This huge mass of oceanic crust approached from the east-northeast, with the subduction front facing in that direction, and docked at the subduction zone thus causing a reversal of subduction polarity due to its' inability to submerge – being too buoyant. The sheer size of the plateau covers the entire eastern PNG plate front of the Pacific Plate and is currently the result of active tectonism by way of deformation due to compressional stress that is being exerted on the islands of this segment of the Melanesian Arc system. The near-vertical subduction of Solomon Plate slab, especially in the region of western Bougainville shown by the trend of earthquakes is the result of collision with the thick oceanic crust.

Within PNG and the region, research is continuing on the identification of and the actual distribution and the nature of plate boundaries, as well as the identification of deforming regions. GPS observations have made it possible for monitoring tectonic motions and regions of crustal stress, and the establishment of crustal blocks not known previously.

Earthquakes occur along most coastlines where communities have built and settled, making them vulnerable to ground shaking, and to secondary hazards in tsunamis, landslides and floods. It is therefore imperative that seismic stations deployed in the networks in the country and in the global network are maintained, not only to properly monitor earthquake activity and research in to the nature of their occurrences, but also for the long-term purposes of determination of earthquake hazard parameters resulting from improved and complete earthquake catalogues. Earthquake awareness and early warning to coastal communities does have positive benefits resulting from readily available systems for earthquake information disseminations.

Intense tectonic activity has resulted in rapid uplift rates, rapid erosion, landslides, floods and intense volcanic activity. Two tectonic events of significant effects are noted to have occurred within the region. The first was the obduction of the Papuan Ophiolites during Oligocene causing metamorphism of continental margin sediments, and second is the arc-continental collision during Pliocene, which resulted in intra-continental deformation. The effects of tectonic activity are evidenced in the landscape that was shaped by these events and exists today, and that is evolving.

As the nation of PNG develops, the dangers of living in the tectonically active region become more and more evident, and the need for improved infrastructure planning becomes apparent. The need for the revision of the existing earthquake (building) loading code seismic zoning map developed in the 1970s has been realised in recent times. The maps are noted for inadequacies, having been formulated using insufficient data, and not so compatible area/region data. The code as a result does not genuinely represent PNG conditions. Better methods for determining the seismic hazard, even with data from abroad (particularly from similar tectonic environments) are now available. This project is embarked on and based on data now existing and which can be used, making possible a review of the hazard maps. Reasons guaranteeing a useful review include the work already done to understand local seismicity, especially within the last four decades, which has led to greater understanding of one of the worlds' most active regions. Earthquakes are known to be associated with regional lithosheric plate movements, and large earthquakes are frequent, with magnitude 7.0 or larger events about two every year. The geology of the region is not only better understood, but appears to correlate well the seismicity. The existing earthquake data is used together with available regional geology, geophysics and geodesy data to assist in determining seismotectonic source zones of the region.

Shallow earthquakes posing danger and risk to existing cities, towns and infrastructure occur mainly either on plate boundaries or near plate boundaries and, also along areas of crustal deformation where stress build-up is released. In the current hazard map the highest hazard zone is that corresponding to highest activity around the northeast Solomon Sea, and the lowest hazard zone is that area in the south and southwest of PNG. However, the recognised plate boundaries and seismic zones of the Bismarck and Solomon Seas are not reflected in the old seismic zone map. It is also noted that the eastern coast Bougainville zone should be narrower as attenuation of intensity is very rapid across the Bougainville arc as shown from known isoseismal maps.

Acknowledgements

I thank Professor James Cull for his excellent supervision, commentary, guidance and management of resources during the course of the project, including at the eventual write-up of the program thesis and associated papers.

Dr. Gary Gibson of the Seismological Research Centre, Environmental Systems and Services in Melbourne was and provided the backbone of the program. His unending efforts in discussing the program schedule and directions, is evidenced in the achievements endorsed through the thesis. The end results of the work will greatly benefit PNG, both in the public and private sectors, a showcase of Gary's passion in the region that saw him through the humble beginnings of his seismological life. Gary's professional life-long colleague and a once PNG resident seismologist Kevin McCue provided invaluable commentary. I looked forward to the exchange that was on-going and wouldn't have missed it for anything.

My heart felt appreciations to Monica who's always been the strength of the family and to our children Vanessa, Keith and Tonilya for their undivided support given me in seeing the program through. To Vanessa, the most important years of her early adulthood life sacrificed with quality time spent away from her. My daughter achieved tremendously seeing herself through senior high school and first year at university, and second year at the date of the submission of the thesis.

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My institution of employment, the Port Moresby Geophysical Observatory, through the Government of PNG supported the bid for sponsorship and eventually endorsed study leave. My appreciations go to Chris McKee who persevered in his assistance drawing up the study program proposal, and who assisted throughout the duration of the program.

It is with greatest appreciation that I dedicate the thesis to my parents, Senior Anton Lolale and Ma'am Katarina Baitote of Rovan Village, Palmalmal, East New Britain Province, PNG. My parents made sure of a good education for me earlier in life, and they both had been patient with me and my own now grown-up family during these many recent years.

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Glossary of Terms and Acronyms

CTBTO – Comprehensive nuclear Test Ban Treaty Organisation based in Vienna, Austria

Earthquake – Break or rupture (sudden or slow) of rocks of the crust caused by faulting or volcanic activity. Earthquakes can occur in the near surface rocks or down to as deep as 700 km below the surface. The actual area of the earthquake is called the focus; the point on the earth's surface above the focus is called the epicentre.

Earthquake hazard – parameters indicating significance of the earthquake activity, measured in terms of return periods of magnitude, shaking or ground motion and probabilities of occurrence, and their frequencies of occurrence

ES&S – Environmental Systems and Services Pty Ltd, Melbourne

ISC – International Seismological Centre

IRIS – Incorporated Research Institutions for Seismology

Lithosphere – Crust or outer shell of the Earth, which is made up of hard brittle rocks

Lithospheric plates – Blocks of crust that make up the outer parts of the Earth, which have definite boundaries and which move relative to each other

PMGO – Port Moresby Geophysical Observatory

PNG – Papua New Guinea

SRC – Seismology Research Centre

PTWC – Pacific Tsunami Warning Centre

Tsunami – Sea waves caused by earthquake rupture of seafloor by earthquake faulting or by offshore sediment slumping during earthquake shaking. Other mechanisms of tsunami generation have been debris from volcanic eruptions or volcano cone collapse, landslides and, infrequently, spontaneous offshore sediment movement.

USGS – United States Geological Survey

WWSSN – World-Wide Standardised Seismograph Network

Chapter 1 Introduction

Papua New Guinea (PNG) is located immediately south of the Equator and northwest of the Solomon Islands, bordered in the west by the Indonesian Province of Papua and in the south by Australia. The location map of PNG in relation to the region of the southwest Pacific is shown in Figure 1.

PNG is situated within the western-south-western most segment of the Pacific Rim of Fire. Similar to any other sections of this significant circular feature running the entire length and circumference of the Pacific Basin, there exist concurrent associated geomorphological and geographical features. Such features include deep depressions offshore marking trenches, and long onshore depressions marking long valleys, steep terrains and hilly topography evidently marked by high mountain ranges, and long lines of volcanoes along volcanic arcs – here dominated by the New Guinea/Bismarck Volcanic Arc. Many of these features are delineated remarkably well by existing intense earthquake and volcano activities, particularly along and paralleling the trenches, volcanic arcs and valleys that define Quaternary faults.

The region of study, here termed the *PNG region*, is shown in Figure 2, encompassing the Papua Province of Indonesia in the west and by the Solomon Islands to the east, from 130° East to 163° East. Topographic features are shown in Figure 2 while some geographical names of the region are shown in Figure 3 and listed in Appendix 1.

Just as it is like in any regions of the Pacific and possibly the world for that matter, the accuracy of earthquake locations has improved dramatically since the 1960s after the installation of World-Wide Standardised Seismograph Network (WWSSN – short period and long period seismic stations) by the United States Geological Survey (USGS) globally. The establishment of local PNG seismic networks was even more important. As well, the enormous advances in computer technology enormously have assisted earthquake surveillance and research. These achievements have eased the identification of earthquake distributions and patterns, and aided enormously in attempts to identify seismic source zones of PNG. The interpretation of earthquakes in terms of tectonics, and earthquake source mechanisms led to identifying the structural fabric that exists.

However, the capabilities required to sustain seismic stations maintenance and continuing operation have been hindered by the lack of commitment of resources. This has led to the gradual run-down of and resulting in the eventual decommissioning of most local PNG seismic stations.

As with any seismic zones of the Pacific-rim of fire, earthquakes in the PNG region are related to local, but mostly regional tectonic kinematics. The earthquakes delineate and define quite well plate boundaries and regions of plate deformation, defining separate lithospheric plate blocks. Recent geodetics studies through GPS observations have confirmed the existence of numerous minor tectonic plates in the region, many of which were not identified in previous studies (Tregoning, 2002; Tregoning *et al.*, 1998; 1999; 2000; Tregoning and McQueen, 2001; Wallace *et al.*, 2004; 2005).

Many workers have contributed in numerous researches and investigations conducted in the region - an exceptionally intriguing and complex region of tectonics and geology. Yet, there are many more unanswered questions remaining about the complex region and research efforts in PNG are to be encouraged to find answers for them.

Earthquake hazard studies have also been attempted but these were based on limited data and, consequently, there has been limited work in the last decade or so. Hazard determination methods have now improved, especially with the advances in computer technology and the longer periods of data accumulation.

Just as important, the tectonics of the region must be appreciatively understood before the earthquake hazard can be correctly assessed. Anton, Gibson and McCue (2008) determined that the first stage of any earthquake hazard study is to develop an understanding of the tectonics and the resulting earthquake distribution of the region. The choice of tectonic model for earthquake hazard assessments in PNG may result in very different assessments of earthquake risk at any location. Relevant up-to-date data including, regional geology, geophysics, geodesy, but principally shallow seismicity have been used to justify the existing structural fabric.

The use of improved earthquake hazard analysis methods and the use of available earthquake data, with added constraint from current regional geology (including Quaternary faults), geophysics (particularly gravity, and magnetics) and geodesy, assisted the development of the source zone model. The results of the work will effectively invalidate those of earlier work and thus justifies the need for review of currently used maps, especially those in the PNG Earthquake Building (Code) Zoning for building construction.

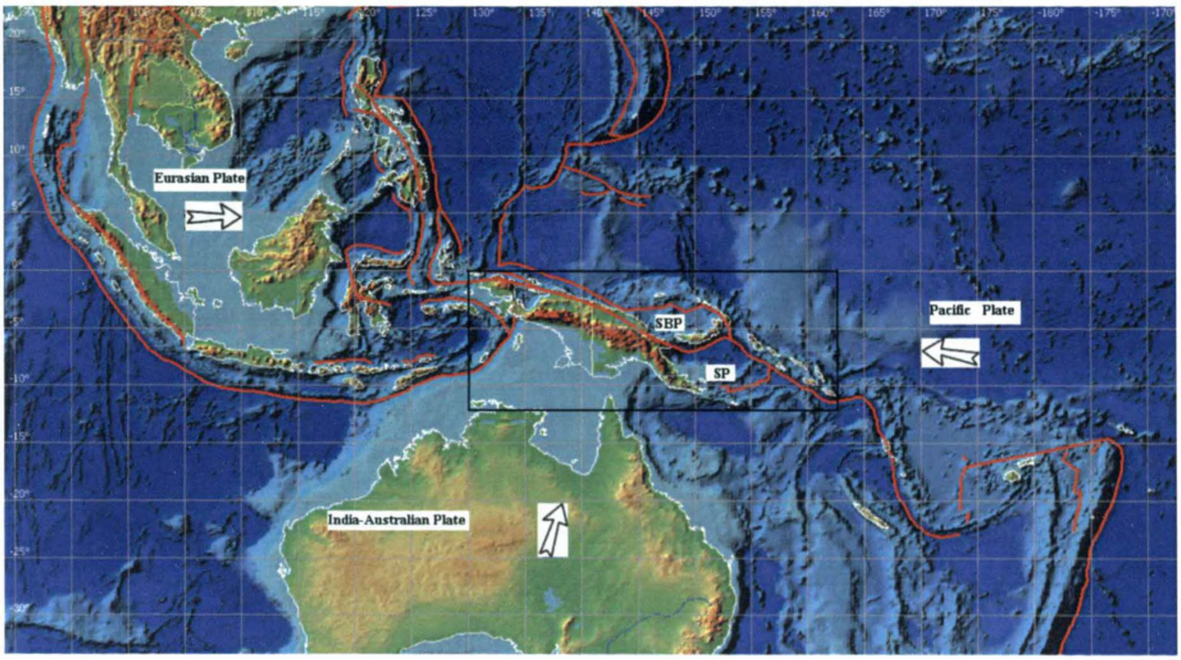

Figure 1: Locality map of the Papua New Guinea region.
The Papua New Guinea region is located area in the central rectangle, showing the relationship to the southwest Pacific region, superimposed on the tectonic plate boundaries (from USGS). SBP denotes South Bismarck Plate and SP Solomon Plate. The approach of the India-Australian Plate in the Figure is to the north-northeast, as indicated.

Tectonic activity responsible for shaping the landscape which now exists and is continually evolving is characterised not only by intense earthquake activity, but as well as volcanic activity, and associated rapid uplift, erosion, landslides and flooding. Further, rapid exhumation enhanced by rapid crustal block rotation, geological structure bending and collapse define quiet clearly the rapid intense processes that are involved. The uplift of

Pleistocene coral terraces in PNG are noted on the Huon Peninsula (Crook, 1989; Abers and McCaffrey, 1994) and uplift of coral reef complexes along the south coast of New Britain, the east coast of the Gazelle Peninsula, the southwest and northeast coasts of New Ireland, and on Buka Island (Blake, 1967; Blake and Miezitis, 1967; Brooks *et al.*, 1971; Hohnen, 1978).

Anton and McKee (2005a) noted in an analysis of the 16 November 2000 southern New Ireland magnitude Mw 8.0 great earthquake that such significant thrust earthquakes as these are indicative of ongoing uplift in recent times. This is supported by the elevation of recently formed reefs in many locations noted throughout the region of intense tectonic activity. In some locations such as at Jacquinot Bay near Pomio on the southeastern coast of New Britain, reef terraces are as much as 500 m high (Ryburn, 1974; 1975; 1976; Milsom, 1974). Typical events of uplift included that reported by Everingham (1977) who documented an earthquake related emergence at Gasmata on the southern New Britain coast during the earthquake of 02 February 1920. Anton and McKee (2005a) determined that the major earthquake (Mw 8.0) of southern New Ireland and the resulting sequence, particularly the consequent two magnitude 7 events showed under-thrusting mechanisms typical of earthquakes responsible for ongoing uplifts in the region. The earthquakes occurred hours to less then a day apart from each other, posing the question of possibly another doublet of the Solomon Sea and region. As many as five such doublets have occurred since the early 20th Century (Lay and Kanamori, 1980; Schwartz, Lay and Ruff, 1989).

In relation to the occurrences of large regional earthquakes, observation should be made of changes in the geological properties of the seismogenic regions, including the mapping of geological faults and measurement of crustal deformation using geodetic instruments and tide gauges, and using dense networks of simple seismographs to map the general seismicity. Much of these tools have been lacking and consequently, there is normally little or no proper study of such great events in the PNG region. Other observations have been identified to include continuous variations of Earth's magnetic field and electric currents in rocks, sampling of chemical and temperature fluctuations in geothermal regions, and groundwater cataloguing, and of course the study of the patterns of historical earthquakes and their cycles, as explained by Bolt (1993). Again there is a significant lack of the type of work in the region, thus making difficult a better measure of the recurrence parameters.

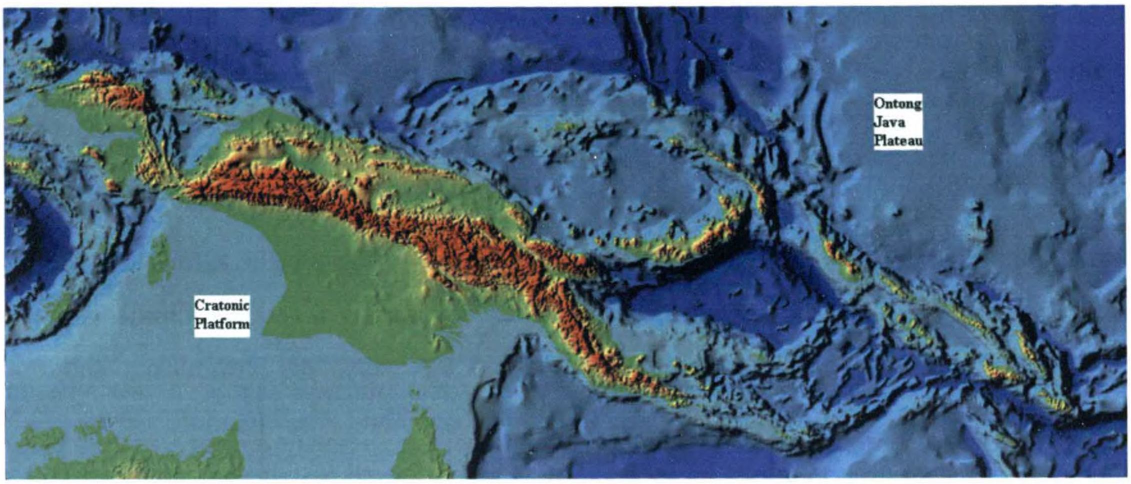

Figure 2: Topography of the PNG region.
The region considered was shown by the rectangle in Figure 1, and encompasses Papua Province of Indonesia to the west, and the Solomon Islands to the east, in the geographical region 0-12° South and 130-163° East. High topography running the length of New Guinea (shown in brown) indicates the collision zone while depressions outline boundaries of some of the many existing crustal blocks.

As efforts were made to document the effects of major earthquakes in PNG, earthquake databases for both earthquake hypocentres and earthquake intensities were established. As well as being used for research into PNG seismicity and tectonics, these databases are invaluable for determining the earthquake and related hazards, one of most significant concern being tsunami hazard. Most PNG region tsunamis are known to have been caused by earthquakes, either co-seismically or slumping caused by near shore and offshore earthquake shaking.

1.1 Objectives

The objectives of this thesis project are firstly, to evaluate and map earthquake hazard in Papua New Guinea (PNG) at different scales, utilizing data and improved methods now available; focusing on specific sites of population density and sites of important national industrial activity; and making available the results as the basis for a much-needed revision of the PNG Earthquake (Building) Code.

Further, it is the aim to develop a set of modern earthquake hazard maps of the PNG region, particularly of specific sites such as at Port Moresby, Lae, Kokopo, Madang and Wewak and; secondly, to determine the earthquake response spectra at these and other sites in the PNG region.

Overall this detailed study embarked on is aimed at providing a basis for earthquake risk mitigation in PNG. The work carried out includes developing a seismotectonic model of PNG, with consideration of tectonic processes as the cause of earthquakes and their distribution strongly influenced by regional geology and the tectonic stress field. Generally, past source models have been developed based solely on seismicity. The seismotectonic model developed here (PNG1) is based on geology, geophysics, tectonics and seismicity, all on a regional scale. The model includes information on tectonic provinces, basins and ranges, valleys and trenches, gravity, magnetics, topography, bathymetry and seismicity. Also used was a compilation of the literature of numerous studies of the region.

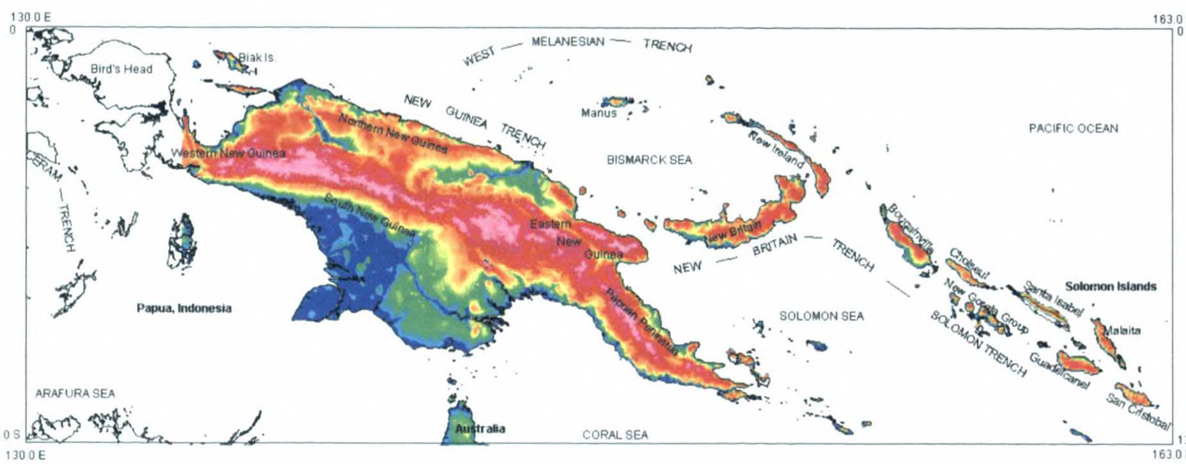

Figure 3: Geography map of the PNG region.

This encompasses the Papua Province of Indonesia, PNG and the Solomon Islands. Elevations of landmasses are greatest in red and patches of white, up to heights of 3 to 5 km (the central collisional ranges) and are lowest in blue and green (the cratonic and *foreland in the SW), and intermediate heights in orange and yellow (island arc in the N, NE and E).*

As a later component of this work it is envisaged that for site-specific earthquake hazard studies, active faulting can be incorporated to provide fault source zones. To develop an earthquake hazard map, based on a geologically defined seismotectonic model it was proposed to obtain attenuation relationships for use based on those for similar tectonic regions as strong motion data is lacking, and calculate from these the ground motion recurrences.

Finally, the earthquake hazard maps and response spectra obtained here are proposed to form the basis for a revision of the existing Earthquake (Building) Code.

1.2 Overview

It is thought that for a project whose outcome benefits of results both in public and private sectors, opportunities are abundant for earthquake hazard studies in PNG. Two choices of practical significance are those of dominantly earthquake seismology and dominantly earthquake engineering. This program focuses more of the former approach, or rather a combination with the later.

The seismology oriented projects would provide emphasise on earthquake locations, magnitudes and attenuation, catalogue, recurrence, clustering behaviour, and so forth. Engineering oriented topics include the development of seismotectonic models for hazard studies, selection of appropriate attenuation functions for ground motion recurrence calculations, and estimation of hazard for particular locations. A longer-term objective would be the development of an earthquake hazard map for PNG, replacing the very old map that is currently in use. This could eventually be a major component of a country-specific earthquake building code. Measurement of the spectral characteristics of local PNG earthquakes and site response at particular locations are other areas with associated engineering orientation.

1.2.1 The PNG (Earthquake) Building Code

Over the past few years there has been increasing use of geological and geophysical data in both seismological oriented and engineering oriented studies. This has reached the extent where it is believed that the most useful developments will involve input and understanding from seismology, engineering and geology. This therefore makes it quite necessary for studies that will benefit civil engineering and the construction fraternity, and in particular earthquake engineering. As a country that is rapidly developing economically and socially PNG would stand to benefit. Being situated in a geographically seismic intense region makes this study, like others, more than just being necessary. Studies have since been undertaken to support building codes for earthquake design of bridges (Beca *et al.*, 1976), and for buildings (Jury *et al.*, 1982). These included peak ground acceleration maps for a recurrence interval of 20 years, and a seismic zonation map based on these estimates. The hazard and vulnerability aspects of both are now in need of revision.

The 1970s studies were approved by the then PNG Department of Works and Supply. The building code was revised first in 1983, and although critically commented on by PNG based seismologists and engineers, including comments by McCue (1984), the fundamental and critical issues were not addressed and taken onboard during the review.

1.2.2 Data

The years following the development of the code saw the accumulation of data that did not exist at the time of the formulation of the code; including raw strong motion data (accelerograms) that have been obtained in PNG, including those obtained during the early 1970s, only a few of which having been analysed to date. This ideally is the basis for a revision of the code; coupled with the rapid growth of the country in all sectors, including areas of building construction and infrastructure development as towns expand, and thus the need for these services.

A large part of the PNG seismic data that has been accumulated resides in databases recently re-formatted. An extension of that re-formatting exercise was the use of the data as part of the process to determine the earthquake hazard and risk at the selected locations of the region, particularly where risk is high due to concentrations of infrastructure and population, such as in cities, towns and resource project sites.

A minimal component of this project was to initiate work on an earthquake hypocentre database that will be of benefit for use back in PNG, especially at the Port Moresby Geophysical Observatory (PMGO). The database is based mainly on catalogues from ISC, the existing PMGO catalogue (especially for magnitudes of large earthquakes, including some earthquakes that occurred prior to 1900) and the United States Geological Survey/National Earthquake Information Centre (USGS/NEIC). The PMGO catalogue is based on much research of work and records of many workers published in the literature, and also numerous local research studies for example Everingham (1974; 1977), and Ripper and Letz (1991).

1.3 The Project

In essence, the project was designed to develop a seismotectonic model that can be used with the Cornell Method to estimate the ground motion recurrence hazard, initially for major towns and sites of national resource projects, and later to produce a contour map of hazard covering all of PNG. The work will commence on Lae City, the second largest city of PNG (population, transport infrastructures, health, and education services). Lae is also a major manufacturing industrial centre, the main gateway to the highlands region of PNG for economic and social services, and a major shipping port, a hub of air services throughout PNG, and a hub of telecommunications for PNG.

As Lae City is situated on an active earthquake zone, it is no doubt that a damaging earthquake in Lae would be disastrous not only for the City of Lae but also for PNG as a whole, economically and socially.

The proposed study is to identify and confirm the potential earthquake hazards of Lae, and other sites resulting from the significantly intense tectonic activity. To fully achieve this, the work would at a later stage include identifying features, both linear and perpendicular (to the island arc) features such as faults, and the activity on or close to the faults. It would be ideal, in addition, the determination of possible ages and rate of movement on these faults and rate of uplifts, possibly uncovering palaeoseismicity and eventually analysing existing earthquake hazard, as well as landslide and flooding hazards.

Ripper and Letz (1993) determined seismic hazards of regions within PNG including Lae, and Ripper and Anton (1995) for Lae, but these studies, like many others, require updating with data that is now availability and improved methods. Further, available regional geological data as well as geophysical data combined with the seismicity data to properly determine seismotectonic zones for better earthquake hazard mapping is now possible.

The results of the study will be used to assist mitigate the potential impact of large earthquakes and resulting hazards in major sites including Port Moresby, Lae, Kokopo (Rabaul), Madang, Wewak, Kimbe, Buka and Honiara. The preliminary hazard analyses work will be extended iteratively and systematically to include other areas of the region over time. But in general, it is hoped that the foundation of the revision of the hazard map will have been established.

The program is intended to form the initial stage of the development of a seismotectonic model for earthquake hazard studies, the selection of appropriate attenuation functions for ground motion recurrence calculations, and the estimation of seismic hazard for particular locations in PNG. An intermediate goal to a longer-term objective is to develop an earthquake hazard map that will be used for a much-needed revision of the PNG Earthquake (Building) Code. The spectral characteristics of local PNG earthquakes and site response were evaluated by use of a continental (Chiou and Youngs, 2008) and a subduction (Atkinson and Boore, 2003) models arbitrarily chosen. Analysed earthquake strong motion records archived at the Port Moresby Geophysical Observatory (PMGO) in PNG, and in Australia at Geoscience Australia (GA) and the Seismology Research Centre (SRC) were too few and not used. With a few more raw data also provided by Lihir Gold Mine future plans are to determine attenuation functions suitable for PNG conditions soon.

The benefits of the project include the development of capacity in the field of earthquake seismology, and the engineering aspects of seismology. Knowledge and skills acquired will be of benefit to local and regional endeavours in areas including early warnings for tsunamis generated within PNG and elsewhere in the Pacific Basin-wide. Collaborations with experts around the region and further abroad on seismological related studies in PNG will be enhanced. The current network of local PNG seismic stations and global seismic stations existing in the region, stand a better chance of getting the attention for improved coverage. In the future, there must be improvement in the accuracy of earthquake locations, including well-determined earthquake depths. In fact this does require that the epicentre must be located within the seismograph network, and that the nearest seismograph should be as close as possible to the epicentre, relative to the depth. This makes possible the calculation of earthquake source mechanisms, and delineation of active faults, linking the seismicity to local geology and existing stress field patterns.

The production and generation of modern earthquake hazard maps will have applications in conducting awareness and education programs that will benefit many communities within areas of active earthquake zones, and in tsunami-prone coastal communities throughout the region. The building industry and town planners will benefit from the endeavours achieved in the project.

As active tectonism is responsible for intense earthquake activity and earthquake induced tsunamis, landslides and floods, the project included discussions on these associated hazards. It has to be noted that processes of mountain building and volcanic activity are true manifestations of active tectonism. While these other hazards may not be the focus of the project, earthquake hazard discussions and thus the results of the earthquake data analysis (the project output) will not be complete without these hazards being properly addressed.

1.4 Study outline

The preparation of the set of modern earthquake hazard maps of the PNG region involved:

- *Extracting data from the PMGO earthquake database, ISC and SRC, and combining that with available geological, geophysical data (e.g. gravity and geomagnetics), and geodesy, to develop maps showing the source zones (tectonic elements) of PNG earthquakes and their activity rates*
- *Analysing isoseismal maps and strong motion data to define attenuation of ground motion with distance from earthquake sources*
- *Using commercial software to grid the earthquake hazard*

The analysis software used EZ-FRISK is a commonly utilised in seismological observatories, and the licence owned by the Seismology Research Centre (SRC) at the Environmental Systems and Services (ES&S). The facilities at ES&S included computer hardware and software, apart from the analysis software. Determination of response spectra for typical rock units and soils in PNG for deep and shallow earthquakes involved:

- *Compiling relevant data on geology and geomorphology*
- *Collating all useful PNG strong motion data, and possibly digitising analogue PNG strong motion records (accelerograms)*
- *Computing response spectra at specific sites*

1.5 Earthquake hazard and associated problems

Earthquake catalogues exist for PNG commencing from about 1900, though not complete (Anton and Gibson, 2007; 2008). There is also a brief record of large earthquakes prior to this date, sourced from numerous agencies and individuals. Using data from about 1964, hypocentral distribution patterns and tectonic interpretations have improved, and in particular with the installation of local and global seismic networks. As well, very few determinations have been made of the attenuation of strong motion with distance in PNG. However, local seismic networks have not been maintained for sufficient time and therefore individual station operations not sustained. Mostly, this has been due to the lack of resource as there has been no firm commitment in this regard.

Except for the southern Papuan Peninsula (area including the national capital Port Moresby) and the southwestern part of PNG mainland (Western Province), virtually all of PNG landmasses and offshore regions have experienced earthquake occurrences. Thus as the nation continues to grow earthquake activity and the risk/hazard it poses, must be determined and considered in planning of infrastructure in cities and towns, and in the area of major national projects. While earthquake occurrence is obvious, it is important to quantify the hazard so that infrastructures can be planned adequately with earthquake-inbuilt provisions to safe guard against earthquake shaking (and possible damage) at respective locations. To achieve this, proper instrumentation of soft and strong motion recorders must be deployed. Suitable instrumentation had been lacking as a result of a lack of funding and lack of commitment from all levels of government.

The funding needed is hard to get and increases costs compared to other areas, because the region is active and geologically complex. For the most part, not one attenuation relationship suits the whole of PNG, from the few strong motion records analysed. The region is very complex with steep topography, the valleys, the trenches, the existing crustal blocks (minor plates) and faults that divide them, and heavy sediment accumulation onshore along valleys and offshore. Things can be made easier though, such as by learning from the work of very experienced institutions abroad (such as in Australia and New Zealand), and acquiring the knowledge and expertise from them through collaboration. Spence (2007) enforces this notion when discussing the benefit of sharing of resources and expertise available in the richer countries with those most in need of help, especially poorer developing countries. It is worthy of a re-emphasising of the comment that the engineering community must counter the widespread fatalistic attitude that future earthquakes are bound to be at least as destructive as those of the past.

Not enough effort has been made to sustain funding and associated resources for earthquake monitoring and research, a contribution of funds even from the public purse to fund research work that has proven globally to have economic and social implications, though not given much thought about. There are reasons for this, although not necessarily excuses. Firstly, there persists the need for adequate economic management to ensure that the benefits of abundant natural resources are properly managed. Secondly, not enough awareness has being raised at the country's top executive levels on earthquake hazard and consequent risks. An added reason may be that when a high percentage of the populace are not adequately educated about the consequences of earthquakes, poor decisions have been made about resources given to earthquake monitoring and research. Proper earthquake monitoring and hazard analysis therefore remains under-achieved, and local seismic networks become starved of proper seismic equipment and associated resources.

The opportunity made possible by the Australian Government to fund this study is being used to at least start addressing the issues, by way of the results of this project. This assistance is an indication of how the developed world embraces economic development with earthquake hazard management and related studies. The intentions to embark on the process here are not only to save life but also for economic reasons. Spence (2007) stated that such objectives are obviously to save lives and reduce the enormous cost (social and economic) of such destructive events as earthquakes, and herein earthquake-induced tsunamis, landslides and floods.

The opportunity here provides us the chance not only to assist strengthen the capabilities and capacities of the institutions responsible but for these institutions to start working on addressing the issues considered of no economically benefit for PNG. Earthquake hazard and earthquake risk mitigation is important for the fact that in a country so vulnerable to earthquake shaking and related effects, the economy of the country can collapse in a single event. Major cities and towns of PNG are not at all immune to the situation of damaging events. Significant earthquakes, earthquake-induced tsunamis, volcanic eruptions, landslides and floods are frequent. Being located in a very tectonically active region, the chances of a devastating event are always very highly likely (Anton and Gibson, 2007).

During the project, seismic hazard parameters for use at specific locations in PNG were developed and presented herein.

Chapter 2 Geology and tectonics of PNG

The Island of New Guinea was formed from the major collision of the India-Australia, Eurasia and Pacific Plates. Now embedded in the collision zone are the subsidiary Philippine and Caroline Plates (Gochioco *et al.*, 2002) in the north and west, and numerous other small plates across the collision zone to the east and southeast. Along with the formation of the island was the development of the central ranges of New Guinea Island, or the orogenic belt, about 100 km wide and 1300 km long with many peaks of over 3 km high. The orogen was developed in the middle Miocene when the northward collisional under-thrusting of the Australian continent occurred at the Melanesian Island Arc. Uplift occurred in the Pliocene-Pleistocene resulting in the formation of the highest peaks (Weiland and Cloos, 1996), within the central ranges.

About 2500 km long and 600 km wide, the island is indicative of an arched fairway formed by the Papuan Fold Belt (PFB) in PNG and the Irian Jaya Fold Belt (IJFB) in the Indonesian Province of Papua. Gochioco *et al.* (2002) observed from the unusual high-mountain region that the structural geology in the western IJFB is more complex than in the PFB. The southern half of the island is part of and has geological affinity to the northern Australian continent. The colliding plate margins have caused deformation of the crust especially the leading edge of the India-Australia Plate evidenced by the PFB and IJFB, and associated high peaks. The fold-and-thrust belts form the high mountain ranges that extend along the entire central spine of the island. The fold-and-thrust belts are thick Late Proterozoic-Tertiary sedimentary sequences that were deformed as a result of the Late Miocene-Recent arc collision with the northern Australian continental margin (Gochioco *et al.*, 2002). This central mountain range is the result of convergence of the northern margin of Australia with island arcs during the northward drift of Australia by some 3000 km during the last 37 million years (Audley-Charles, 1991). The convergence is oblique with a current collision rate of 110 mm/yr. As a result of deformation the island has been fragmented into a complex array of micro-plates, many not previously known. These buffer plates, as they are also referred to, play important roles through time, in their individual existence assisting in shaping what is physically PNG today.

The 30-25 Ma New Guinean Orogeny occurred when arc complexes, oceanic plateaux and micro-continents collided with the northern margin of the Australian Plate (Pigram & Davies, 1987; Hall, 1996; 2002). These and many other workers have especially considered the collision between the buoyant 130–110 Ma Ontong Java Plateau along the northeastern margin of the Australian Plate at 6 Ma as the most having significant event in the region. At the margin this massive oceanic plateau jammed the subduction system resulting in forcefully reorganizing global plate kinematics (Betts *et al.*, 2002).

North of the northern continental margin, Crowhurst *et al.* (1996) inferred that north-dipping subduction occurred beneath islands of the Melanesian Arc, and subsequently arc accretion by the Late Oligocene. Fold and thrust belt developed as a result during about the Pliocene (8–5 Ma) and was followed by transgression (Hall, 1996).

Hill *et al.* (1993) inferred a south-dipping subduction beneath continental crust, and Crowhurst *et al.* (1996) interpreted the development of metamorphic core complexes, and associated starvation of sedimentary basins as a consequent of retreating subduction that was responsible for extending the overriding plate during the Early Miocene.

The mechanism operating in trench arc-back arc systems is normally dominated by subduction of oceanic lithosphere, typically fitting the tectonic framework that dominates the PNG region. It is now becoming apparent of the relationships that are responsible for sea floor spreading and consequently back-arc basin development. Through GPS observations, plate rotation is now coupled with subduction within existing tectonic framework as the initiating mechanisms to account for regions of sea floor spreading. Two regions of such nature exist within PNG. These are the Manus and Woodlark Basins developed by subduction at the New Britain Trench, and rotations of the South Bismarck Plate (clockwise) and Solomon Plate (counter clockwise) respectively (Tregoning and McQueen, 2001). It is also questioned whether the subduction model can explain all the major features of the trench-arc-back arc systems (Uyeda, 1981). In the subduction zone are thrust type inter-plate earthquakes and deep earthquakes along Wadati-Benioff zones, and the occurrences of extensional spreading and high heat flow in the back arc region is evidenced by active associated volcanism.

The world's subduction zones can be classified as either causing compressional stress regime in the arc and back are regions, or causing tensional stress Uyeda (1981). In PNG, the New Britain region has been identified as strongly extensional with back arc spreading (Jarrard, 1986), with the overlying South Bismarck Plate of the subduction system retreated away from the New Britain Trench (Ripper *et al.*, 1996). The New Britain subduction system is generating seafloor spreading and thus opening the back arc basins in the Bismarck and the Woodlark Seas. Schellart *et al.* (2007) proposes this as being a consequence of the faster rate of plate edge retreat, along the New Britain segment of the Melanesian Subduction Zone.

Pre-Neogene orogenic belts in the region have each preserved a record of major changes in tectonics including subduction polarity reversals, elimination of volcanic arcs, changing plate boundaries, and extension within an overall contractional setting. Rapid tectonic changes were proposed by (Hall and Wilson, 2000) to have occurred within periods of less than 5 million years.

2.1 Structural fabric

Lying parallel to the India-Australia/Pacific plate boundary are two prominent mountain ranges. The first, and located in the north, is the western segment of the Melanesian Island Arc system, is a discontinuous alignment of arc terranes. Currently active, especially to the east in the Solomon Sea, the arc system indicates that the northern range formed as the arc terranes collided very obliquely with the India-Australia Plate margin beginning about early Pliocene (Silver *et al.*, 1991; Pubellier and Ego, 2002; van Ufford and Cloos, 2005).

The second prominent mountain range is the southern New Guinea Highlands fold-and-thrust belt. The fold-and-thrust belt was a result of two separate tectonic events. The first involved the obduction of the Papuan ophiolites during Oligocene, resulting in the metamorphism of the continental margin sediments (Davies, 1971; Davies, 1980; Davies, 1981; Davies, 1990; Davies and Smith, 1971; Davies *et al.*, 1984; Davies *et al.*, 1996; Dow *et al.*, 1988; Lus *et al.*, 2004; Pubellier and Ego, 2002; van Ufford and Cloos, 2005).

The second event involved arc-continent collision, which caused intra-continental deformation responsible for the production of prominent features in the Pliocene to the Present (Dewey and Bird, 1970; Cooper and Taylor, 1987; Kulig *et al.*, 1993; McCaffrey, 1996; Pubellier and Ego, 2002; van Ufford and Cloos, 2005). Detachment and uplift of the fold-and-thrust belt and reactivation of the thrust front of the fold belt are manifestations of these events. In particular, the large shear connecting to the Tarera fault and further west to the Seram Trench (Abers and McCaffrey, 1988).

Several distinct geological provinces have been identified in PNG, basically defined by the existing structural fabric. Davies (1990) noted these as, firstly the south-western continental (Australian) craton or platform – a stable zone, and secondly the central collision zone also known as the mobile belt – the orogenesis or a zone of rapid mountain building, and thirdly the north-eastern volcanic islands zone – a zone of young (Quaternary to Tertiary) volcanic intrusions, and associated limestone deposits and coral reef terraces. Figure 4 (Audley-Charles, 1991) and Figure 5 (Mann and Taira, 2004) show the regions of these respective geological provinces.

Hill *et al.* (2002) noted that Neogene orogenesis created four tectonic belts of the New Guinea Orogen, which are from north to south, the Accreted Palaeogene Volcanic Arc; the Mobile Belt; the Fold-and-thrust Belt; and the Stable Platform. A five-stage Neogene–Holocene evolution of the New Guinea was also proposed (summarized in their Figures 2.1a and 2.1b).

The New Guinea orogen docked with the Australian craton 9-10 Ma (Pigram and Davies, 1987) at about the time subduction at the New Guinea Trench began (Tregoning and Gorbatov, 2004). In the west, the Caroline Arc has accreted to the New Guinea margin while across the region in the east, the subduction of the Ontong Java Plateau (OJP) beneath the Solomon Arc has locked up. The Ontong Java Plateau (OJP) arrived at the West Melanesian Trench 25-20 Ma, in what was termed "soft docking", but experienced "hard docking" or forceful collision only about 4-2 Ma, and has been actively accreting since. Prior to hard docking, about 12-6 Ma the southwest-directed subduction reversed polarity, initiating arc volcanism and northeast subduction (Yan and Kroenke, 1993; Mann, 1997; Petterson *et al.*, 1999; Mann and Taira, 2004).

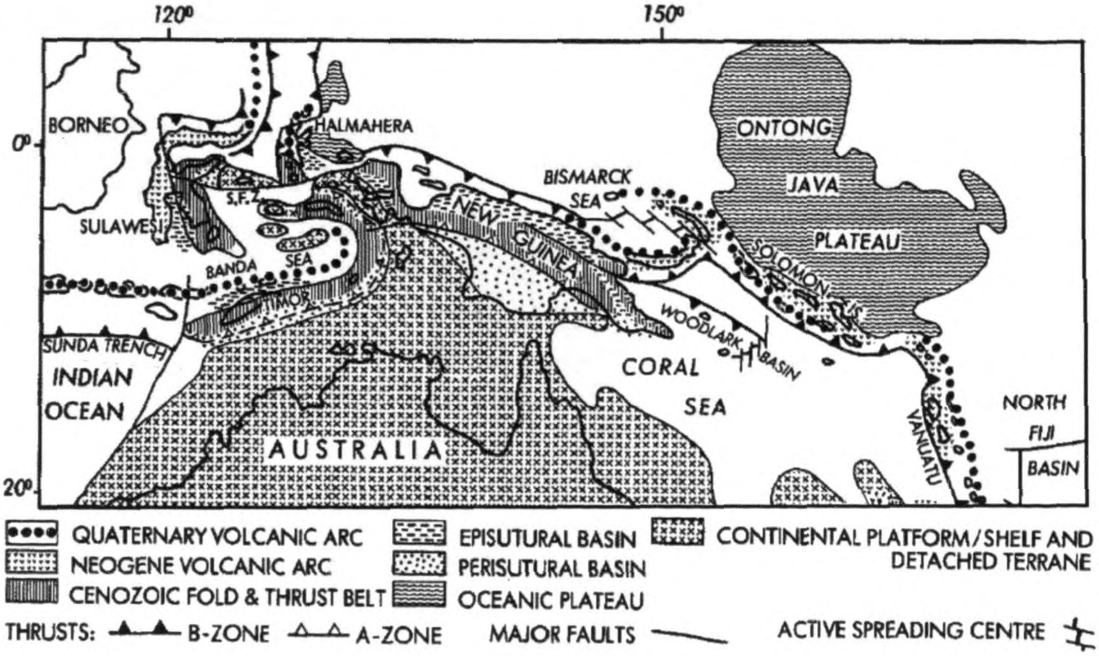

Figure 4: Geological provinces of the PNG region.
The three geologic provinces (modified from Audley-Charles, 1991) are the southwestern stable or cratonic zone (denoted by continental platform), the central collisional zone or mobile belt (Cenozoic Fold and Thrust Belt), and northeastern volcanic islands zone (Neogene-Quaternary volcanic arcs). SFZ denotes Sorong Fault Zone.

Neogene convergence in the region involves the New Guinea–Bismarck Sea–Solomon Sea in between the 50 km thick India-Australia Plate and the 33 km thick OJP, as shown in Figure 5 (from Mann, 1997; Mann and Taira, 2004). In the region of the converging India-Australia and Pacific Plates are several minor plates isolated by back-arc spreading or convergence. The Solomon, North and South Bismarck Plates are interacting within the collision zone of the two large plates and their motions have been modelled through geodetic observations using GPS (Tregoning, 2004; Tregoning *et al.*, 1998). There is evidence of numerous other crustal blocks not recognised previously, for example Wallace *et al.* (2004), Wallace *et al.* (2005), Bird (2003) and Anton, Gibson and McCue (2008).

The PNG region is indeed a region of intense activity, the region of collision of the major plates buffered by numerous tectonic blocks – characterised by structural complexity, consequently resulting in the higher levels of seismicity and volcanism, and rapid evolution of the boundaries of plate involved (Honza *et al.*, 1987).

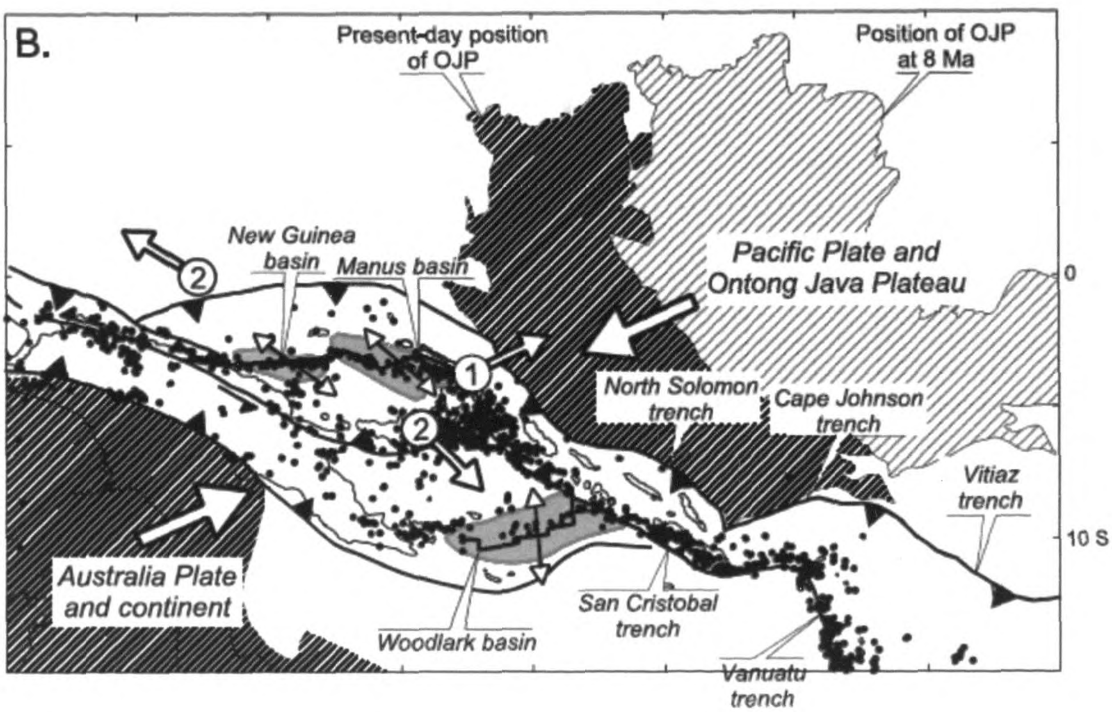

Figure 5: Tectonic plate motion in the PNG region.
The map shows the region of convergence of the massive continental Australian Plate and the thick Ontong Java Plateau (Figure 7B from Mann and Taira, 2004). Labels and signs correspond to their observations.

2.1.1 The stable continental craton

This is the zone in the far southwest of PNG and the northeastern most part of the Australian continental, the continental platform. The zone is stable in that it is relatively free of earthquake activity, and therefore void of present-day mountain ranges that result from mountain-building processes, which include volcanic activity.

The New Guinea region contains the northern margin of the Australian craton. Within the region the India-Australia Plate has undergone oblique convergence with the Pacific and Philippine–Caroline Plates, immediately east and west of PNG respectively, at least since the Eocene. As a result of the collision a number of oceanic and/or arc terranes have accreted to the New Guinea margin (Struckmeyer *et al.*, 1993; Hall, 1996) resulting in the current active margin tectonics and associated activity (Page 1976; Hill *et al.*, 2002).

The geology, especially ages and contents of rocks, have close affinity to those of northeastern Queensland. PNG central highlands blocks, particularly the Kubor and Bena Bena Blocks, form part of the Australian craton margin, modified by rifting during the Mesozoic and re-inverted during Cenozoic compression. Van Wyck and Williams (2002) have also noted the Australian craton exposures in the highlands of PNG, as far north as the Markham Valley.

2.1.2 The mobile or orogenic belt

The mobile belt includes the PNG central highlands region, where the oldest rocks making up the Kubor Metamorphics are much younger than those of the Australian craton. Fragments of cratonic rocks are traced widely, as far wide and northwest as the Sepik region and compare very well with rocks of the stable Australian continental craton.

The central New Guinea mountain belt appears simpler than the extremities, especially the western end where blocks of lithosphere have escaped, thus escape tectonics (Pubellier and Ego, 2002), referring to the lateral motion of the Bird's Head crustal block away from the main strain axis.

The Kubor Range (composed of the Kubor Metamorphics) forms the mountain range that is the backbone of the mainland PNG. The range is the result of the continuing collision of the major India-Australia and Pacific Plates in the PNG region. The plate front is being folded and faulted, and pushed up creating the mountain ranges in the central PNG highlands region. This process is being facilitated and evidenced by the occurrence of earthquakes, especially in the southern Highlands and central Highlands where compressional stresses have propagated towards the southwest. To the north, the rugged accreted parts of the collided arc have exposures of these igneous and metamorphic rocks (Milsom, 1973; 1985).

In the eastern PNG highlands, the Australian craton extends at least as far north as the Markham Valley, the northern edge of the central terrane (Wyck and Williams, 2002), and possibly the northern boundary of the mobile belt.

2.1.3 The north-eastern volcanic islands zone

The youngest of the rocks consists of the volcanics are found in the northeastern part of the country, are made up of the Quaternary to Tertiary volcanic island arcs. The volcanics are of Eocene age and are mostly overlain by uplifted Miocene coral and limestone. The rocks are typically Eocene and younger arc type volcanics basement of the Melanesian arcs (Honza *et al.*, 1987), in the region covering the southwest Pacific including Solomon Islands, PNG, and Halmahera in Indonesia.

Regarding the Bismarck Sea opening, models generally only account for the last 3.5 Ma while little is known of the tectonic evolution since the Upper Eocene. Lindley (2006) suggested from the presence of extensive Miocene platform carbonate that New Ireland and New Britain have experienced only gentle tilting and uniform uplift even though being located in tectonically dynamic areas. In the volcanic islands zone, Eocene and Oligocene volcanoclastics and intrusions are unconformably overlain by large slabs of Miocene platform carbonate.

This is the region of plate extension, evidenced by zones of seafloor spreading and back-arc basins. The two zones of significant seafloor spreading are the Woodlark Basin in the Solomon Sea and Manus Basin in the Bismarck Sea, and continental rifting in the southeastern Papuan Peninsula.

The Woodlark Basin is postulated by Martinez *et al.* (1999) to be young (6 Ma), formed by seafloor spreading following continental rifting of the Australian passive margin in late Miocene. This basin forming period was followed by an earlier period of continental collision with arc lithosphere in the region west of Woodlark Basin. The Papuan Ultramafic Body or Ophiolites of the Papuan Peninsula are manifestation of obduction during collision in early Miocene (Little *et al.*, 2007).

Similar to other regions of the western Pacific margin, including Solomon Islands to the southeast, PNG and Halmahera to the west in Indonesia (Honza *et al.*, 1987), convergences during the Eocene faced the Pacific Plate with the subduction facing westward or southward. These plate boundary configurations have changed and subduction directions changed as margins evolved.

2.2 Seismotectonics

The structural configuration is dominated by the presence of the two major tectonic plates of the Pacific and India-Australian Plates, on a collision course within the PNG region, with the near-stationary Eurasian Plate in the west. The azimuths of approach are WSW for the Pacific Plate that is dominated by the OJP in the northeast, and NNE for the India-Australian Plate in the south-southwest. The pole of rotation was first given by Le Pichon (1968, 1970) as 51.1°S, 161.1°E. This was modified by Chase (1978) to 62.0°S, 174.3°E, collision rate 12.72 $\times 10^{-7}$ degrees/year, which transforms to a collision rate of approximately 13 cm/yr at an azimuth of 072° at the northern coast of New Guinea. Tregoning *et al.* (1998) re-defined the approach of the Pacific Plate as at 13 cm per year at an azimuth of 316°.

Recent and follow-up GPS observations have improved and redefined much of plate movements in PNG and region (Tregoning *et al.*, 1998; Tregoning *et al*, 1999; Tregoning *et al.*, 2000; Tregoning and McQueen, 2001; Wallace *et al.*, 2004; Wallace *et al.*, 2005).

The collision zone of these major plates is buffered by several minor plates that lie in a NW-SE trend within PNG, including from the southeast the Solomon Plate, South Bismarck Plate, North Bismarck Plate to the Caroline Plate in the northwest and outside of the PNG region. The existence of several more other are suggested, for example Bird (2003), Anton *et al.* (2008), and Wallace *et al.* (2004, 2005). The North Bismarck Plate was long postulated. Relatively low levels of earthquake activity prevail at the boundaries between the Pacific, North Bismarck and Caroline plates, being remnants of mid-Tertiary activity, so that for present purposes the North Bismarck and Caroline plates can be regarded as parts of the Pacific Plate. Although seismically less intense, the region is active (McCue, 1988) and outlined by a pronounced bathymetric depression, and described as the deforming front of the Pacific Plate (Ripper, Letz and Anton, 1996). Weissel and Anderson

(1978) suggested the existence of a North Bismarck Plate, but Curtis (1973), Kraus (1973) and Taylor (1979) didn't concur. Tregoning (2002) claimed that the geodetic data confirms the existence of a North Bismarck Plate.

Based on the Le Pichon (1968) plate rotation model, and assuming internal minor plate rigidity, Johnson and Molnar (1972) determined relative plate motions of the plates in the PNG region. They determined that at the northern margin of eastern New Guinea, the India-Australia Plate and the South Bismarck Plate are colliding at the relatively slow rate of 3.3 cm/yr on an azimuth of 023° (NNE-SSW).

Surface evidence of convergence in this region is the migration of crustal folding and thrusting, more than 300 km from the northern coast of New Guinea to the region of the Papuan Fold Belt in PNG and Irian Jaya Fold Belt in Papua, Indonesia. The northwest-southeast striking features are the result of internal deformation of the India-Australia Plate front due to intense convergence across New Guinea. The seismic zone is proposed to serve as the southern boundary of the proposed New Guinea Highlands lithospheric block (Wallace *et al.*, 2004; Anton, Gibson and McCue, 2008; I.D. Ripper per. communication).

While it may be the collision of the major Pacific and India-Australia Plates that is the ultimate cause of all the seismotectonic activity of the PNG region, the annihilation of the Solomon Plate out of the region has intensified and complicated activity. Micro-plate motion and/or rotation occurs thus generating back-arc spreading and associated transpressional activity responsible for marginal extensions in the Bismarck and Solomon Seas. The New Britain region has been suggested to undergo extension (Lindley, 1988; Lindley 2006; Ripper *et al.*, 1996), for example as evidenced, by the generation mechanism of the central New Britain earthquake of 1985 (Mori *et al.*, 1987).

Wallace *et al.* (2004) first proposed the new, New Guinea Highlands Block (NGHB) but did not demarcate it from other prominent blocks existing in the region, for example the Bismarck Sea blocks. Many workers actually declined to admit the existence of the North Bismarck Plate. What then is the source of the seismic activity? Is there really a North Bismarck Plate? Geodesy data through GSP measurements is revealing aspects of crustal blocks not previously recognised, as mentioned previously for example the existence of the NBP (Tregoning, 2002), and the NGHB (Wallace *et al.*, 2004).

2.2.1 Lithospheric Plates

An example of a tectonic plate configuration model of the PNG region is shown in Figure 6 (Ripper and Letz, 1991; 1993). This one is based on shallow seismicity and possibly topography. The azimuths of the motions of the major India-Australia and Pacific Plates are northeast and west-northwest respectively. Within the collision zone there exist numerous minor plates. An example of these is the Solomon Plate, which lies to the southeast and is subducting north-northwestwards beneath the New Britain plate front of the South Bismarck Plate. The South Bismarck plate, which lies in the centre, is in turn advancing southeastward.

The Solomon Plate is also subducting beneath the northeastern mainland PNG (Pegler *et al.*, 1995), and sinking westward, as far west as 142°E and possibly further west (Ripper *et al.*, 1996). As well, the Solomon Plate is subducting northward and arching in the region of southern/central New Ireland, and also subducting northeast beneath Bougainville front of the Pacific Plate.

With the southeastward advance of the South Bismarck Plate at the New Britain subduction front, the Bismarck Sea is being pulled open to form the back-arc basin, i.e. the Manus Basin. Earthquake activity on the spread zone indicate left-lateral strike-slip movements with evidence of off-set transform faulting especially in the eastern end, with associated normal faulting, typical of extensional plate boundary earthquakes.

Likewise, the Solomon Plate is being pulled forward to the northwest by its own sinking beneath New Britain, pulling open the Woodlark Sea and creating the Woodlark Basin. Earthquake activity in the Woodlark Basin indicates normal and strike-slip faulting within the east-west trending seismic zone, again typical of extensional plate boundary activity. It has been suggested that a notable feature of the Bismarck-Woodlark region is the rapid changes in tectonic boundaries during the last 5-6 Ma.

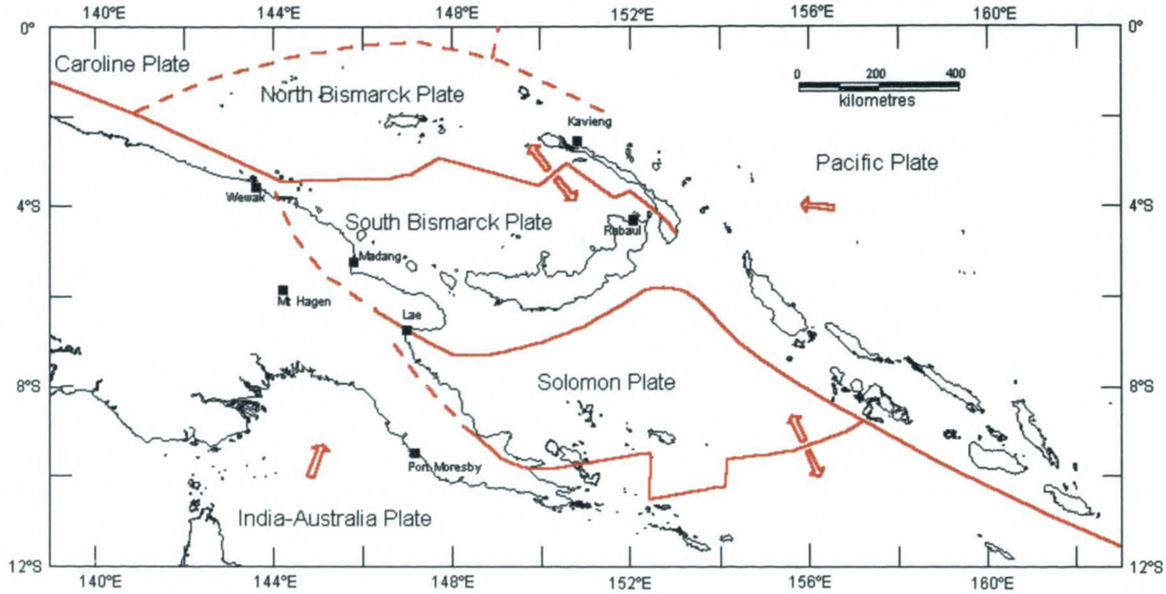

Figure 6: Tectonic configuration of PNG.

The map shows the main tectonic boundaries of the PNG region, the tectonic plates, and their relative direction of motion (from PMGO; Ripper and Letz, 1991; 1993).

Using this model, it is possible there are more than six separate plates exist in the region, between the West Melanesian (Manus) Trench in the northwest and the Pocklington Trough in the southeast. From geodetic observations through GPS measurements (Tregoning *et al.*, 1998) have confirmed the existence of the North Bismarck, South Bismarck, Solomon and Woodlark Plates. Manus (Melanesian) Trench and Trobriand Trough are possibly relics of former plate boundaries. Many more lithospheric blocks existing in the region have gone unrecognized but improvement in GPS observations is helping the discovery of them.

2.3 Seismic source zones

There are numerous other distinct tectonic blocks existing in the PNG region, within the collision zone between the Australia-India and Pacific Plates amongst the many now known, such as the New Guinea Highlands Block (Wallace *et al.*, 2004; Anton, Gibson and McCue, 2008). The model of the tectonic plates shown in Figure 7 was developed based on many known models, for example Bird (2003), and from the literature and available data (Anton, Gibson and McCue, 2008).

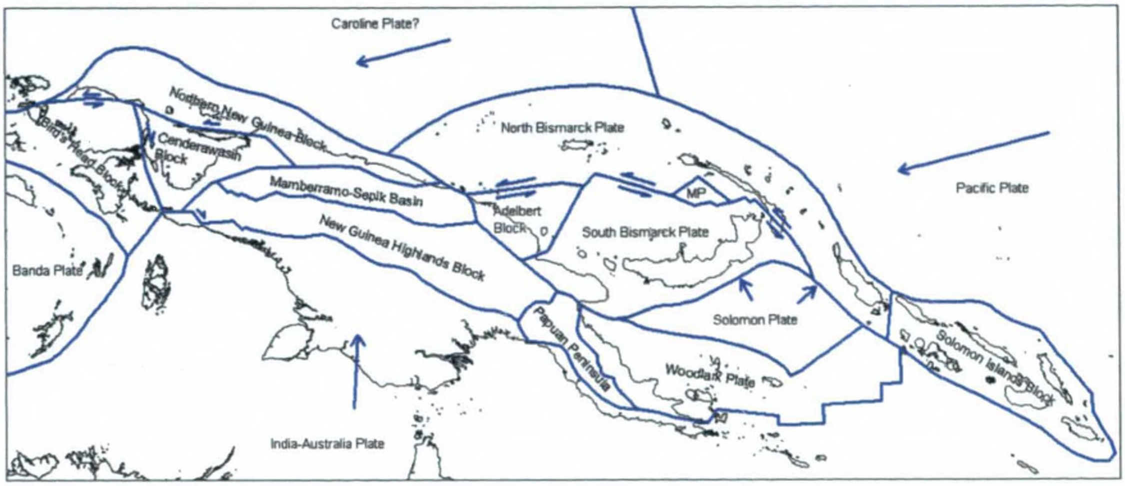

Figure 7: Detailed tectonic map of the PNG region.

Detailed tectonic map the PNG region (Anton, Gibson and McCue, 2008), their Figure 4 with corresponding labels and direction of motion of plates.

GPS data in recent times have assisted refine past investigation findings. The GPS-derived velocities are used to explain the kinematics of major tectonic blocks in the region and the nature of strain accumulation on major faults in PNG (Wallace *et al.*, 2004). Recent observations have redefined the structural configuration in the region, shown for example in Figure 7.

On-going seismological studies are revealing the geological structure and dynamics of the PNG region on both large and smaller scales. The boundaries of the lithospheric plates in the PNG region are becoming clearer although some boundaries remain uncertain. The nature of the processes at the plate boundaries are also being revealed by these many studies, in recent times and by geodesy observations.

The PNG region is a natural laboratory, including all aspects of geology and geophysics, particularly seismology. Earthquakes and related activity, such as that associated with crustal deformation on plate fronts and boundaries along volcanic arcs within the existing tectonic structural arrangement, involve most earthquake generation mechanisms. The plate tectonic configuration and elements responsible for the earthquake generation do in fact compare well with any others identified elsewhere around the globe, regardless of the size of these existing tectonic structural elements.

Audley-Charles (1991) claimed the New Guinea region as the world's outstanding field laboratory for studying active tectonic processes where consequences of convergent plate movements are exceptionally well displayed. Here volcanic arcs expose a very wide range of development and active spreading in back-arc basins is evident from basins, such as the Manus and Woodlark Basin.

The main seismic zone occupies the northern half of mainland PNG, which extends east to include New Britain, southern New Ireland and southeast to Bougainville, extending further southeast through to the Solomon Islands, and beyond.

The Solomon Plate is being pulled forward to the northwest by its own sinking (subduction) beneath New Britain, opening the Woodlark Basin in southeastern PNG. Activity there is evidenced by normal and strike-slip faulting within the east-west trending seismic zone. These two seismic zones are connected to the main zone, which include zones of extensional and transform faulting trending east-west across the Bismarck and Solomon Seas respectively. The Solomon Sea seismic zone continues northwestward along the Papuan Peninsula and links up with the main seismic zone near to Lae. The Bismarck Sea seismic zone connects the main seismic zone near Wewak in the west, and southern New Ireland in the east.

The other seismic zone is the one trending northwest-southeast along the entire southern highlands of PNG. Ripper and McCue (1981a, 1983) noted that the earthquakes here are caused by folding and thrusting of the India-Australia Plate front due to its collision with the South Bismarck Plate.

As well, the Solomon Plate is sinking westwards beneath northern New Guinea to 142°E and possibly further west of 142°E, evidenced by intermediate depth (150 km) earthquakes (Pegler *et al.*, 1995; Ripper *et al.*, 1996). These intermediate depth earthquakes are different to those of northern mainland PNG and thus form a separate seismic zone.

GPS has been used as a tool for monitoring tectonic motion, with now an extensive database of geodetic observations since the 1990s (McClusky *et al.*, 1994; Stevens *et al.*, 1998; Tregoning *et al.*, 1998; Tregoning *et al.*, 1999; Tregoning *et al.*, 2000). The rapid clockwise rotation of the South Bismarck Plate as proposed by Wallace *et al.* (2004) is controlled by edge forces initiated by the collision between the Finisterre arc and the New

Guinea Highlands. Further, the pole of rotation of the South Bismarck Plate is determined to be vertical and located within the region. Binns (2004) furthered this notion by suggesting that the South Bismarck and Solomon micro-plates are rotating clockwise and anticlockwise, respectively, and converge by rollback subduction on the active New Britain Trench. It can be envisaged that plate edge retreat at this end of the Melanesian Subduction Zone system (Schellart *et al.*, 2007) is having an impact as to the existing plate boundary styles and their continuing evolution in the PNG region.

Wallace *et al.* (2005) documented a clear link between convergent plate boundary micro-plate rotation of the South Bismarck Plate and extension in the Manus Basin back-arc region, and suggested that the torque exerted on the micro-plate by an along-strike change in the subducting Solomon Plate buoyancy does actually trigger localised extension in the back-arc.

Seismic zones can also be identified by associating them with a specific structural province and to a cluster of shallow earthquakes, such as those defined for the western New Guinea Island. Pubellier and Ego (2002) identified nine areas in and around the Papua Province based on this method, where in each area fault plane solutions were inverted for stress and moment tensors summed to estimate strain rates. Identification of other zones in the PNG region is also based on known geological features such as faults, marked by trenches, mountain ranges, and areas of obvious significant topography and morphology, and abnormalities (significant changes) noted in gravity and magnetic data. The discussions of these are outlined as follows.

2.3.1 Southern New Ireland – Eastern New Britain region

Within this region, the Solomon Plate is subducting and arching beneath southern and central New Ireland, and also subducting beneath New Britain.

As the Solomon Plate subducts north-northwestwards, the New Britain plate front of the South Bismarck Plate in turn advances southeastward. Marked by the New Britain Trench, the subduction rate is rapid. The convergence rates have been determined and re-defined by many workers. Krause (1973) and Curtis (1973) suggested increasing rates along the trench to the northeast in the range 6.4 cm/year to 12.5 cm/year.

Uplifted Tertiary limestone and volcanics on New Britain occurred where the island mountain chain terminates at about 149°E (Ripper, Letz and Anton, 1996), but the volcanic arc continues northwestwards along the northern coast of New Guinea.

Three shallow seismic zones are juxtaposed in the region. They are firstly, the zone associated with the subduction of the Solomon Plate beneath Bougainville, which extends on a northwest trend beneath the Solomon Sea off the Bougainville coast and southern New Ireland. Secondly, the zone associated with the subduction of the Solomon Plate beneath New Britain, which extends on a northeast trend past the Solomon Sea coast of New Britain to southern New Ireland. And thirdly, the zone associated with the northwestward movement of the New Ireland part of the Pacific Plate past the eastern New Britain part of the south Bismarck Plate, or the strike-slip plate boundary, extending from southern New Ireland northwestward through St. Georges Channel, with some earthquakes occurring beneath northeastern Gazelle Peninsula.

The intense activity, dominated by thrusting and dip-slip movements, results from the interactions of three lithospheric plates in the vicinity of their triple junction that is located under the northern part of the Solomon Sea as postulated by Gaull (1979). The precise location of the triple junction is somewhat uncertain because one of the plate boundaries, between the Pacific and South Bismarck Plates, is not clearly defined – it may in fact be a broad zone plate boundary. The Weitin and Sapom Faults of southern New Ireland may well be part of that system. The New Britain Trench is a clear indication of the locations of the other two plate boundaries in the region – the southwest and southeast trending arms of the trench. The axis of the trench marks the southeastern and southwestern limits of the South Bismarck and Pacific Plates respectively in this region, and the northeastern and northwestern surficial limits of the Solomon Plate. The bend in the trend of the trench marks the general vicinity of the triple junction.

2.3.2 Huon Peninsula – Papuan Peninsula region

Tiffin *et al.* (1987) postulated that the New Britain Island and the Huon-Finisterre-Adelbert area of northern PNG were once a part of the West Melanesian Arc, contiguous with New Ireland and Manus islands. Their structural, stratigraphic, and age similarities compare quite well with those of the islands of the arc.

Three tectonic plates, shown by shallow seismic zones, converge to form a triple junction in the vicinity of Lae. Figure 6 and Figure 7 show Lae and other locations of PNG, in relation to the tectonic plates of Ripper and Letz (1991; 1993) and Anton *et al.* (2008) respectively.

Three earthquake zones thus converge in the region of Lae, delineating respective plate boundaries. The first is the seismicity beneath the New Britain Trench, NE of Lae, due to subduction of Solomon Plate beneath the New Britain front of the Bismarck Plate. The second is the seismicity being caused by the collision of the Australia-India and South Bismarck Plates NW of Lae, and the third is the seismicity extending SE along the Papuan Peninsula from Lae. Investigations such as by Abers and McCaffrey (1988), Copper and Taylor (1987), Davies (1990), Milsom (1981), and Johnson and Molnar (1972), have all given insights to the seismicity, tectonics and geology of the Huon Peninsula. There is new data available and many of these works do need revisiting. Cross-arc features, possibly geological faults that are shallow and trend perpendicular to the island arc system which Huon Peninsula is part of needs further investigation. These features are possible candidates for locations of future large shallow earthquakes, and need to be identified.

Apart from the shallow earthquakes, there are intermediate and deep earthquakes beneath and west of Lae originating from the westward subduction of the Solomon Plate. Tiffin *et al.* (1987) noted that Quaternary deformation in sediments along the Ramu-Markham Fault Zone and its offshore continuation, and subsidence along the Morobe coast to the south, as well as rapid Quaternary uplift on Huon Peninsula (Crook, 1989) and in the Markham Valley area all indicate strong and continuing tectonics near Huon Gulf.

There is onshore data and offshore data suggesting past collision and current ongoing collision under northern Huon Gulf (Tiffin *et al.*, 1987), and a disappearing of trenches and within the area of the actively subducting Solomon Plate. The earthquake activity in the region is the result of under-thrusting of the lower plate. Further, this is where the lower plate requires large additional downward forces to force itself beneath the Huon Peninsula (Abers and McCaffrey, 1994).

2.3.3 Northeastern New Guinea – western Bismarck Sea region

In the Huon Peninsula, the Australia continental crust is colliding with the Finisterre Range front of the South Bismarck Plate along the Ramu-Markham Valley fault, thus causing uplift of the region (Abbott and Silver, 1991; Silver *et al.*, 1991; Abbott et al., 1994; Abbott *et al.*, 1997). This collision might have occurred much earlier in the western part of New Guinea and progressed eastward at a relatively slow rate (Tiffin *et al.*, 1987), a view supported by recent GPS observations (Tregoning *et al.*, 2000), which suggested a no clearly defined boundary of the South Bismarck Plate. However, GPS velocities estimates agree with the rigid plate motion of the South Bismarck Plate (Tregoning *et al.*, 1999; Tregoning *et al.*, 2000), especially in this region of transition from the South Bismarck Plate to the Australian Plate, where both rigid plates are moving with nearly the same velocity (Wallace *et al.*, 2004).

The effect of the interactions of the Australian, South Bismarck and Solomon Plates in PNG is noted as the source of frequent earthquakes in the NNGWBS region. The westward subduction of the Solomon Plate is occurring beneath the region while the arc–continent collision is taking place above it, causing intermediate and shallow seismicity respectively. It is potentially possible a large size earthquake could occur near Lae.

Along the southern boundary of the South Bismarck Plate, Tregoning and McQueen (2001) gave evidence of a discontinuity of horizontal azimuth of slip vectors from available earthquake data, compared with those to the west of 148°E, and confirmed rotations of these by ~20–30° clockwise compared to those located east of 148°E. It was confirmed from GPS observations since 1991 that the contact of the southern boundary of the South Bismarck Plate was between the underthrusting Australian and Solomon Sea Plates. The two plates change from Australian Plate in the west to Solomon Plate in the east, between 147°E and 148°E. It is further proposed that within this transition zone there may be direct interaction of the Woodlark Plate with the South Bismarck Plate, although there is in-sufficient data for actual confirmation (Silver *et al.*, 1991; Tregoning and McQueen, 2001; Bird, 2003). Further it is possible the southern boundary is associated with a separate New Guinea Highlands Block (Wallace *et al.*, 2004; Anton *et al.*, 2008). The SBP and related features are shown in Figure 8.

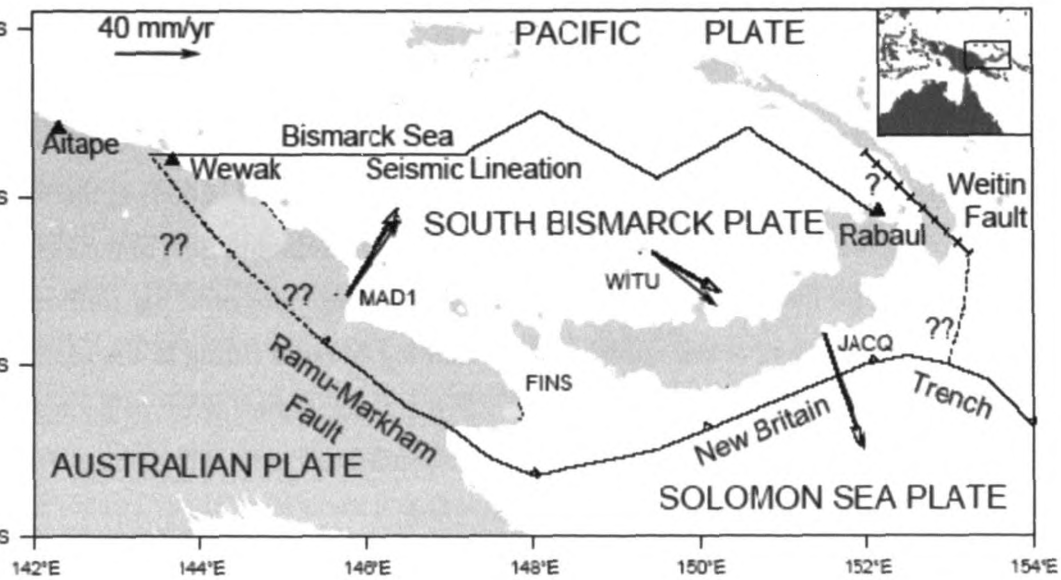

Figure 8: South Bismarck Plate and related features.

The map is from Tregoning and McQueen, 2001, their Figure 1. Labels and signs correspond to their GPS ITRF97 observations.

Uplift and subsidence are linked to the processes of subduction of plates in the region. Harvard CMT and field observations of tsunami run-up and coral terrace uplifts caused by the magnitude 7.8 thrust earthquake of 9 September 2002, The Wewak Earthquake (Anton and McKee, 2005b), matched those predicted from a thrust event on the New Guinea Trench (Borrero *et al.*, 2003). Here on the trench, present-day thrusting occurs as far east as 143° East and possibly further, and thus indicative of uplift occurring the length of northern New Guinea.

Tregoning and Gorbatov (2004) showed in recent seismic tomography imaging that southwestward subduction is occurring along the entire length of the New Guinea Trench, an active inter-plate boundary. This work, improved by the use of data set of P and S wave arrival times and hypocentral locations, is supported by the frequent occurrence of large (Mw > 7) thrust earthquakes known to have occurred on the trench. From the trench, lithospheric slab is imaged to depths of about 300 km and is subducting southwest at dip angles varying from 30 ° at 136° East to 10° at 143° East. Earthquakes defining these trends and those dipping gently south beneath central New Guinea are typical overthrust mountain building events (Denham, 1969) caused by interacting tectonic blocks within the zone of collision of the major India-Australia and Pacific Plates.

In the region, the boundary changes from collision between the Finisterre Range and the underthrusting New Guinea Highlands tectonic block (Wallace *et al.*, 2004) in the west, to subduction of oceanic crust at the New Britain trench in the Solomon Sea, in the east. GSP observations indicate that SBP rotates clockwise at an average rate of 8° per million years (Tregoning, 2002), relative to the collision thus resulting in rapid rifting in the Manus and New Guinea Basins (Wallace *et al.*, 2004). This is consistent with palaeomagnetic evidence, which further confirms that clockwise rotation has been taking place since the Finisterre collision was initiated (Weiler and Coe, 2000).

2.3.4 North Bismarck Sea

Ocean floor spreading connected by left-lateral transform faults along the Bismarck Sea Seismic Lineation (BSSL) in the Manus Basin (Taylor, 1979) marks the northern boundary of the South Bismarck and North Bismarck Plates (NBP). This left-lateral structural feature was confirmed by multibeam bathymetry and side scan sonar imagery during the offshore New Guinea/Bismarck Volcanic Arc survey (Silver *et al.*, 2005). The westerly trending feature across the Bismarck Sea toward Wewak was mapped and a large ridge that was split in half by the fault and displaced 40 km in a left-lateral trend was identified. The island of Wei sits atop the northern segment of this ridge.

If there is in fact a NBP as proposed by Weissel and Anderson (1978) and suggested confirmation of by Tregoning (2002) using GPS observation, the northern boundary of than must be the Manus Trench for example McCue (1988). This boundary is particularly identified by offshore topography and sparsely scattered (less-intense) seismicity. Many workers did questioned the existence of NBP (Curtis, 1973; Krause, 1973 and Taylor, 1979) and argued that the Trench may be the remnant of an older plate boundary, proposing that the earthquake activity along the Trench region must be due to crustal deformation caused by the westward movement of the massive Pacific Plate, for example McCue (1988). The seismicity, which should indicate any interaction of the two plates as they make contact, is not high and it may be that the low activity indicates that the NBP may have docked in the advancing front of the massive Pacific Plate.

2.3.5 Papuan Peninsula – Southwestern Solomon Sea region

In the west the Solomon Plate is subducting beneath northeastern mainland PNG (Pegler *et al.*, 1995), and sinking westward, evident by intermediate earthquakes as far west as 142°E and possibly further west (Ripper *et al.*, 1996). An inverted U-shaped doubly-dipping subducted slab is noted beneath eastern New Guinea, east of 145°E (Pegler *et al.*, 1995; Ripper *et al.*, 1996; Tregoning and Gorbatov, 2004). The southwestward subducting slab of the SBP is envisaged to lie above this U-shaped slab (Tregoning and Gorbatov, 2004), but sufficient resolution is required to adequately identify separately the U-shaped slab (of the Solomon Plate) and the slab subducting at the NGT (of the South Bismarck Plate). This would require spatial resolution less than 50 km, which means data from a very dense local seismic network over the zone of study, equipment, and thus data that do not currently exist. Figure 9 shows the focal mechanisms of the Papuan Peninsula and Solomon Sea (From Abers *et al.*, 1997).

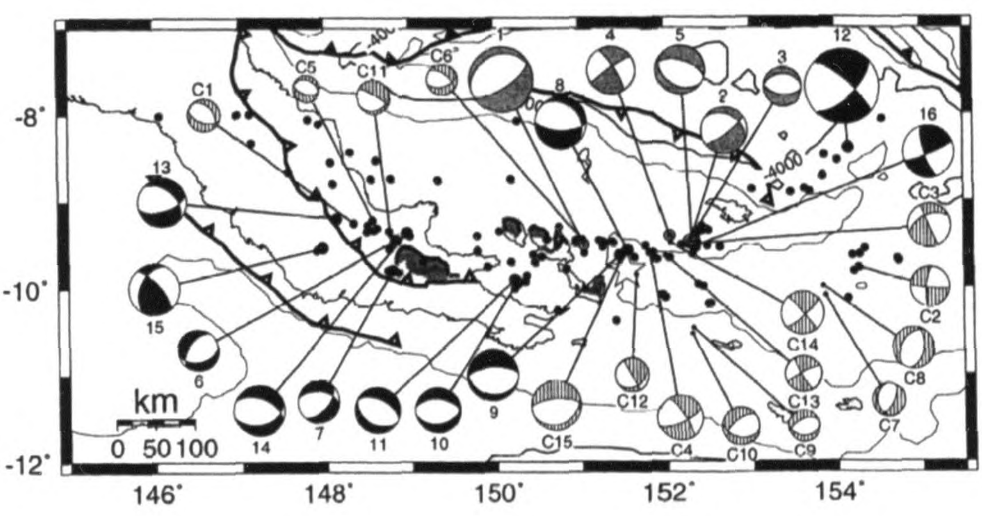

Figure 9: Focal mechanisms from Papuan Peninsula and the Solomon Sea. The data are from Abers et al. 1997, their figure 2.

Further southeast, the area of the south Solomon Sea is marked by very weak seismic activity and relatively moderate earthquake depths which may be associated with a Wadati-Benioff zone dipping to the south (Ripper, 1982).

This zone of seismicity extends to the west beneath the northeastern margin of PNG, where it converges with the north-dipping zone beneath New Britain to form an inverted U-shaped profile with arms dipping both north and south, postulated by Ripper (1982), Pegler *et al.* (1995), Ripper *et al.* (1996), among others, and because of lack of data disputed by others for example Abers and McCaffrey (1988, 1994), and Abers and Roecker (1991). A high level of shallow to intermediate seismicity above the apex of the U-shaped, or an inverted V of Honza *et al.* (1987), exists beneath the Huon Gulf and the Finisterre-Huon deformation zone.

Initial processes of lithospheric rupture in the western Woodlark Basin makes the area ideal for probing in to what underlies the complexities of active continental rifting and seafloor spreading. This area of crustal extension (Hill *et al.*, 1995; Taylor, B., Goodliffe, A.M. & Martinez, F., 1999; Monteleone *et al.*, 2001) is ideally accommodated by normal faulting within the latest Cretaceous to early Palaeocene oceanic crust.

Processes associated with continental rifting, including low angle normal faulting, sedimentary basin evolution, and the movement of footwall blocks during the final stages of rifting and prior to seafloor spreading initiation have been examined (Taylor, B., Goodliffe, A.M. & Martinez, F., 1999; Taylor, Brian and Huchon, Philippe, 2002). The Woodlark Basin is located in the Solomon Sea where the present-day tectonics are the result of interactions between micro-plates, here the Solomon and Woodlark Plates, caught in and formed during oblique convergence between the Pacific and Indo-Australian plates, for example Tregoning *et al.* (1998).

Unlike the South Bismarck Plate, the Solomon Plate is rotating counterclockwise within the collision zone of the India-Australian and Pacific Plates, and thus generating the development of the Woodlark Basin oceanic spreading centre (Tregoning and McQueen, 2001). It was determined that sea floor spreading began at least 6 Ma (Weissel *et al.*, 1982; Taylor *et al.*, 1995; 1999; 2002), mostly from analysis of magnetic anomalies. Having propagated westward into eastern PNG or eastern New Guinea, the Woodlark rift is amongst the fastest spreading systems on the planet, separating at >20 mm/yr (Abers, 2001; Wallace *et al.*, 2004), and one of several places on Earth where normal faults have been shown to be seismogenically active at dips of <30°, for example Abers (2001).

The region west of the seafloor spreading centre has been extensively studied (e.g., Davies, 1973; Smith, 1976; Hegner and Smith, 1992; Davies and Warren, 1988; Hill *et al.*, 1992, 1995; Hill and Baldwin, 1993; Baldwin *et al.*, 1993; Stolz *et al.*, 1993; Hill, 1994). A bathymetric high named the Moresby Seamount is located east of the zones of active metamorphic core complexes, which with full and half grabens and rift-related peralkaline volcanism are manifestation of continental extension. The seamount has been studied and proposed to be bounded in the northern side by a seismically active, low-angle normal fault that strikes east-west and dips 25°– 30° toward the north (Abers *et al.*, 1997; Taylor *et al.*, 1999; 2002), and suggested to allow for continental extension.

This region comprises the shallow seismicity associated with the Owen Stanley Fault system on the south and earthquakes associated with the Trobriand Trough, which mark the southern boundary of the Solomon Plate. It is not certain whether the proposed Woodlark and the Solomon Plates do actually exist as individuals or as one, since there is insufficient sub-aerial GPS data for confirmation of the tectonic patterns in the region of the New Britain Trench (Tregoning and McQueen, 2001). For the plates to be considered separate, convergence is actually required across the Trobriand Tough in the region of low seismicity. However, Tregoning *et al.* (1998) made no distinction between the Solomon Sea Plate and the Woodlark Plate due to lack of geodetic data.

A double-dipping slab that has subducted both to the north and south beneath the Huon Peninsula is actually the Solomon Plate subducting both at the Trobriand Trough and the New Britain Trench (Davies *et al.*, 1984; Cooper & Taylor, 1987, Pegler *et al.*, 1995).

The western part of the Woodlark Basin is spreading faster then the eastern part. The basin is divided by the N-S striking Moresby Transform (MT in Figure 10), where the western part began spreading about 2 Ma and spreading rates decreases to the west (Martinez *et al.*, 1999).

A velocity model by Ferris *et al.* (2006) shows three main features are noted as follows. Firstly the velocity structure near 151° E which define and is indicative of continental and oceanic crusts to the west and east respectively. The second feature is a thick gradient zone (10-15 km) of unusual velocities (7.0-7.9 km/s), which may indicate underplated lowermost crust, or may be magmatic intrusion into the lithospheric mantle. Thirdly, closer to the active spreading tip and along strike of the rift axis farther east of 151° E is a zone (40-60 km wide) of thin crust (8-18 km thick).

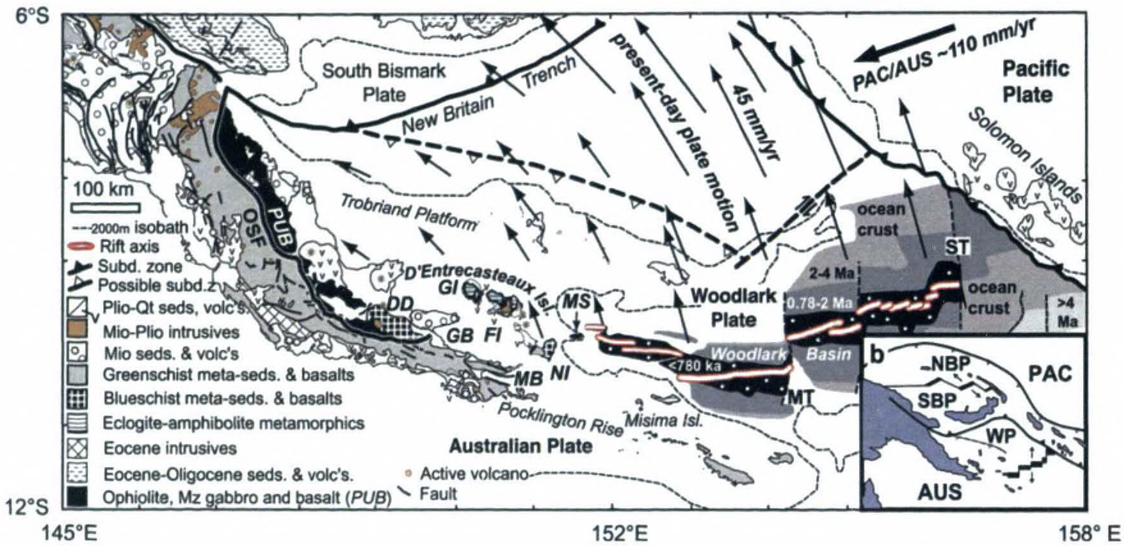

Figure 10: Geology index map of PNG.

This map is from Figure 1 of Little et al., 2007 with simplified geology from Davies and Smith, 1971; Davies, 1981. MT is the Moresby Transform.

2.3.6 Eastern Solomon Sea – Solomon Islands region

Detachment tectonics in the Woodlark Basin that partly dismembered the Oligocene–Pliocene collisional orogen (Betts *et al*., 2002) is a result of extensional tectonism along the northern margin of the India-Australia Plate. Metamorphic core complexes of the Solomon Sea are also manifestation of such activity since 3 Ma.

The islands of New Britain, New Ireland, Bougainville and the Solomon Islands make up Bismarck Archipelago. Within the region and parallel to New Ireland is the island chain of calcalkaline volcanic island group of over 260 km long including Simberi, Lihir and Tabar to the northwest, and Tanga and Feni to the southeast.

In the northwest within the vicinity of the island chain the plate tectonic setting is the south-westward subduction of the Pacific Plate along the Melanesian Trench, though evidenced by less intense seismicity. The region is virtually the east-southeastern margin between the North Bismarck, South Bismarck and Pacific Plates. Here contemporaneously, intensive calcalkaline volcanism occurred during Oligocene and Miocene time forming the island of New Ireland. Further southeast in the region of Bougainville and Solomon Islands, the southwestward subduction ceased 15 Ma and soon after reversed due to the collision of the Ontong Java Plateau (OJP) with the Melanesian Trench (Coleman and Kroenke, 1981). The OJP is the largest and thickest plateau (33 km) on Earth (Miura *et al.*, 1996; 2004), larger than Alaska in size but the only active accretion of a plateau on Earth (Mann and Taira, 2004). OJP is 18 km thick and isostatically incapable of subduction, (Mann and Taira, 2004) and (Cloos, 1993).

Many investigations such as by Kroenke *et al.* (1986), Kroenke (1989), Yan and Kroenke (1993), and Petterson *et al.* (1997) Petterson *et al.* 1999) noted that the OJP was too thick and too buoyant to be subducted at the North Solomon trench and caused folding north of the Solomon Islands since it's arrival at the trench at 22 Ma (Early Miocene). Sdrolias, Muller and Gaina (2003) proposed that the OJP docked with the Melanesian Arc about 25 Ma. Than 12-6 Ma subduction polarity reversal was initiated, and ''hard docking'' occurred with convergence of the arc in the period 4-2 Ma. This timing is consistent with widespread and discernible deformational and uplift in events in the Malaita accretionary prism attached during the Pliocene (Mann and Taira, 2004).

The Solomon Plate has been subducting beneath Bougainville since than. Further east the collision between the India-Australian and Pacific Plates is also evident, while dominantly NE subduction, good profiles of less intense SW subduction have been noted (Mann and Taira, 2004).

The region of the Woodlark Basin is made up of the Woodlark Rise and Woodlark rift system, one of the worlds' actively forming ocean basins, and where continental extension rates occurring are some of the fastest known on Earth. The extension progresses eastwards to full scale seafloor spreading. Farther east and closer to the active spreading tip, crustal velocities rapidly increase from 6.5 to 7.2 km/s at depths between 8 and 18 km (Ferris *et al.*, 2006). These fast crustal velocities appear in a narrow zone roughly 60 km wide and indicate characteristics typical of oceanic crust. Here in the region there is suggestion of transition from diffuse continental rifting to localized seafloor spreading likely occurs across a narrow zone (Ferris *et al.*, 2006). The basin and related features are shown in Figure 11.

The major earthquake to occur in the region in recent times was the 1 April 2008 Gizo Earthquake of the New Georgia Islands region. USGS (2008) determined rupture to have occurred, but restricted in the northwestward propagation at the Woodlark Rise.

Local earthquake *P* and *S* travel times were inverted for 3-D structures around and ahead of the active spreading tip during a recent passive seismic experiment (Ferris *et al.*, 2006). From these, local earthquake tomographic structures were observed. Seismic velocities in the crust show a sharp contrast between regions that resemble continental crust ahead of the spreading tip and oceanic crust to the east. *P*-wave velocities beneath the continental crust increase from 5.6 km s−1 to 6.9 km s−1 in the depth range 10 and 25 km depth, similar to other continental regions. At the Moho (23–28 km depth) seismic velocities range from 7.0 to 7.9 km s−1, and reflect an underplated mafic, granulite facies lowermost crust, or perhaps magmatic intrusion into the lithospheric mantle (Ferris *et al.*, 2006).

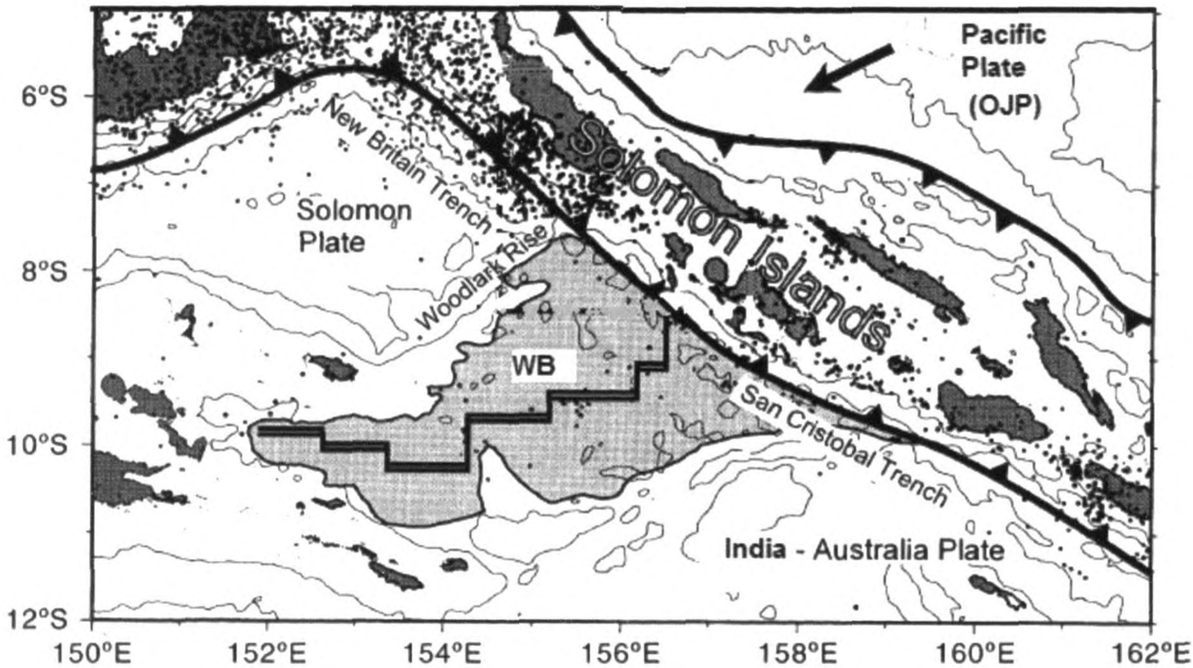

Figure 11: Woodlark Basin and related features.

These include the Ontong Java Plateau OJP (modified from Figure 1 of Yoneshima et al., 2005).

2.3.7 Eastern Bismarck Sea – Southern New Ireland region

Active subduction at the New Britain Trench is instigated by the northward movement of the Australian Plate, and is causing back-arc spreading to develop in the Manus Basin (Taylor *et al.*, 1994). Sea floor spreading evidenced by the Bismarck Sea seismic lineation marks the boundary between the South Bismarck and North Bismarck Plates. The region has been mapped (Taylor, 1979; Taylor *et al.*, 1991; Martinez & Taylor, 1996) and Tran tensional tectonics understood to dominate (Taylor *et al.*, 1994).

With the advance of the South Bismarck Plate, the Bismarck Sea opens up or is pulled open to form the back-arc basin, the Bismarck or Manus Basin. Earthquake activity trending east-west along the central Bismarck Sea is evidence of activity on this spreading centre. The seismic zone consists of left-lateral strike-slip movements and offset transform faults especially in the eastern end, with associated normal faulting earthquakes.

Seismicity in the southern New Ireland region represents a combination of strike-slip movements and thrust faulting (Mori, 1989). Taylor (1979) suggested that New Ireland was once marginal to the Solomon Sea, as an extension of the Bougainville-Solomon Island arc. As southwestern New Ireland is carried to the northwest on the southwestern marginal zone of the Pacific Plate, it experiences intense shearing and compression. Seismicity at depths greater than 50 km beneath New Ireland is indicative of northward subduction of the Solomon Plate beneath southern and central New Ireland, or, as proposed by Ripper, Letz and Anton (1996), upward and southern rebound of the South Bismarck and Pacific Plate margins after having been dragged down by the subducting Solomon Plate.

The deeper seismicity of the region is associated with the gradual annihilation of the Solomon Plate beneath the advancing fronts of the Pacific and South Bismarck Plates (Ripper and McCue, 1982). Earthquakes to depths exceeding 450 km beneath central New Ireland define the leading edges of the warped and splintered remnants of the northward-plunging Solomon Plate (Cooper and Taylor, 1989).

2.3.8 Southwestern PNG region

The seismicity of the region is a result of folding and thrusting of the India-Australia Plate front as it collides with the South Bismarck Plate along the Ramu-Markham Valley Fault, in the region of Huon Peninsula. Continental-arc collision has propagated southwestward to the region of the southern Highlands.

In the region encompassing 4.5 to 9.5° South and 141 to 146° East, the Fly Platform or foreland basin which lies to the south is free of earthquakes, this being part of the stable continental cratonic crust of the India-Australia Plate which forms basement. North of the platform is a sequence of folded and faulted platform rocks which make up the fold-and thrust belt, thus the Papuan Fold Belt (PFB). The folding and thrusting extends much of the highlands, making the entire PFB is seismically active. The seismicity comprises two elements, the Southern Highlands Seismic Zone and the Mount Hagen Seismic Zone (Ripper and McCue, 1983). The dominant seismicity is that of the Southern Highlands Seismic Zone, which extends throughout the PFB, into Papua, Indonesia to 139°E and possibly linking the Irian Jaya Fold Belt (IJFB). The Mount Hagen Seismic Zone is a narrow belt of seismicity branching off the Southern Highlands Seismic Zone at about 6.5°S, 144°E, and extending and deepening north-northeast past Mount Hagen and intersecting the intermediate-depth seismicity beneath the Ramu-Markham Valley.

Overthrust earthquake focal mechanism solutions, such as that for the 3 March 2000 Gobe Earthquake (Anton, McKee and Abers, 2001) showed nodal planes trending northwest. This orientation is consistent with the local structural fabric. The northeast dip of mapped faults and axial planes of folds in the central-eastern part of the fold belt (southeast Gobe) suggest that the fault movements responsible for the earthquakes were on the northeast-dipping nodal plane. The aftershock distributions are also aligned parallel to the strike of the nodal planes, but the location errors are too great to determine whether the aftershock locations define dipping planes. The aftershock sequence distribution for the Gobe Earthquake extended approximately 35 km northwest-southeast and was approximately 15 km wide. This configuration is consistent with the trend of folding and faulting within the Papuan Fold Belt (Anton, McKee and Abers, 2001; see Figure 12).

Structural interpretations of the Papua Fold Belt have been typically model-driven because of insufficient data on deeper structures. However, the detailed study of the earthquakes of this region, particularly earthquake focal mechanisms and the spatial distribution of mainshock-aftershock sequences, provides vital information on dynamics at depth, and allows refinement of structural interpretations. In doing so, it has been established that earthquakes such as the Gobe Earthquake occurred at a mid-crustal depth (13 km) within basement. Studies of this earthquake and other large earthquakes in the Papuan Fold Belt show that: (1) faults penetrate basement (>10km), (2) fault planes dip steeply 35°-60°, assuming that the northeast-dipping nodal planes are the fault planes, as suggested by surface geology, and (3) fault mechanisms are characteristically thrusts or sinistral strike-slips.

The earthquakes of the Papuan Fold Belt probably do represent a plate boundary and properly regarded as a result of stress build-up within the front of the northeast approaching India-Australia Plate colliding with the southwest approaching South Bismarck Plate. This intra-plate seismicity was thought to represent the fracturing of the India-Australia Plate front from its collision with the South Bismarck Plate (Ripper and McCue, 1981b; Ripper and McCue, 1983). Anton, Gibson and McCue (2008) proposed it to be the southern boundary between the New Guinea Highlands Block (Bird, 2003; Wallace *et al.*, 2004) and the South Bismarck Plate. The northern collision boundary of this block is marked by the zone of earthquakes trending northwest-southeast along the northern mainland PNG (Ripper, Letz and Anton, 1996). Some effects of this collision have possibly migrated to the southern PNG Highlands.

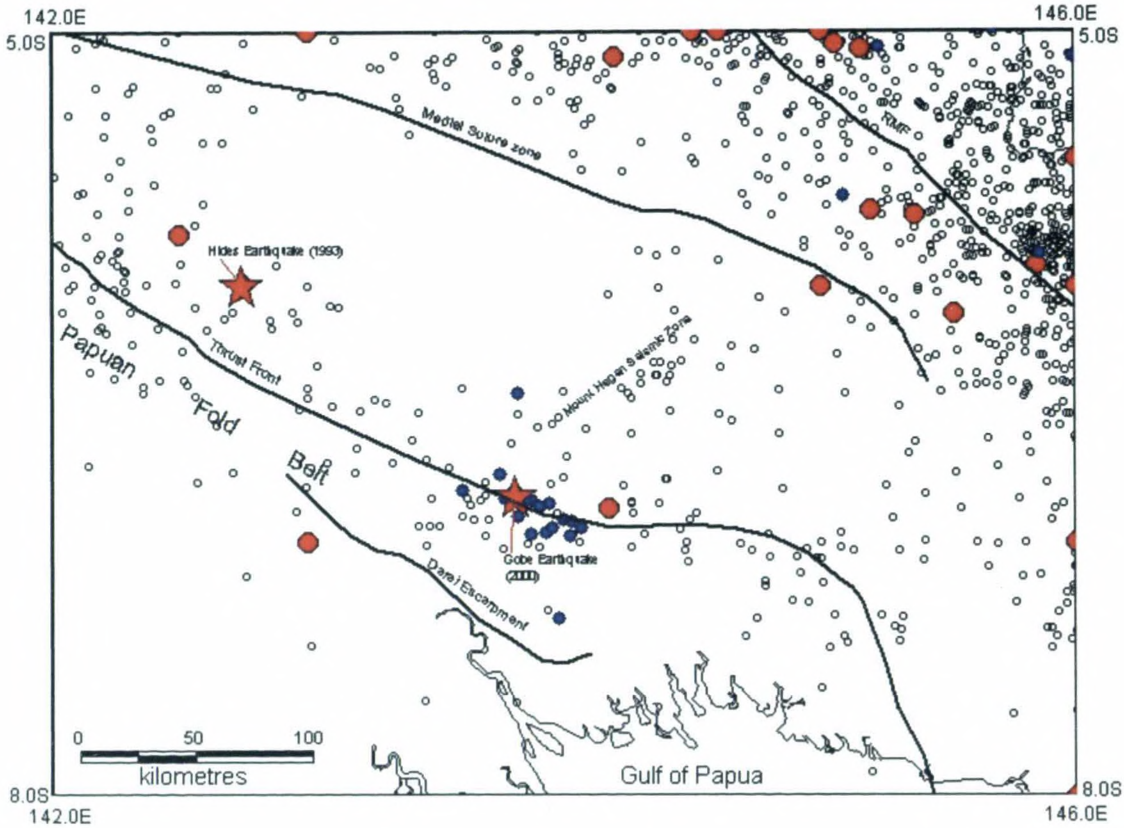

Figure 12: Seismicity of the central PNG mainland and Papuan Fold Belt. Magnitude 6.0 and above earthquakes are denoted by red solid circles while the general seismicity is denoted by smaller open circles. Locations of the Gobe (2002) and Hides (1993) Earthquakes are denoted by the stars and aftershocks of the Gobe Earthquake are denoted by the solid blue circles. Thick lines are faults, RMF denotes Ramu-Markham Fault zone in the far northeast.

The folding and anticlinal uplift of the Fold Belt are ongoing, and if there were any doubt that the faulting is also ongoing, the current high level of seismicity on the Fold Belt would dispel this, despite field evidence of Quaternary faulting being not particularly apparent. The zone of shallow (<50 km deep) earthquakes, the Southern Highlands Seismic zone (Ripper and McCue, 1981b; 1983), is related to folding and northeast-dipping thrusting of the Papuan Fold Belt.

The Main Frontal Thrust or Hegigio Fault follows the Fold Belt seismic zone, although earthquakes occur both in front of and behind the thrust. Although mostly shallow, the seismicity extends to at least a depth of 45 km (Abers and McCaffrey, 1988).

Therefore the tectonics of the Papuan Fold Belt is not exclusively "thin-skinned". Basement faulting occurs beneath the thin-skinned deformation of the Mesozoic-Cainozoic sedimentary cover sequence. Thus, movements on high-angle basement faults contribute to the total crustal shortening beneath the mountain range of the Papuan Fold Belt. And, the crustal shortening that is taken up in the sedimentary section by folding and by detachment and low-angle thrusting, may be accommodated in basement by high-angle thrust faulting, as previously suggested by Abers and McCaffrey (1988). The visible result has been the development of overthrust anticlines (Muller, Gobe, etc) by thick-skinned tectonics, which involves thrusting within crust. This has been accompanied by thin-skinned tectonics, which involved upper crust sediment only and do not involve crust with decollement evidenced extensively in the highlands. Another effect of the thick-skinned tectonics may have been the development of the Southern Highlands seismic zone of Ripper and McCue (1981b; 1983), with foci in the 25-45 km (crustal) depth range.

2.3.9 Northern New Guinea – Papua region

Based on stratigraphic and palaeomagnetic data, McCaffrey and Abers (1991) noted a similarity between the Bird's Head and Australia. Parts of the back-arc Banda basin to the south are trapped older crust, which have lithologic similarities with the Bird's Head suggested by Silver *et al.* (1985) as slices of it brought about there by faulting during the middle to late Miocene. The Bird's Head, as well as southern New Guinea and other islands of eastern Indonesia especially the Banda Arc, have been claimed to be of similar origin to northern Australia (MaCaffrey and Abers, 1991; Hamilton, 1979; Viser and Hermes, 1962).

Tarera-Aiduna and the New Guinea thrust belt are suggested to be the accommodation zone for the west to southwest motion of the Bird's Head with respect to Australia (McCaffrey and Abers, 1991). The fault zone was identified by side-looking airborne radar image (Hamilton, 1979), but is not obvious in the surface geology east of about 135.5°E where observation of traces is made difficult by extreme topography and landslides

(McCaffrey and Abers, 1991). Earthquake focal mechanisms that are consistent with left-lateral motion of the Tarera-Aiduna fault zone are apparent to 140.0°E, north of the New Guinea fold-and-thrust belt. Thrust earthquakes and the topography are evidence of crustal shortening (and thickening) in the Highlands (Abers and McCaffrey, 1988). Hamilton (1979) has estimated a lateral offset along the fault zone of about 50 km since the middle Pliocene, which equates to a slip rate of about 15 mm/yr. Utilising a 22-year period (1964 to 1985) of earthquake data, Abers and McCaffrey (1988) calculated a slip rate of 5-25 mm/yr. This slip rate could easily be doubled with other data (from 1900 to 1985) later available (McCaffrey and Abers, 1991), and improved further with data obtained since 1985. It was further noted that the Tarera-Aiduna fault system is accommodating tectonically significant motion.

The buoyant Caroline Plate arrived at the convergent margin of the New Guinea Trench in Late Oligocene-Pliocene, marked by orogensis and obduction of oceanic crust from the marginal basin (Crowhurst *et al.*, 1996; Crowhurst *et al.*, 1997). The margin is presently a region of active deformation indicative of continuing convergence (Dow and Sukamto, 1984).

This region covers western mainland PNG and the eastern province of Indonesia, Papua Province, to the west. Along the northern coast of New Guinea, marked by the topographic depression just of shore outlining the New Guinea Trench, the North Bismarck Plate is converging obliquely west-southwestward beneath New Guinea obliquely. The lithospheric plate configuration here includes a North Bismarck Plate, a notion debated by many workers in past studies including McCue (1988) but confirmed by recent GPS observations (Tregoning *et al.*, 1998; Tregoning *et al.*, 1999; Tregoning, 2002). Earthquake activity has been noted along the northern boundary with the Pacific Plate although less intense, affirming the notion of a broad zone of plate front deformation. The collision of the NBP north of New Guinea is not necessarily with the India-Australia Plate but rather a separate block. This is a region of active and complex convergent margin, involving a complex array of existing lithospheric segments with oblique subduction occurring in the New Guinea Trench.

Onshore and offshore subsidence of segments of shoreline during earthquakes, as well as near shore bathymetric focusing makes the region vulnerable to tsunami generation (Tappin *et al.*, 2001). Tsunami generation is a result of tectonic activity, through faulting and slumping from earthquake shaking.

It is suggested (Pigram and Davies, 1987) that subduction along the New Guinea Trench commenced 9 Ma. This suggestion was supported by (Tregoning and Gorbatov, 2004) who considered the length of the subducted slab beneath New Guinea to subduct at a constant rate of 70 mm/yr, and suggested that earlier convergence across the Papuan Fold and Thrust Belt was more rapid than currently thought.

The Solomon Plate slab exists beneath New Guinea from 143°E extending west to at least 135°E, consistent with a Wadati-Benioff zone identified in previous studies such as Cooper and Taylor (1987), Ripper (1982), Pegler *et al.* (1995) and Ripper *et al.* (1996). The occurrence of inter-plate, thrust-type events located on the New Guinea Trench such as the 1996 Biak Island Earthquake (USGS, 1997; Davies, 1999), 1998 Aitape Earthquake (Davies *et al.*, 2003; Tappin *et al.*, 1999; Tappin *et al.*, 2001) and 2002 Wewak Earthquake (Anton and McKee, 2005b) are also evidence of subduction on the trench.

At the far western end of the map region, the Tarera-Aiduna fault zone and its associated pull-apart basin mark the new active Pacific-Australia plate boundary. Abers and McCaffrey (1988) noted that the broad shear zone is clearly outlined by young morphology and trends of features consistent with stress patterns shown by focal mechanisms of shallow earthquakes. It is also suggested thrust faulting accommodating crustal thickening and shortening is indicative of significant convergence between New Guinea and Australia (McCaffrey and Abers, 1991). Further west, and known from offshore seismic data, the fault connects with the Seram trench (Jongsma *et al.*, 1989; Pubellier and Ego, 2002).

2.4 Quaternary faults and historical seismicity

Surface faulting observations from earthquakes in PNG have been few. Observations of surface ruptures may have been limited as result of remoteness, landslides that follow earthquake shaking covering fault traces, and possibly the general harsh environment making access difficult.

However, two significant observations of surface faulting following earthquakes have been made. The first was on mainland PNG in the Gusap Valley, on southern foothills of the Finisterre Mountains following the M7.1 earthquake of 13 October 1993 (Tutton and Browne, 1994). The second was on southern New Ireland, where more than 5 metres of displacement was observed on the Weitin Fault following the Mw 8.0 earthquake of 16 November 2000 (Itikarai and Tregoning, 2004; Anton and McKee, 2005a).

As well there are known instances of significant uplift though, at the time of initial rupture or during earthquakes. Carey (1990) related experiences at the time of the 1935 Torricelli Mountains, during which items were thrown upwards, defying gravity, and Marshall (1937) documented extensive landsliding of whole mountainsides. Also at Gasmata in 1920 after a magnitude 7.7, water from the harbour rushed out and did not return, indicating permanent uplift.

Significant Quaternary fault systems and regions of Quaternary uplift do exist in places in PNG, but there may be no or few associated earthquakes. These regions constitute a significant seismic hazard. Shallow seismicity is a more reliable indication of location of geological features, particularly faults, especially where earthquake distributions delineate the fault outcrop.

Many earthquakes in Papua New Guinea are deep beneath the surface and do not produce surface ruptures, so the earthquakes cannot be positively associated with a particular fault. Because of the sparse local seismograph network in PNG, earthquake locations have high uncertainties, and many have high random and systematic errors in epicentre and depth, both making it difficult to associate events with faults. Also, landslides are numerous and can often conceal fault outcrops. Thus it is can be very difficult to identify active faults, and especially to estimate fault slips and long-term slip rates.

As well as defining the entire length or sections of faults, the foci of aftershocks will normally indicate direction of fault dips, where the direction of displacement of crust in the area of fault rupture has been identified.

It has to be noted that the existence of Quaternary Faults does not necessarily increase seismic hazard where seismicity is already intense, except in the immediate vicinity of the fault.

In many seismically active regions of the world there have been documented reports of fault sources with earthquakes having disastrous impacts on whole towns and cities. The 15 October 1979 Imperial Valley Earthquake, California and the 16 January 1995 Kobe Earthquake both had devastating effects in the US and Japan respectively.

It is too often wondered if building codes are adequate enough to enable infrastructure to withstand earthquake shaking. Too often building codes lack earthquake-resistant provisions needed to sustain the strength of structures during shaking.

If this can be what happens in these seismological advanced countries one wonders what disadvantages exist for not-so-well-to-do countries like PNG. Having said that, though, the lessons can be learned and adopted.

The following sections outline known geological and geographical features that had records of earthquake activity; if not on the features, in the vicinity.

Many of observations of surface ruptures have not been made although surely such ruptures would have occurred. Remoteness, landslides covering fault traces, and the general harsh environments are probable reasons. Not all recognised or inferred Quaternary fault systems appear to be seismically active, but where a confirmed Quaternary fault appears to be inactive, a level of seismic hazard must be inferred. Active shallow fault systems are indicated by the contemporary seismic activity itself, despite non-recognition of specific active faults.

2.4.1 Sorong-Yapeng Fault Zone

The Sorong-Yapeng seismic zone, delineate by numerous large earthquakes occurring along the fault zone, marks the boundary of the Pacific Plate to the north. Large earthquakes have occurred on the fault. Seismic slip rates for the zone are four times higher, i.e. about 80mm/yr, then that of the Tarera-Aiduna fault zone (McCaffrey and Abers, 1991) bounding the broad left-lateral shear zone to the south.

2.4.2 Tarera-Aiduna Fault Zone

This is a shear zone accommodating tectonically significant motion between, where the Bird's Head region has moved southwest with respect to Australia. Earthquake focal mechanism solutions are consistent with such motion, where slip rates are estimated at

20mm/yr (McCaffrey and Abers, 1991). The fault zone intersects with the Seram Trench further west at about 132°E.

2.4.3 Bewani Fault Zone – Torricelli Mountains

The Bewani seismic zone is on the zone of intense shallow seismicity north of the Sepik River, possibly delineating the Bewani Fault Zone. Shallow earthquakes are scattered about the fault zone, but do not define it, and earthquakes presumably occur on the zone. Recognition of the Quaternary fault system does not increase seismic hazard of the fault region, although earthquakes may be expected to occur on the fault in the future. The 1935 magnitude Ms7.9 earthquake Torricelli Mountains may have occurred on the fault zone. This earthquake caused very extensive landslides which devastated so much of the mountainous country, and massive loads of sediments were transported and deposited offshore by river systems of that part of northern New Guinea region.

2.4.4 Gogol and Banam Faults – Adelbert Range

The fault region between the Adelbert Mountains and Ramu Valley is seismically active with the suggestion of seismic lineaments parallel to the faults. A magnitude 7 earthquake may well occur on one of the faults. In 1970, a magnitude 7 earthquake occurred just north beneath the Adelbert Mountains. The existence of the faults does not increase the recognised seismic hazard of the region.

2.4.5 Ramu Markham Fault Zone – Finisterre Range

The Ramu-Markham lineament marks the southern border of the very active Finisterre Huon Peninsula region. No surface faulting has been observed on this fault. Much of the seismicity of this region may well occur on the Wongat Thrust and similar parallel thrusts. Most of the region of the Ramu-Markham has locked since docking and is suggested (Wallace *et al.*, 2004) which may have seismic hazard implications for the region.

Recognition of these Quaternary faults does not increase the seismic hazard of the region. The triple junction of the India-Australia, South Bismarck and Solomon Plates is situated beneath the headwaters region of the Ramu and Markham Valleys, virtually beneath the Wongat Thrust. Two magnitude 7 thrust earthquakes occurred here, in the Finisterre Mountains in October 1993.

2.4.6 Bundi Fault Zone – Schrader and Bismarck Ranges

The zone is situated to the southwest of the Ramu Valley in a region of weak seismicity. Two magnitude 5 earthquakes have occurred on or near the zone since 1964, in 1973 and 1993. However, its Quaternary activity indicates that a large earthquake could still occur on the fault in the northern margin of the Schrader and Bismarck Mountains, in the PNG Highlands.

Seismicity in the Asaro Fault region is relatively quiet. However since 1964, one magnitude 5 earthquake occurred on or close to the fault, in June 1975, with a felt intensity 5 at Goroka. The fault is about 20 km long and so a magnitude 6.0 + earthquake of fault length about 10 km could conceivably occur on the currently inactive fault. The town at greatest hazard from such an earthquake would be Goroka.

2.4.7 PNG Highlands

As a magnitude 7 earthquake is associated with a fault length of about 50 km with a corresponding throw of about 1 metre, and a magnitude 6 earthquake has a fault length of about 10 km with a corresponding throw of 30 cm (Wells and Coppersmith, 1994), a significant seismic hazard exists from the shallow Quaternary fault systems of the PNG Highlands.

Mapped Quaternary faults exist south of the Sepik River and throughout the Highlands. These include the Fiak-Leonard-Schulz Thrust, Frieda Fault, April Fault, Korosamari Fault, Karawari Fault, Bismarck Fault, Stolle Lagaip Kaugel Fault, Star Mountains Thrust, Hanimu Fault, Kerewa Fault and Mendi Basement Fault.

The level of shallow earthquake activity is low. The region lies between the strong north coast and Papuan Fold Belt seismic zones, although the Star Mountains Thrust, Hanimu and Kerewa Faults are only just north of the Papuan Fold Belt seismic zone.

Two magnitude 5 earthquakes occurred in April and May 1985, on or near the April and Stolle-Lagaip-Kaugel Faults, near Porgera and Laiagam in the Enga Province.

A magnitude 5.7 earthquake occurred near Pangia in the Southern Highlands Province in November 1975. It may have occurred on the southeastern extension of the Stolle-Lagaip-Kaugel fault. It was felt in Pangia intensity 5.

As a magnitude 7 earthquake has a rupture length of the order of 50 km, a large earthquake could conceivably occur on one of these Quaternary Highlands faults and cause considerable damage in the Highlands.

2.4.8 Papuan Fold Belt

The Gobe Earthquake of March 2000 is the most recent example of mid-lower crustal seismicity taking place on steep, approximately northeast-dipping thrust faults in basement beneath the sedimentary basin sequence. This faulting is responsible for some of the crustal shortening that is a consequence of the compressive mountain-building stress regime maintained by the collision of the India-Australia and pacific Plates.

The Main Frontal Thrust or Hegigio Fault follows the Fold Belt seismic zone, although earthquakes occur both in front of and behind the thrust.

No earthquakes have occurred on the Darai and Komewu Faults in front of or southwest of the Main Frontal Thrust, but some small earthquakes are located on the northwest extension of the Darai Fault.

The location given by Everingham (1974) for the 1922 magnitude 7.5 earthquake, 7°S, 143°E, would place it on the Darai Fault, but the location was only an estimate.

No earthquakes are located anywhere near the Quaternary faults of the Fly River and Mt Bosavi, the nearest being north of Mt Bosavi on the Papuan Fold Belt seismic zone.

The Quaternary Darai and Komewa faults in front of, or southwest of the main Papuan Fold Belt Frontal Thrust are in an apparent aseismic region southwest of the main seismic zone in the Gulf and Fly Provinces. Also the Fly River and Bosavi fault systems are located well away from the recognised seismic zone. However Everingham (1974) determined that the magnitude 7 earthquake of 19 January 1922, which was strongly felt on the south coast, might have occurred in this region to the southwest of the main seismic zone.

2.4.9 Sunshine Fault - Bulolo Graben

A magnitude 6.0 earthquake occurred within the graben in October 1972 and possibly occurred on either the Sunshine Fault or a fault of the Bulolo Graben. The earthquake struck Wau hard but only for a few seconds. A car (presumed stationary) reportedly jumped off the ground.

2.4.10 Owen Stanley Fault System – Papuan Peninsula

Earthquakes have occurred along the whole length of the Owen Stanley Fault System, including the Timeno and Gira Fault regions. But in the midway region including the Gira Fault, only scattered magnitude 4 earthquakes have occurred. This is the section of the fault system closest to Port Moresby, about 50 km.

In the northwest section, which reaches the Huon Gulf in the vicinity of Salamaua, magnitude 5 earthquakes are common but there have been no recorded magnitude 6 earthquakes.

In the southeast section, southwest of Mt. Victory including the Musa River region, several magnitude 5 and one magnitude 6 earthquakes have been recorded. The magnitude 6.2 earthquake occurred on 16 September 1976, during the first anniversary of PNG Independence. The earthquake was moderately felt in Port Moresby (Ripper and McCue, 1981b; Ripper and Moihoi, 1996c).

The Quaternary fault extension into the Abau area of the southeastern end of the Papuan Peninsula is not matched by contemporary seismicity. This area of the Peninsula is virtually aseismic. Instead, the seismicity is occurring to the north in the Goodenough Bay and Goodenough Island regions. Magnitude 6 earthquakes could occur in the aseismic Abau area of the Papuan Peninsula.

No earthquakes have occurred close to the Kemp Welsh fault on the southern side of the Owen Stanley Ranges. However, several very small earthquakes have occurred close to the Owen Stanley Range Southern Fall fault. More significantly, the magnitude 6.2

earthquake that shook Port Moresby on 9 March 1979 occurred at depth 46 km in the Southern Fall region. As the depths in the figures only go to 40 km, the earthquake does not appear in Figure 8, but its occurrence at depth 46 km could indicate that the Quaternary fault systems of the Papuan Peninsula, including the Owen Stanley Fault System, extend deep into the crust. The earthquake has been described by Ripper, McCue and Wolter (1980), Ripper and McCue (1981a), and Ripper and Moihoi (1996c).

Large earthquakes can be expected to occur again in the Southern Fall fault area. Seismic activity of the Owen Stanley Fault System as a whole is ongoing, but the largest recorded earthquakes are only of magnitude 6.2. An earthquake of magnitude 7 on the Owen Stanley Fault System would not be unexpected.

2.4.11 Milne Bay

Although no seismicity appears to be closely associated with the Milne Bay Graben, the graben could be a potential earthquake site.

A low level of seismicity does occur in the region of the Quaternary Faults on Goodenough and Fergusson Islands, but the seismicity does not appear to follow the trend of the faults. However the D'Entrecasteaux region is highly seismically active, with the Woodlark Basin spreading system passing through the islands into Goodenough Bay. Magnitude 6 earthquakes have straddled the region, and minor damage has been caused by earthquakes of magnitude as low as 4. In view of Quaternary faulting and the high level of current seismicity, a damaging magnitude 7 earthquake would not be unexpected.

Since 1964, no significant earthquakes have occurred onshore at Woodlark Island. However the island is located on a zone of seismicity, which follows the Woodlark Ridge towards Bougainville Island. Two magnitude 6 earthquakes occurred close to Woodlark Island in 1960 and a magnitude 5.9 earthquake in 1992. The existence of the Quaternary faulting on Woodlark Island however indicates that a magnitude 6 or higher earthquake could occur on Woodlark Island itself.

In the Solomon Sea, Misima Island appears to lie in a seismicity gap between east and west Woodlark Basins but contains Quaternary faults. Woodlark Island lies on a seismic zone. Magnitude 5 earthquakes that occurred about 40 km WNW of the island are the largest close significant earthquakes. But the presence of Quaternary faulting on the island shows that potential for larger, magnitude 6 say, earthquakes to occur on Misima Island itself.

2.4.12 New Ireland

Central New Ireland contains two Quaternary faults, the Ramat and Andalon Faults, which give the normally aseismic region a significant seismic hazard.

The Quaternary fault system of southeastern New Ireland, particularly Sapom and Weitin Faults, would have no impact on seismic hazard because the region is already highly active. The largest earthquake was of magnitude 7.2 and occurred in 1985. However this high level of seismicity does not extend to central New Ireland, where the Quaternary Andalon and Ramat Faults are situated. Seismicity in the Bismarck Sea does come close to the faults in the southwest and seismicity between Lihir Island and New Ireland on the northeast. Hence central New Ireland in the vicinity of these Quaternary faults could be the site of future large earthquakes, the most recent being the magnitude 8.0 earthquake of 16 November 2000.

2.4.13 New Britain

Shallow earthquakes occur inland in the Gazelle Peninsula, probably associated with many large-scale structures (Madsen and Lindley, 1994) that dominate including the Baining, Mediva and Wide Bay fault systems. The level of activity is only a fraction of that of the subduction system to the south. However the magnitude 7.0 earthquake which occurred within the Gazelle Peninsula in January 1941 probably occurred on the Baining fault system (Macnab, 1970) and is indicative of the seismic hazard of PNG Quaternary faults. Fisher (1944) gave a detailed account o the effects of the earthquake.

Since the 1941 magnitude 7 earthquake, there have been virtually no shallow earthquakes on the Mediva or Baining Fault, most earthquakes occurring at greater depth on the subduction zone.

The existence of Quaternary faults in western New Britain does not add to the seismic hazard, already high from the intense subduction related shallow seismicity of the area.

2.4.14 Admiralty Islands

The Quaternary faults of Manus and Los Negros Islands suggest that the Admiralty Islands could be vulnerable to a large earthquake.

Only scattered weak seismicity exists through the Manus Island region. However, the existence of Quaternary faulting on Manus and Los Negros Islands indicates that these islands of the Admiralty group could experience a magnitude 6 or even 7 earthquake.

Magnitude 7 earthquakes have occurred elsewhere in the general north Bismarck Sea region.

2.4.15 Bougainville Island

No Quaternary faults are reported for Bougainville Island. The seismicity beneath the island itself is deep except in the southwestern corner, but the island regularly experiences strong earthquakes from the subduction system of the eastern Solomon Sea.

2.5 Exploring the collision zone

The PNG region is richly endowed with natural resources which include gold, copper, silver, natural gas, and oil; not surprisingly, a direct result of a very active geological past and present. Mineral exploration spans the region of plate margins, from far west and to farthest east, and possibly beyond these boundaries. The Bonaparte Basin, of North West Shelf of Australia, and the Papuan Basin, on eastern New Guinea which all form part of the complex convergence system on Australia's northern continental margin are the two prominent examples. Late Tertiary convergence between the Indo-Australian and South-East Asian plates has caused significant modification of sedimentary basins along this margin, many which are prospective for hydrocarbon exploration. The Papuan Basin in PNG has been strongly inverted and is now a well developed fold and thrust belt. Further east is an environment of continental extension which forms the Woodlark Basin, now known for its' mineral deposits. Similarly in the northwest is Manus Basin, a zone of back-arc spreading also interesting for abundant mineral deposits.

Recent advances in earthquake and other geophysical data interpretation are enabling better understanding of the tectonics and structural fabric of the PNG region. An improved understanding of the relationship between the ongoing tectonic activity (going on for millions of years), geology and mineral occurrence is emerging as a result. Seismicity has been the basis for better understanding the structural fabric, especially the tectonic configuration of the PNG region. Even with the enormity of work done by many researchers in the region the tectonic processes are extremely difficult to understand, and making it even harder by the number of plates and smaller tectonic fragments or blocks dominating, and the rates and complexity of their motions which exhibit rotations. These complexities does however help understand the setting of magmatic activity which has in places lead to huge economic mineral deposits, but much of which still remain only a mystery in the region (Hill *et al.*, 2001).

Locally, a number of recent studies have shown the value of monitoring earthquake sequences (main event and aftershocks) resulting in the mapping of active faults and determination of sense of the motion on the faults. Understanding the structural controls on and tectonic setting of mineral and hydrocarbon systems is the key to the mapping of and the development of these resources. The progressive study of earthquake sequences helps to define crustal structure both by direct evidence on individual faults and by association between elements of fault systems. In many cases, this information will be relevant to existing mineral and petroleum deposits, which are located in areas of young, active and evolving tectonics.

There are many discoveries of mineral deposits, some of which compare well to world-class mineral deposits. The locations of these discoveries, some existing mines, correspond to current plate boundaries and areas of volcanic activity. In the area of southern Highlands and parallel to the main plate boundary are the operating mines of Ok Tedi and Porgera. There are discoveries on New Britain, and on New Ireland, Lihir, and on Bougainville, and extending the isles southeast through the Solomon Islands. These locations are within very active tectonic regions parallel to current plate boundaries and may themselves be in the regions of plate boundaries previously not recognised.

There are also offshore discoveries of mineral deposits being planned for mining. Manus Basin in the eastern Bismarck Sea, within the extensional plate boundary is currently envisaged as an area of huge economic potential in mineral deposits.

Mining and related activities from the under-sea mining include those that would be carried out by Nautilus Minerals Exploration Limited, with the assistance of the East and New Britain, and New Ireland Provincial Administrations. The under-sea mining operations are being carried out between the waters of New Britain, New Ireland and Manus. Nautilus Minerals Exploration Limited discovered huge gold deposits (as well as other precious metals) under the seabed stretching from an area between Gazelle peninsula, the Saint George's Channel and West coast of New Ireland. The geology of northeastern PNG (Djaul Island and New Ireland) was investigated by Stewart and Sandy (1988).

The company has made similar discoveries in outlying islands of Manus, and farther a field to the southeast, in the regions of Fiji and Tonga.

In the PNG mainland region, and extending west to include Papua in Indonesia, pre-existing structures such as tilted blocks of the former margin of Australia and associated basement structures, control the direction of the escape zone (Pubellier and Ego, 2002). Added important roles of the basement structures are manifested in the location of mining potential in this region (White and Muir, 1989) as well as for the location of earthquakes (Abers and McCaffrey, 1988). The region of the PFB and IJFB are potential for hydrocarbon deposits, and in fact stand to sustain PNG and region economies when extracted for some considerable lengths of time.

Chapter 3 Seismology

Seismology is the study of earthquakes and their effect on the surrounding environment, in particular their impact on people and infrastructure. This is achieved through the analysis of seismic waves (and thus energy) generated by the earthquakes. This ultimately gives rise to the explanations of the deformation of the whole Earth, evidenced by earthquake activity along plate boundary edges, and as well as within plates where associated stresses develop.

A deforming plate margin is the result of colliding plates manifested in the creation of mountain ranges and valleys, hilly topography, volcanic arcs, and deep ocean trenches.

A terrane in geology is a fragment of crustal material formed on, or broken off from, one tectonic plate and accreted, or "sutured", to crust lying on another plate. The crustal block or fragment preserves its own distinctive geologic history, which is different from that of the surrounding areas (hence the term "exotic" terrane). The suture zone between a terrane and the crust it attaches to is usually identifiable as a fault. A PNG example would be the Finisterre-Sarawaget Ranges, and the Ramu-Markham Fault (Suture) to the south bordering the New Guinea Highlands crustal block.

The study of earthquakes ground motion, and the distribution patterns and sizes of earthquakes, would have been very limited without earthquake monitoring instrumentation. However, many historical seismological documents do reveal that quite a bit can be achieved by observing earthquake effects. In earlier times, long before the days of modern equipment it was the intuitive work of very dedicated and talented men who possessed extraordinary qualities of life, and who had "sufficient leisure, zeal and scientific information to enable them collect and describe with accuracy" (Bolt, 2006) the significant events, in particular earthquakes, as they happened. Modern seismologists have the advantage of being armed with sophisticated monitoring equipment, including computers and accessories, which improve seismograph network operations - earthquake surveillance and research - the whole globe over - with amazing results.

However, in regards to proper modern monitoring seismic equipment, the same cannot be said about many local operations. Surprisingly this includes some of the most seismically active regions, particularly those in disadvantaged parts of the globe including the PNG region.

Due to the difficulties faced in keeping the seismic network operational, the PNG local seismic network configuration has not improved. Currently the nearest seismograph to a typical PNG earthquake is at a distance of many hundreds to more than a thousand kilometres. This has resulted in large errors in earthquake locations by up to tens of kilometres. Because of the sparse network, only events larger than about magnitude 4 to 4.5 are routinely located using the global seismograph network. Because of the complex lithosphere, analyses using this distant data have limited accuracy, for both hypocenter determinations and magnitude.

Seismic hazard studies through variation of ground shaking, has developed in recent times and is now established as a very important branch of seismology. The enhancement of shaking due to the nature of earthquake faulting and fault rupture propagation, as well as geological conditions, does pose special risk to regions, particularly to those of dense populations of cities and towns. The study of earthquakes makes possible the identification of regions particularly vulnerable to earthquake shaking, and related dangers posed by the occurrence of surface rupture, liquefaction, and landslides. Deformation of the sea floor and earthquake triggered submarine slumping may result in the generation of tsunamis that may have devastating impacts on low-lying coastal community regions.

In PNG, regions of landslides caused by earthquakes are numerous and those areas vulnerable to tsunamis generated by earthquake shaking are being identified. It is worth a mention here of the significant 17 July 1998 Aitape Earthquake and Tsunami which devastated villages near the Sissano Lagoon along the northern coast of mainland PNG. The earthquake and tsunami have been extensively investigated (Ripper, Anton *et al.*, 2000), especially the tsunami, thus making it the most widely studied tsunami in the region – particularly in relation to its cause. One controversial analysis, is that a submarine landslide, with an estimated volume of slump debris 5-10 km^3 (Tappin *et al.*, 2001) but could have been much less at 3.8-4.6 km^3 (Sweet and Silver, 2003), was triggered by the magnitude 7.1 earthquake and triggered the tsunami. The slide generated a wave of about a metre 25 km offshore, which with the aid of seabed topography focused and amplified onto Sissano Lagoon and villages, thus causing devastation.

There are known cases of spontaneous landslides and slumping which have resulted in the generation of tsunamis, for example the Ritter Island volcano cone collapse of 1888 and the Voco Point, Lae, tsunami of 1972. However, it is known that the generation of tsunamis in the PNG region are largely by earthquake induced fault movement. Sweet *et al.* (1999) noted how complex faulting on the New Guinea continental margin is resulting in both extensional and compressional features evident from slumping, normal faulting and uplifted blocks – all indicative of active subduction erosion. Along the region of northern coast of mainland PNG, it has been revealed that a drowned coral reef complex (Tappin *et al.*, 1999) was identified and postulated as evidence of complex, and intense activity.

On even more advanced fronts, seismology has been a most effective tool in probing the inner parts of the Earth (Bolt, 1993). The kind of work involved began much earlier as the 1910s with the discovery of the core and inner core but became prominent only in the 1950s, and is being continually improved in recent times. Earthquake activity in all regions of the Earth, including that in PNG, has been used for such tomographic investigations.

3.1 Seismology in PNG

Denham (1969) first interpreted the seismicity of the New Guinea region in terms of tectonics. Ripper, Letz and Anton (1996) utilized data for subsequent years to 1994 and gave a detailed account of the seismicity and tectonics of PNG. Many investigations have assisted in developing and improving concepts of PNG earthquake distribution patterns and tectonics, including Johnson and Molnar (1972), Curtis (1973), Ripper (1975), Dziewonski *et al.* (1981), Cooper and Taylor (1987), Abers and McCaffrey (1988).

These and many other regional seismological investigations have uncovered and exposed the existence of much within this tectonically complex region of the southwestern section of the Pacific rim-of-fire. Although these many investigations have revealed much information many more geological questions remain unanswered. The location of the region has presented itself as being one of the most intriguing of the study of and investigation into the processes of tectonics which is the cause of intense earthquake activity. For instance, within the region there may be zones of ocean basin formation where continental rifting is developing into full scale seafloor spreading. The Woodlark Basin Rift in PNG (Ferries *et al.*, 2006) is one such known zone of continental rifting comparable to only a few other locations on the whole planet. The Woodlark rift is the zone of the transition from continental rifting to seafloor spreading akin only to three other such regions. The Gulf of Aden, the Red Sea, and the Gulf of California are other regions of studies of lithospheric structure during active continental breakup and where rapid extension is occurring (e.g. Weissel *et al.,* 1982; Taylor *et al.,* 1999).

Earthquakes are undoubtedly associated with active tectonism, marking the plate boundaries. In the PNG region, all known types of plate boundaries exist – from subduction along trenches, to zones of plate extensions or seafloor spreading along mid-oceanic ridges and zones of transform faulting. As noted from seismicity, bathymetry and topography, the main subduction regions are marked by the New Britain-Bougainville-San Cristobal and New Guinea Trenches, while the Woodlark and Bismarck Basins are dominated by zones of seafloor spreading. The Weitin Fault system of southern New Ireland and the Ramu-Markham Valleys Fault system of Huon Peninsula, and possibly the Owen Stanley Range Fault system of the Papuan Peninsula, mark known regions of transform plate boundaries. The Owen Stanley Range Fault system has a huge component of dip-slip and less dominant transform faulting, and a good example of diverse plate boundary styles. To the east of the Papuan Peninsula is the zone of continental rifting which is developing to seafloor spreading further east in the Woodlark Basin.

Geology and geophysics data (especially gravity and magnetic) were also used to assist in defining the structural fabric, and thus make easier the clarification of the seismic source zones in the region.

3.1.1 Earthquake distribution

The seismicity is best understood to be the result of the interaction of tectonic plates in the region. Earthquakes are distributed along plate boundaries that include broad zones of crustal deformation, such as the Papuan Fold Belt and the northern boundary of the Bismarck Sea along the length of the West Melanesian Trench. It is envisaged that the plate boundary along the West Melanesian Trench defining the northern margin of the North Bismarck Plate with the Pacific Plate may have locked and currently moving westward in unison with the leading Pacific Plate front, westward. Further west, the movement of this massive plate front together with the thick and buoyant lithosphere of the Euripik-New Guinea Rise part of the Caroline Plate (Den *et al.*, 1971) are responsible for the current oblique collision with the India-Australia Plate along the northern New Guinea margin. The absence of volcanoes associated with this plate boundary, westward from about Wewak also indicates that the lower plate response to convergence is not typically of pure subduction (Anton and McKee, 2005b) but is highly oblique, with a component of strike-slip. Ten earthquakes world-wide have accounted for 80% of 1 million casualties in the last 50 years (Spence, 2007). In the global context, some of the world's great earthquakes have occurred in PNG. Table 1 shows the list of major earthquakes of the PNG region, and the list of magnitude 7 and above earthquakes are shown in Appendix 2. As recently as in the year 2000 and again in 2007, the PNG region sourced the magnitude 8 earthquake to have occurred anywhere in the world. Other worldwide great earthquakes include the Ms 8.0 of Sumatra on 4 June 2000, Ms 8.0 of Cocos on 18 June 2000, magnitude 8.2 of Kuril Is on 13 January 2007 and magnitude 8.4 of Sumatra on 12 September 2007.

Table 1: Known great earthquakes in PNG
(from Abe and Noguchi, 1983; Engdahl et al., 1998; Pacheco and Sykes, 1992; ISC; USGS).

Date Year-mm-dd	Time hr:min	Lat °S	Long °E	Depth km	Ms	Moment 10^{20}Nm	Mw
1906-09-14	16:04	7.00	149.00	Shallow	7.4	12.70	8.0
1935-09-20	01:46	3.50	141.75	Shallow	7.9	14.50	8.0
1971-07-14	06:11	5.50	153.90	53	7.8	12.00	8.0
1971-07-26	01:23	4.90	153.20	48	7.7	18.00	8.1
1996-02-17	05:59	0.89	136.95	33	7.8	24.00	8.2
2000-11-16	04:54	3.98	152.17	28	8.2	12.40	8.0
2007-04-01	20:39	8.47	157.04	24	7.7	16.00	8.1

Seismicity in the region of the northern Solomon Sea, adjacent to New Britain and Bougainville Islands, has been described as one of the most intense in the world (Cooper and Taylor, 1989; Ripper and McCue, 1982; Ripper and Letz, 1991; Ripper and Letz, 1993). Out of 109 magnitude 7 and 8 earthquakes that occurred within PNG during the 108 year period 1900-2008, almost half, forty-seven, occurred in the region of the northern Solomon Sea. The largest earthquake being only of magnitude 8.2, the total moment is a lot less than that for Chile, Alaska, the Kurils, or Sumatra – those regions having recorded higher magnitude events, some multiples of earthquakes. Earthquake activity in the whole PNG region, in the period 1900 to 2008 is shown in Figure 13. In this figure, shallow earthquakes (less than 40 km depths) are shown in red circles with increasing sizes indicating increasing magnitudes. The triangles and inverted triangles indicate intermediate depth ranges (40 to 300 km depths) while the deep earthquakes (300 km and deeper) are denoted by stars.

Shallow earthquakes occurred at depths indicating interactions within the crust of lithospheric blocks. These earthquakes are occurring in areas of crustal extensions within oceanic spreading centres, and along areas of major fault zones, as well as in zones of crustal deformation, including shallow earthquakes at subduction zones. In the region two main regions of seafloor spreading creating new basin areas are the Manus and Woodlark Basins. Here active crustal extension rates are amongst the fastest in the world. Abers *et al.* (2002) determined at rifting rate of 20-35 mm/yr. Other modern zones of continental rifting include the Gulf of Aden, the Red Sea and the Gulf of California (Ferris *et al.*, 2006). Zones of crustal bending as subducting slabs bend downward in subducting zones connect these spreading centres, in particular along the New Britain-Bougainville-Solomon Trench and along the New Guinea Trench. Shallow earthquakes connect these zones with transcurrent fault systems of southern New Ireland with the New Britain Trench and the Ramu-Markham Fault system, while the Owen Stanley Range Fault system connects with the Woodlark Basin. The main zone of crustal deformation identified is the Papuan Fold-and-Thrust Belt in PNG, while the Irian Jaya Fold-and-Thrust Belt is located in the west in Papua Province, Indonesia across the shared border. These are the main regions of intense shallow earthquake activity.

On the other hand, intermediate depth earthquakes would be mostly recognized in zones associated with subduction of lithospheric slabs, or segments of slabs. Such is the subduction of the Solomon Plate along the New Britain-Bougainville-Solomon Trench, and the South Bismarck Plate along the New Guinea Trench. Intermediate earthquakes are recognized beneath eastern New Guinea resulting from the westward subduction of the Solomon Plate. The sinking lithosphere here may be progressing as far west as 135°East (Ripper, Letz and Anton, 1996). North and south sinking limbs have also been recognized (Pegler et al., 1995), generating intermediate depth earthquakes along the entire eastern and northern PNG mainland, to at least 142° East.

Earthquakes at depths greater than 300 km occur under northern New Britain, central or southern New Ireland, western Bougainville and northern Bougainville. These earthquakes define the segments of the Solomon Plate now deformed, detached or partially melted and becoming part of the mantle.

From the earthquake data available so far, it is seen that the frequency of earthquakes occurring decrease with both depth and magnitude size. In general, there are far fewer earthquakes at very deep and very large.

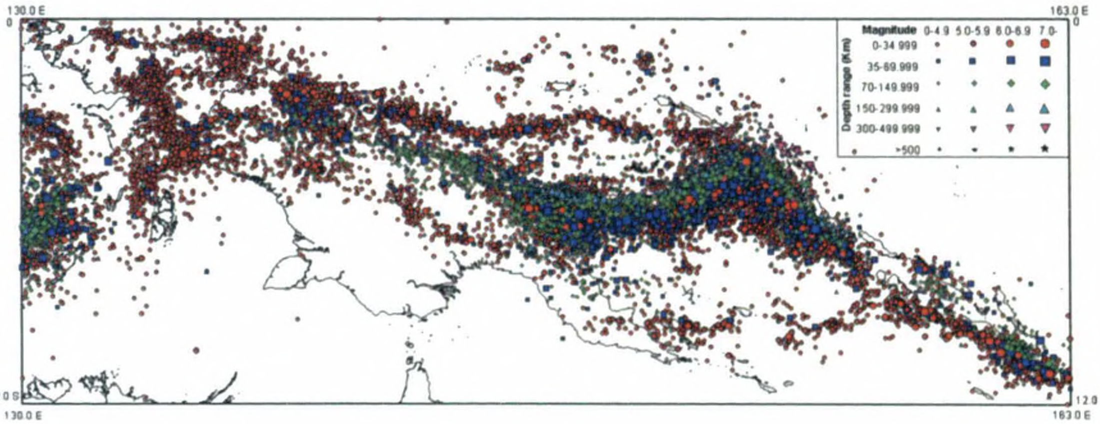

Figure 13: Seismicity of the PNG region for the period 1900 to 2008.
The map region includes Papua Province, Indonesia to the west and the Solomon Islands to the southeast.

It has also been suggested that the felt effects of intermediate to deep earthquakes are mitigated due to radiation pattern and population distribution, so while shaking may not be strong at places near the epicentres, the effects at more distant places may be more profound. In particular earthquakes of great depth beneath Long Island, eastern New Guinea are usually widely felt through the Highlands, some strong enough to cause damage. Typically in deep earthquakes from this region, the energy apparently is channeled up through the sinking Solomon lithospheric plate slab southwest into the Highlands, as suggested by Denham (1971). The slab is the western segment of the Solomon Plate, which is subducting beneath the New Guinea/Bismarck Volcanic Arc.

The Port Moresby Geophysical Observatory (PMGO) has established and maintained earthquake databases containing information about earthquakes that occurred in the PNG region, as well as earthquake intensities since 1900. Figure 14 shows the major significant earthquakes (magnitude Ms 7 and above) for the region, between 1900 and 2008.

Seismicity reports outlining patterns and distribution of earthquakes in the region, such as those by Denham (1969, 1971, 1974, 1975), Everingham and Sheard (1980), McCue (1979, 1982), Ripper (1975, 1977, 1988, 1990, 1991), and Anton (1992, 1993, 1994, 1995, 1996b, 1996c), detailed earthquake effects, and described seismicity in terms of plate tectonics. Denham (1969) first interpreted earthquake activity of the PNG region, and gave a view of the distribution of earthquakes and seismic sources of the region. Ripper and Letz (1991) discussed the distribution and origin of the PNG region in the period 1900 to 1989.

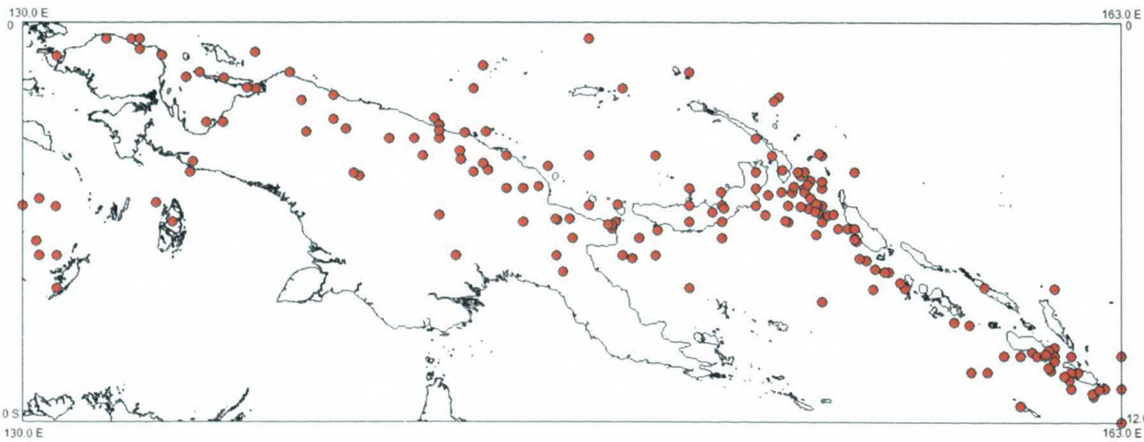

Figure 14: Large earthquakes in the PNG region, 1900 to 2008.

The map shows magnitude 7 and 8 earthquakes of the PNG region. The map region includes the Papua Province of Indonesia to the west and the Solomon Islands to the east.

3.1.2 Seismicity depth zones

Viewing seismicity in 3-D does present a better understanding of occurrence of earthquakes within or along features of the source, in space and possibly time. This alone assists greatly in identifying the source zones of earthquakes. Subducting lithospheric slabs define the Wadati-Benioff Zones beneath the respective segments of New Britain and Bougainville-Solomon Trench. Subduction at places is occurring to depths of more than 600 km. Intermediate depths zones are noted beneath eastern New Guinea and northwestern Papuan Peninsula, defining segments of lithospheric slabs that have now detached and are being assimilating into and becoming part of the upper mantle. Shallower depth earthquakes define the margins of numerous lithospheric crustal blocks of the region. These blocks or plates are numerous, and motions of intense against each other thus making the region significantly active.

Shallow depth earthquakes

Crustal blocks and plates are well defined by shallow seismicity, mostly in the depth range 0 to 40 km. In Figure 15 the shallow earthquakes, either linearly or broad seismic zones best define most of the plate boundaries of the region, those undefined by earthquakes are identified using regional geology, geophysics and geodesy.

Shallow earthquakes also define geological features such as fault systems. Areas where such features are associated with shallow activity include the southern PNG mainland, the Papuan Fold-and-thrust Belt. Earthquakes here are a result of the India-Australia Plate front deformation due to its continuing collision with the South Bismarck Plate. Stress build-up is migrating south from the plate boundary along northern New Guinea to where energy is released along NW-SE trending faults along the zone of folding and thrusting – the Highlands Fold and Thrust Belt (Papuan Fold and thrust and Irian Jaya Fold and Thrust Belts), in front of the India-Australia Plate cratonic platform.

Mid-oceanic ridges and zones of transcurrent fault movements such as those linking to zones of plate subduction are areas of shallow earthquakes. Plate edges are marked by the two zones of mid-oceanic ridges indicating ocean floor spreading in the Woodlark and Manus Basins. Major zones of transcurrent fault movements marked by the Ramu-Markham Valleys suture, indicate the boundary between the New Guinea Highlands and South Bismarck Plates; the Weitin Fault of southern New Ireland, indicating the boundary between the Pacific and South Bismarck Plates; and the Owen Stanley Fault system marking the southern boundary of the Solomon or the Woodlark Plate with the India-Australia Plate.

Perpendicular features existing along the length of the New Guinea/Bismarck Volcanic Arc, here termed cross-arc features (cross-faults) are known to have been zones of occurrence of large shallow earthquakes. Other features with orthogonal seismic zones are a result of tear in the upper plate due to strain release, and exist along the entire New Guinea/Bismarck Volcanic Arc. While the earthquake database is too short (about 100 years) to properly identify these zones, records of recent occurrences of large shallow earthquakes on these zones have assisted enormously in identifying and defining the hazard. The focal mechanism solutions and the aftershock distributions have generally been consistent and complemented each other well, as to the direction of motions on which respective earthquakes had occurred. Geological mapping now confirms the existence of these orthogonal fault structures existing along the arc, and Abers and McCaffrey (1994) referred to them as evidence of extension of the accreting terrane and the compression of the lower plate, both along-strike of the main structural boundary.

Abbott *et al.* (1994) noted from structural mapping in the Finisterre Mountains, and side scan sonar images and potential field data from the western Solomon Sea, a series of NE-SW trending cross faults. The faults are recognized as trending perpendicularly to the dominant structural trend, and having components of left-lateral strike-slip and SE down dip-slip motion.

It is possible that some of these structures extend offshore to areas investigated for the mechanism of tsunami generating debris during the Research Vessel Kilo Moana cruise survey (KM0419) of the New Guinea/Bismarck Volcanic Arc (Silver *et al.*, 2005). One such fault trending north-south that was not previously known is found on the sea floor north of Kimbe Bay in north-central New Britain.

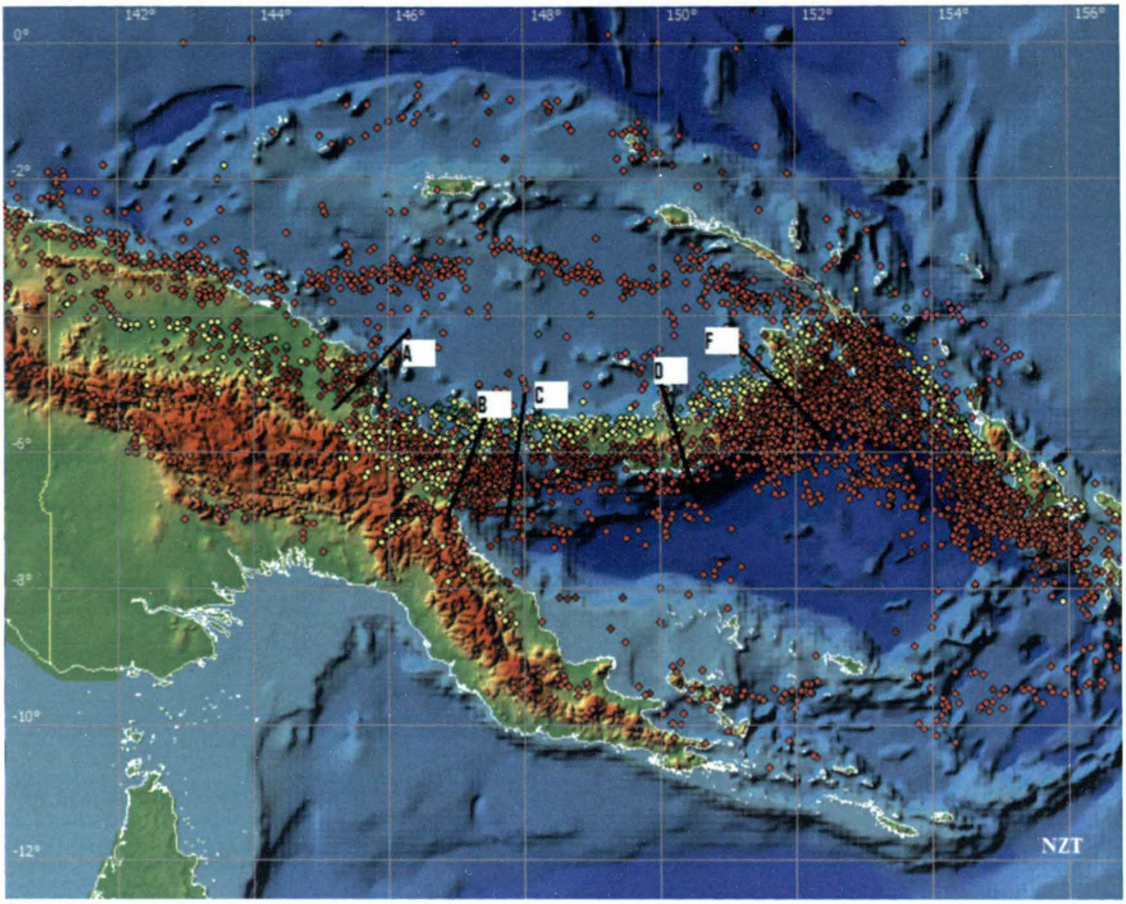

Figure 15: Locations of some cross-arc seismic zones.

These delineate source features. The trend of the Madang 1970 Earthquake and sequence is denoted by A (and shown in Figure 16), B denotes the location and trend of the Lae Seismic Zone, C denotes the trend of the Umboi Earthquake and sequence of 1987 (shown in Figure 16), D denotes the location and trend of the Willaumez Peninsula feature, and E denotes the approximate location and trend of the Wide-Bay Isthmus. Features that trend along strike with the arc exist within the Finisterre Range (e.g. the trend of 1993 Finisterre Range Earthquake and sequence) and central New Britain (e.g. trend of 1985 Earthquake and sequence).

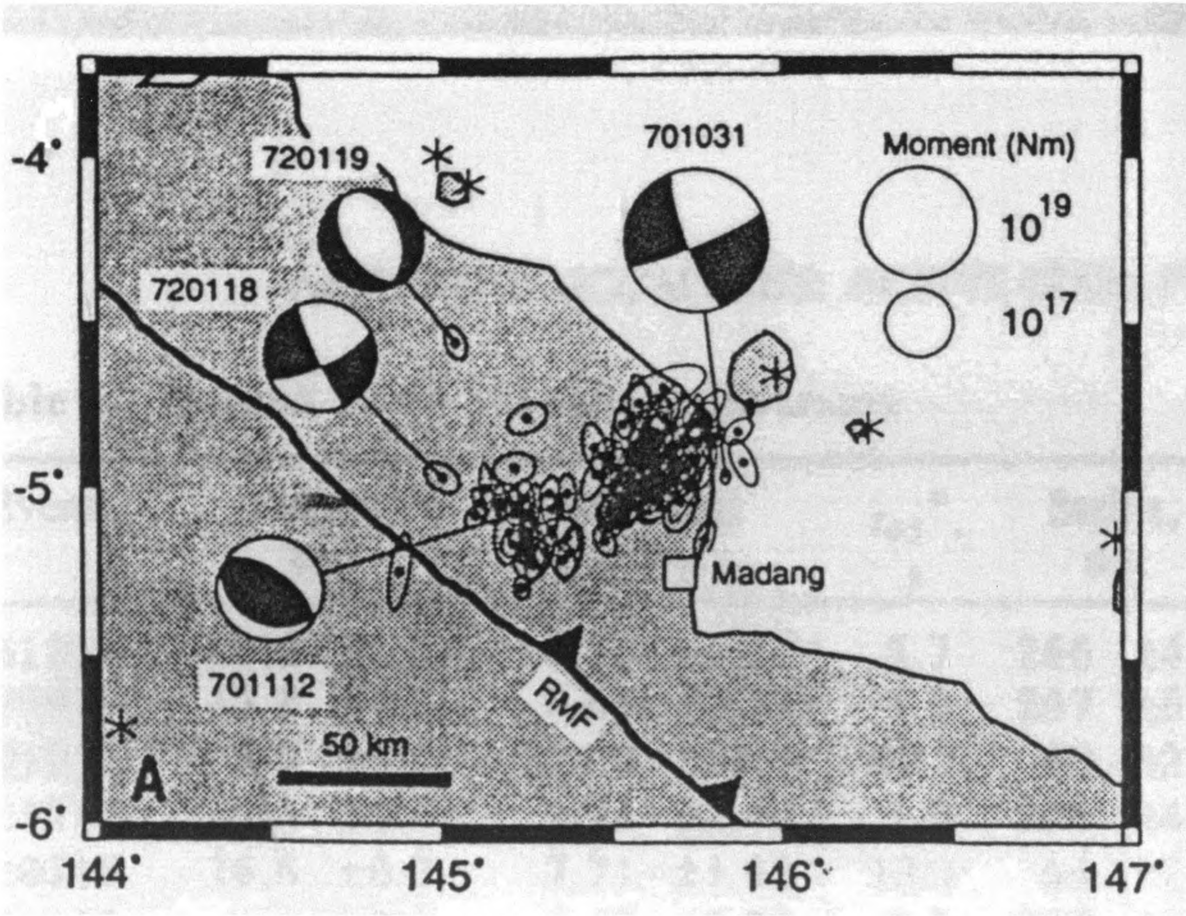

Figure 16: The Madang 1970 October 31 earthquake sequence.
(From Abers and McCaffrey, 1994). The earthquake focal mechanism solution is indicating NE-SW left-lateral strike-slip and the aftershock sequence distribution also elongation in the same trend.

This style of fault movement is quite different to that indicated by and representative of the main stress regime, particularly the stress orientation, and probably indicates activity on structures different to the main rupture surface which experience over-thrusting and possibly some strike-slip movement. The aftershock sequence of the Madang 1970 Earthquake includes strike-slip, reverse and normal faults, and the maximum principle stress is consistent for the strike-slip and reverse events. A feature of the pattern of faulting in the coastal mountain ranges is that of the main "east-west" trending faults being displaced or terminated by cross-faults that trend NE-SW, such as that identified during the analysis of the 08 September 2002 Wewak Earthquake (Anton and McKee, 2005b).

The most significant of these events have been the Madang earthquake of 1970, which had a left-lateral strike-slip focal mechanism solution and aftershock sequence; the Umboi right-lateral strike-slip focal mechanism solution event and sequence of 1987; and along-strike (parallel to the arc) events of Finisterre Range sequence of 1993 and the central New Britain earthquake of 1985. The events striking orthogonally to the arc are indicated their locations on Figure 15.

The 1985 Earthquake of central New Britain was a shallow left-lateral strike-slip with a fault plane of strike 100 degrees, dip of 80 degrees to the north, and fault dimensions of 50 km length x 15 km depth. The aftershocks were distributed in an East-West zone dipping steeply to the South. These results indicate that the main earthquake occurred on a near vertical fault extending for about 50 km in an East-West direction over a depth range of 0 to 15 km, or even 20 km. The mechanism of that earthquake is evidence for tensional stress in the frontal arc (the region between the trench and the volcanic front). This is unusual and local mechanisms and geological evidence usually showing that the upper plate is under compression in the area trench-ward of the volcanoes.

Known cross-arc seismic zones and fault systems have been the Lae Seismic Zone (Kulig *et al.*, 1993) and the Wide Bay/Open Bay isthmus feature, appropriately represented by the Baining Fault System. There has been little or no activity on either of these features in very recent years. Further geological mapping may uncover the existence of more of these zones, some of which may have been defined by the Madang 1970 Earthquake and aftershock sequence (Abers and McCaffrey, 1994), Figure 16, and the Umboi Earthquake of 1987 and aftershock sequence (Abers and McCaffrey, 1994), Figure 16.

The most pronounced cross-arc feature on New Britain is the Willaumez Peninsula (see Figure 18). The Willaumez Peninsula is not part of the frontal arc, so the east-west tension there does not conflict with the view that the frontal arc part of the subduction zone in the central-east New Britain region experiences north-south tension. The tensional stress in the frontal arc is consistent with the view of the geodynamics in the New Britain region such as that viewed by Ripper, Letz and Anton (1996). A view held, and supported by the fault plane solution of the 1985 central New Britain Earthquake, is that suggesting that the arc is under tension (Mori, McKee and Letz, 1987). The mechanism of that earthquake is strike-slip with the tension axis orthogonal to the plate margin.

As for the origin of the Willaumez Peninsula (feature), Davies *et al.* (1987) have speculated that flexure in the subducting Solomon Plate may be responsible for the uplift in central New Britain and development of volcanoes along a linear north-south trend. There is perhaps no where else on Earth where such a record of volcanism perpendicular to the trench axis, with volcanoes overlying the Wadati-Benioff zone (Johnson, 1979) and earthquakes occurring at depths of as much as 610 km further north beneath the Witu Islands (Ripper, Letz and Anton, 1996).

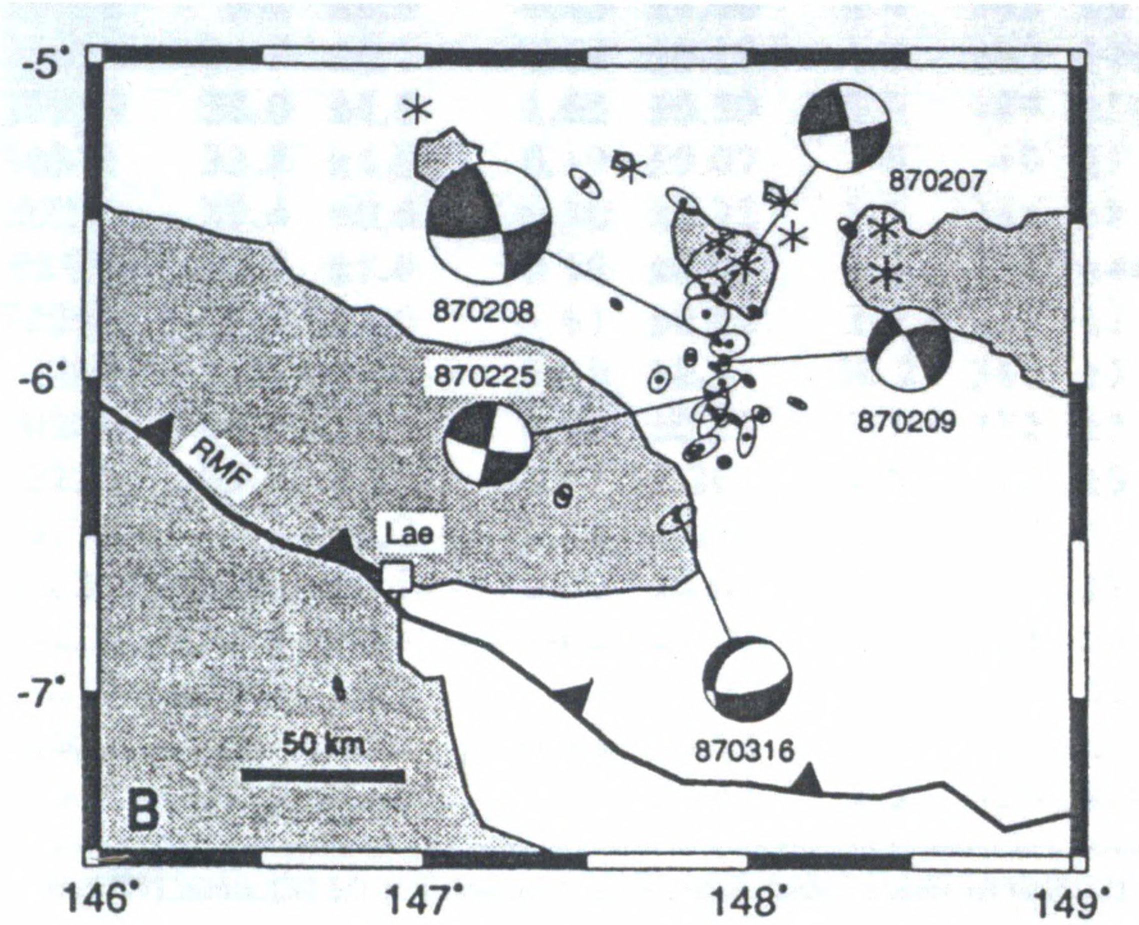

Figure 17: The Umboi earthquake of 1987-02-08 and aftershock sequence. (From Abers and McCaffrey, 1994)

There exist a number of east-west lineaments in the central-eastern New Britain region. Large-scale east-west features are present at Ulawun, Bamus and Hargy volcanoes, for instance (McKee and Lolok, 1998). Some cross-arc features are prominent in the central-western part of the arc, which extends from around the western tip of New Britain to

Madang-Bogia, and includes the Finisterre-Sarawaget Ranges in the centre. On New Britain, it has been suggested that shallow earthquakes having focal mechanisms with the tension axis orthogonal to the plate margin, for instance the earthquake of 10 May 1985, is an indication that the arc is under tension (Mori, McKee and Letz, 1987; Ripper, Letz and Anton, 1996). The present tensional stress may be an indication of a new stage of spreading that will rift New Britain creating a new marginal sea (Ripper, Letz and Anton, 1996).

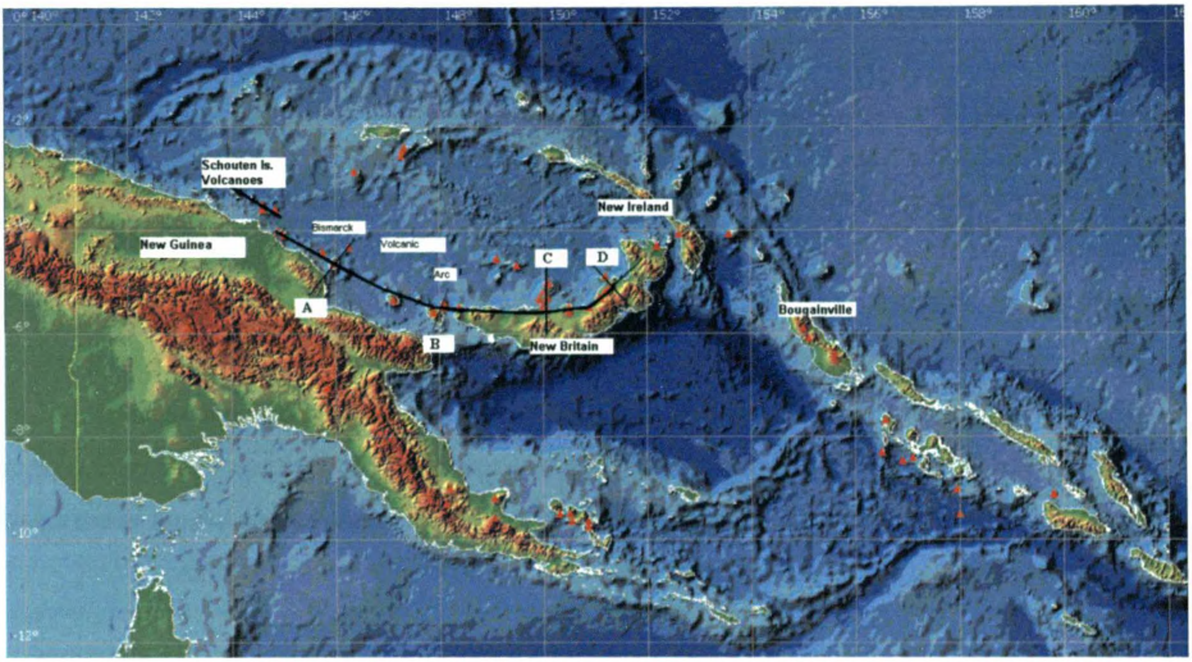

Figure 18: Bismarck Volcanic Arc.
The map illustrates some examples of cross-arc volcanic features; A denotes the Karkar trend, B denotes the Umboi trend, C denotes the Willaumez Peninsula trend and D denotes the Ulawun trend. The Schouten Islands volcanoes are regarded as part of the volcanic arc, but are offset by 25 km from the trend of the volcanoes to the southeast.

Further west, the reactivation of a system of these features may have been evidenced by the occurrences of two magnitude 6 earthquakes after the 8 September 2002 Wewak Earthquake. These earthquakes were located at the western end of the aftershock distribution field. The mechanism of a magnitude 6.6 just southeast of Aitape on 10 January 2002 had a similar mechanism. This and the mechanisms of the 2002 Wewak earthquakes had their normal faulting mechanisms and their locations suggesting movement on a northeast trending cross-fault system, which terminates the main east-west overthrust (and transcurrent) rupture (Anton and McKee, 2005b). The features at these respective locations are zones accommodating southwest oblique convergence along the northern New Guinea front of the New Guinea Highlands plate margin.

Intermediate depth earthquakes

Intermediate depth earthquakes range from about 40 to 300 km. These earthquakes are mostly related to subducting lithospheric slabs, mainly along the subduction zones. In PNG these are the regions beneath the northern-eastern New Guinea and New Britain-Bougainville-Solomon regions, marked by the New Guinea and New Britain-Bougainville-San Cristobal Trenches respectively.

Beneath offshore eastern New Guinea, northern New Britain and Bougainville Islands, the seismicity at these depths can be associated with magma production related to volcanic activity evidenced by the volcanic belt (Figure 18), which dominates the surface above these depths. Although volcanic related seismicity may be shallower and localised to respective volcanic centres, it is actually at these intermediate depths that segments of the subducting Solomon Plate lithosphere begin to melt. The melting lithospheric slabs become the sources of magma production. The magma at depth rises to the surface through weaknesses in the crust, and in the process of doing so developing volcanoes.

Also in PNG, intermediate depth earthquakes are associated with the westward sinking of the Solomon plate beneath New Guinea. The sinking slab is evidenced by inverted U-shaped trending seismicity, one end indicating northward sinking beneath northern New Guinea (Davies, 1990; Letz, 1985) and while the other indicating southward sinking beneath central New Guinea (Ripper, 1982; Pegler *et al.*, 1995; Ripper, Letz and Anton, 1996). This westward sinking has been postulated to extend as far west as 135°E, and the earthquakes are suggested to be genetically different from shallow earthquakes associated with the effects of continental-arc collision between the India-Australia and New Highlands Block, and the New Guinea Highlands Block with the South Bismarck Plates (Ripper, Letz and Anton, 1996; Anton, Gibson and McCue, 2008). Tregoning and Gorbatov (2004) showed evidence for the southwest subducting South Bismarck lithospheric slab and stated that the evidence for the inverted U-shaped doubly sinking Solomon Plate slab beneath eastern New Guinea lies beneath the southward sinking South

Bismarck Plate. Both lithospheric slabs are sources of intermediate depth earthquakes beneath the New Guinea region.

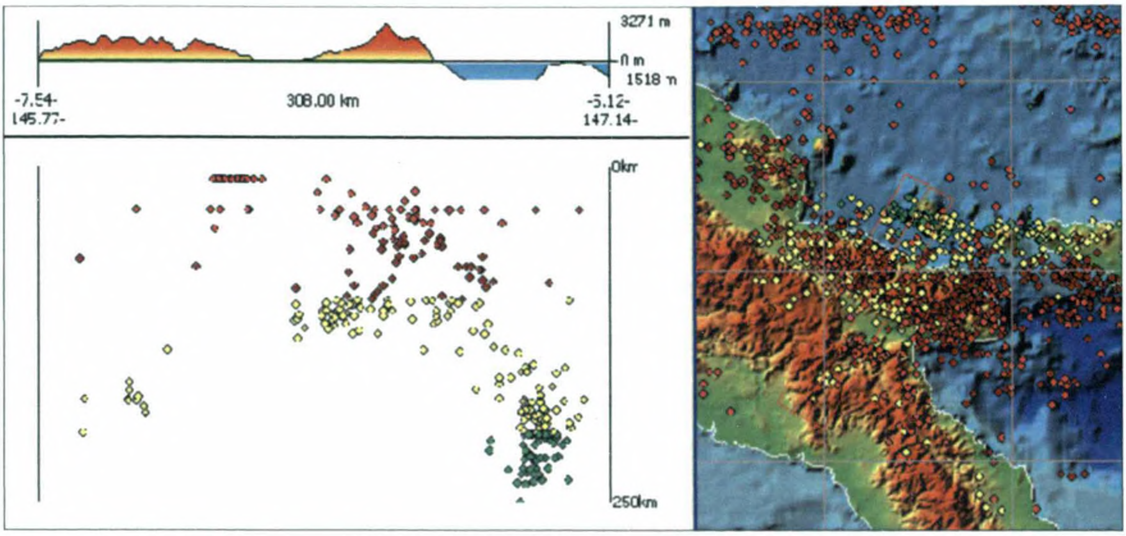

Figure 19: Seismicity profile beneath eastern New Guinea.

Shown is a NE-SW profile beneath Huon Peninsula-Menyamya region. The profile shows intermediate depth seismicity caused by north and south arching of the Solomon Plate as subduction continues west-northwestward, while shallow seismicity is caused by the collision of the South Bismarck Plate and crustal blocks to the south.

However, to properly differential slab activity of earthquakes resulting from the subduction of the South Bismarck Plate to that at depth resulting from the westward sinking Solomon lithospheric slab, there requires much higher resolution seismology than is possible at present. It would need a dense local seismograph network over northern-eastern New Guinea region to provide precise locations and focal mechanisms.

Deep earthquakes

In PNG, deep earthquakes greater than 300 km occur along the edges of the subduction Wadati-Benioff zone of the New Britain Trench. Here the Solomon Plate is subducting and is being annihilated deep northwestward beneath the area of the eastern Bismarck Sea, just to the west of northern New Britain and northwest of Gazelle Peninsula. The Solomon Plate is also sinking northeast to depths greater than 300 km in the area beneath the Cataret Islands, east of southern New Ireland and also deep beneath western Bougainville. The earthquakes deep beneath Bougainville are occurring vertically beneath the intermediate and shallow depths. The vertical depth pattern is a result of and indicates the encountering of the subducting Solomon Plate with the buoyant Ontong Java Plateau beneath the Bougainville front of the Pacific Plate. Bougainville Island is situated in front of the Ontong Java Plateau a continental landmass subsided and docked in front of the westward advancing Pacific Plate in the Pleistocence 70 Ma (Yan and Kroenke, 1993; Petterson et al., 1999; Mann and Taira, 2004).

Very deep earthquakes are also occurring northwards beneath central New Ireland, in the line of a great circle joining the Cataret Islands in the east and Witu Islands in the west. This line of circle basically defines the line of the outer edges of the sinking Solomon Plate at respective locations, and in fact where the lithospheric slab may have detached in places and now pieces of it floating further below into the upper mantle (Cooper and Taylor, 1987). Deepest earthquakes defining the leading edge of the sinking lithospheric plate segments are known to be more than 600 km.

3.1.3 Seismic instrumentation

Local earthquake monitoring began in November 1957 with the installation and operation of a seismograph in Port Moresby followed soon by others, although seismographs were operated at the Rabaul Volcano Observatory more than a decade earlier. The number of stations increased in the early 1960s including the installation and operation of World Wide Standardised Seismograph Network (WWSSN) station in June 1962. By 1965 PNG seismic data began to be contributed to the international Seismological centre (ISC). The number of short period seismic monitoring stations gradually increased to more then ten by 1970, and jumped to 15 or more in the following ten years.

Also by the 1970s strong motion recording equipment and stations increased in number. After PNG gained Independence in 1975, the observatory (with the seismic networks) and the facilities were handed over to the PNG Government. Operations ran smoothly for another ten to fifteen years to about the mid-1980s, with assistance still coming from the Australian Government – including personnel. But operations started to experience failure thereafter, mostly due to the lack of or insufficient resources particularly funding.

By early 1990s the analogue network was replaced with German funded digital equipment. The operations of the digital network never got off the ground to its full capacity. There was no provision for replacement equipment, let alone maintenance spares, so the years through to the turn of the century saw the networks fail through lack of maintenance. Equipment at individual stations was left to run until it experienced failure and then station operation ceased. Funding assistance from the PNG government was not forthcoming and that saw the end of a functional seismic network.

The equipment used in PNG seismograph stations has seen numerous changes over the last three to four decades. The digital equipment deployed in the early 1990s, however, was of a first generation model, and did not last as spare parts were not available to sustain operational maintenance. At the time of writing of this thesis, the local network is almost non-existent. The earthquake activity monitoring in the region is being continued by the global seismic network through USGS/NEIC and IRIS, with collaboration from others such as ISC, CTBTO and PTWC. The global network equipment in Port Moresby (PMG) replaced the WWSSN equipment in September 1993 after more then 30 years of successful operation.

The funding needed for maintenance of or replacement of the seismic station network is not readily provided, and government officials need to be convinced that this spending from the public purse is beneficial and essential. They must understand that all countries have experience damage to property during significant earthquakes, and economies sustain losses as a consequence. If local earthquake data is not available for use in building and construction of infrastructure then significant losses can occur, or less likely, significant expenditure may be wasted on over-design.

Nevertheless, contributions have been made with the availability of seismic data, both raw and analysed data. Waveform patterns from seismograms in PNG and regionally have assisted revealed earthquake source zones, as well as the structural compositions along paths of propagation.

In regard to earthquake hazard and risk mitigation widespread instrumental measurements can help shed light on many important issues. Bolt (2006) in an analysis of the 1979 Imperial Valley Earthquake, California, outlined the issues to include, firstly the repetition of earthquakes along the same seismic zones and fault system, and the implications for earthquake prediction; secondly, the slip on adjacent faults within fault systems in earthquake sequences; thirdly, the variation of strong ground shaking as measured by specially arranged groups of strong motion seismograph arrays; and finally, the seismic resistance of structures with built-in earthquake provisions.

It is quite difficult to achieve any results without proper instrumentation, with both high sensitivity and strong motion seismograph equipment needed. A network of equipment that can achieve spatial resolution much less than 10 km requires a seismograph network surrounding the earthquake with a spacing between instruments of 50 to 100 kilometres, for example as suggested by Tregoning and Gorbatov (2004). Denser local seismograph networks would give even better spatial resolution of the seismicity patterns, and the Japanese are considering a new low-cost high-density seismograph network with instrument spacings reduced from between 10 and 20 kilometres, to between 5 to 10 kilometres. As described earlier, the nearest seismograph to an earthquake in PNG is typically at a distance of hundreds of kilometres to over one thousand kilometres, which is one of the lowest density networks in any populated region, and certainly the lowest in any highly active region. Earthquake hazard studies would consequently improve.

The seismic network configuration is shown in Figure 20. Locations of past and present seismographs, as well as locations of accelerographs are as indicated. At the time of writing, only Port Moresby and Rabaul stations are operating. The rest of the nationwide stations, both seismograph and the analogue accelerograph networks are non operational.

Due to the difficulties faced in keeping the seismic network operational, the network configuration has not been improved and therefore, currently the nearest seismograph to a PNG earthquake is at a distance of many hundreds to more than a thousand kilometres. Apart from the large errors in earthquake locations (up to tens of kilometres), the sparse global seismograph network only records events larger than about magnitude 4 to 4.5. Because of the complex lithosphere, both magnitude and hypocenter determinations have limited accuracy.

Few analogue accelerographs operated in the 1970s and 1980s, so very few strong motion records for attenuation studies are now available.

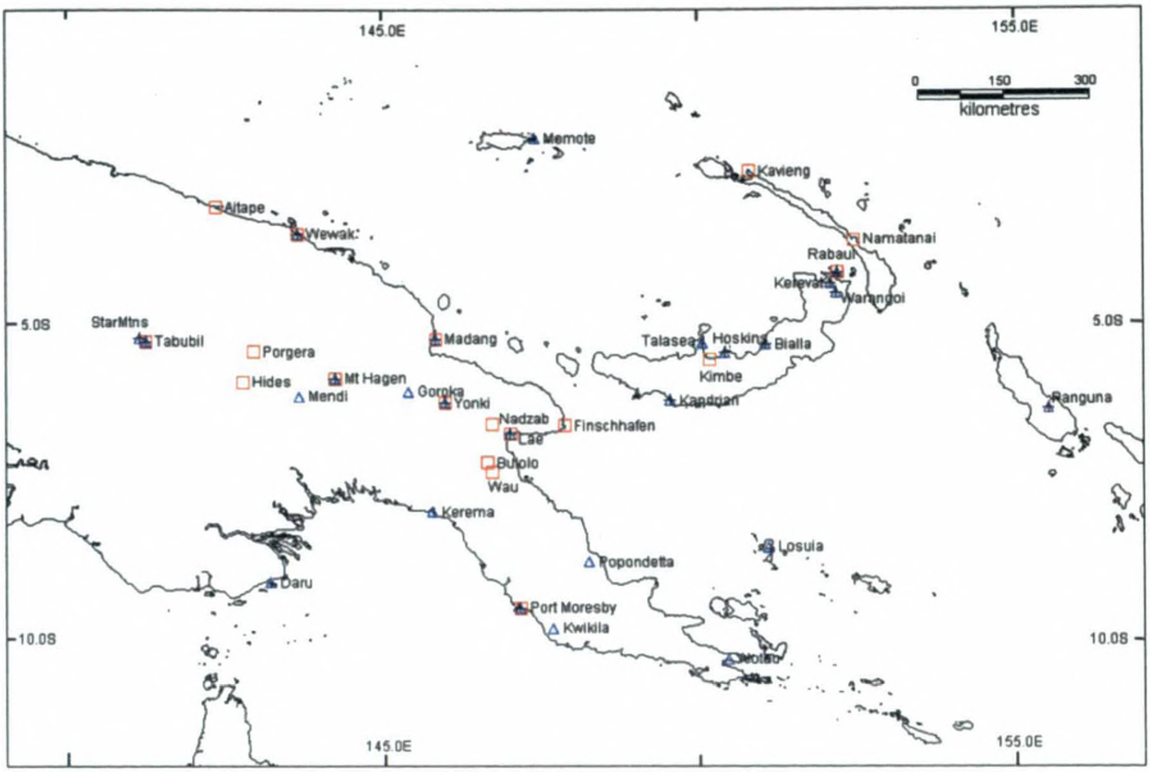

Figure 20: PNG seismograph network, past and present.

Red squares show locations of seismographs operated in the recent past, within the last ten years. The triangles are locations of accelerographs and seismograms operated in the 1970s and 1980s, none of which are currently operating. The only seismographs currently operating are at Port Moresby and Rabaul.

3.2 Significant historical earthquakes since 1900

A brief discussion of historical earthquakes is outlined in this section. The historical earthquakes discussed here are significant because of their size, or may be significant as a result of their area of locations, or damage they have caused. Most of the larger earthquakes have been also listed by Everingham (1977) from earliest records to 1977, and Ripper and Letz (1991) from about 1900 to 1989. Earthquake magnitude sizes are adopted from these works. The discussions that follow are in the order of those of earthquakes of the most intense region, commencing with the Solomon Sea region.

3.2.1 Solomon Sea region

As two magnitude 7.7 earthquakes have occurred in the zone, and two magnitude 8 earthquakes have occurred in the northern Solomon Sea just east of the zone, the maximum credible earthquake here will be at least of magnitude 8.5.

1906 September 14, 1614 UTC, West Solomon Sea, M 7.8

A shallow earthquake of M7.8 occurred September 14, 1906 at 1614 UTC beneath the western Solomon Sea. This earthquake was described by (Sieberg, 1910) as a "Great" world earthquake. Although the effects of the earthquake are known only on the Huon Peninsula and western New Britain, it was felt over a wide area. Damage was reported beyond the western end of New Britain and on the Huon Peninsula. Casualties were estimated at about a 100 people, including the inhabitants of four village huts totally destroyed by landslides. Huge landslides denuded and changed the appearance of Huon Peninsula, and dammed creeks. Damage included that caused to Mission houses on the Huon Peninsula area, while soil cracks and numerous extensive landslides with rock falls were observed on the western coast of New Britain.

The earthquake was followed by a long aftershock sequence.

1920 February 02, 1122 UTC, Northwest Solomon Sea, M 7.7

A magnitude M 7.7 shallow earthquake occurred on February 2, 1920, at 1122 UTC beneath northwestern Solomon Sea and caused damage at Gasmata and Lindenhafen on the southern New Britain coast (Everingham, 1977). The newly built jetty at Gasmata was demolished. At Lindenhafen, two of three European-style houses collapsed. It was reported that the sea rushed out of Gasmata harbour and did not return, which indicated coastal uplift of about 20-24 inches (50-60cm).

1923 November 02, 2108 UTC, Bougainville, M 7.2

Bougainville Island residents were alarmed by the occurrence of this magnitude M 7.2 earthquake. The earthquake occurred beneath southern New Ireland region, northern Solomon Sea. The earthquake was described as "the worst experienced for many years". Damage included broken water tanks at Buka Passage and the mission church at Faisi, and a makeshift camp at Tarara, north of Kieta. The intensity may have reached as maximum of MM 7 as people were reportedly unable to stand.

There was damage to wooden houses at Rabaul, where felt effects reached intensity 6. In Rabaul harbour a tsunami was observed.

This earthquake was felt as far distant as the Huon Gulf, Morobe Province.

1955 October 10, 0857 UTC, Northern Solomon Sea, M 7.3

This magnitude 7.3 earthquake occurred beneath the northern Solomon Sea. Rabaul Observatory documented in monthly volcanological reports the intensities (Everingham, 1979). It was reported that landslides blocked the Rabaul-Kokopo road, and in both Rabaul and Kokopo, buildings, water tanks, and shop merchandise were damaged. In Rabaul, electric wires were snapped and intensity 8 was reported at Warangoi where some landslides occurred.

A small tsunami waves were observed at Sulphur Creek. The water was reported to surge up the creek, reversing the downward course of the stream.

The earthquake was felt as far as Popondetta on the Papuan Peninsula and on New Ireland, Bougainville, Lihir, and Feni Islands.

1957 August 23, 0200 UTC, Northern Solomon Sea, M 6.4

Everingham (1979) extracted intensities information from Rabaul Observatory monthly volcanological reports. The magnitude M6.4 earthquake occurred under the northern Solomon Sea and was felt on Bougainville Island, New Ireland and New Britain, with maximum intensity MM5 or MM6.

1967 October 04, 1721 UTC, Northern Solomon Sea, M 7.2

The magnitude M7.2 earthquake occurred beneath the northern Solomon Sea, off the coast of northern Bougainville Island and was strongly felt across Bougainville. Minor damage was reported from Hutjena on Buka Island. The earthquake was felt on Nuguria Islands north of Bougainville, and also at Garaina in the Morobe Province.

Denham (1971) reported on the earthquake, and Ripper (1975) documented an overthrust focal mechanism solution on a WNW-ESE azimuth, approximately parallel to the plate margin.

1968 February 12, 0544 UTC, Northern Solomon Sea, M 7.2

Denham (1974) reported that the magnitude M 7.2 earthquake occurred at 46km depth beneath the central northern Solomon Sea and was felt over a wide area of PNG.

The earthquake was felt strongly on the upper floors of the multi-storey ANG House in downtown Port Moresby. Minor landslides occurred on the Gazelle Peninsula and minor damage was reported, cement was cracked at Lonbom, southern New Ireland, and old water tanks developed leaks at Hetjuna on Buka Island and on Sohano Island.

Ripper (1977) reported a strike-slip focal mechanism solution, and interpreted a left-lateral motion, on a northwest-southeast trending nodal plane parallel to the New Ireland-Bougainville line fault plane.

1969 August 05, 1632 UTC, Northern Solomon Sea, M 6.4

This magnitude M 6.4 earthquake occurred at 69 km depth beneath the northern Solomon Sea and was strongly felt in the Bougainville, eastern New Britain and southern New Ireland regions, with intensity 6 reported from Taliligap near Rabaul and Sohano on Buka Island.

1971 July 14, 0611 UTC, Northeastern Solomon Sea, M 8.0

The magnitude M 8.0 earthquake occurred at 43km depth beneath the northeastern Solomon Sea. The earthquake has been described by Everingham (1973b, 1975b, 1977), and by Lay and Kanamori (1980) and Schwartz, Lay and Ruff, (1989) who analysed and described the source process.

There was considerable damage in the Gazelle Peninsula. At Gaulim School buildings were badly damaged. There were numerous landslides along the Rabaul-Kokopo road, completely blocking off the road. Numerous water tanks were ruptured and in Rabaul town, people were unable to stand.

A 1-2 m wave height tsunami was reported in the northern Solomon Sea region, including within Rabaul harbour. At least one, possibly two people drowned. In the Wide bay region, the tsunami was reported to have been about 8m high, sweeping 300 m inland.

The overthrust fault plane solution (Everingham, 1975b; Ripper, 1977), as well as the isoseismal pattern (Everingham, 1975b), are aligned parallel to the New Ireland-Bougainville arc, and Solomon Plate margin, in a northwest-southeast trend.

Ripper (1992) reported an acceleration of 0.068g recorded by the underground Rabaul Sulphur Creek seismic vault accelerograph.

1971 July 26, 0123 UTC, Northern Solomon Sea, M 8.0

A second magnitude M 8.0 earthquake occurred in the northern Solomon Sea at a depth of 43 km two weeks after the first (above). This earthquake was also described by Everingham (1973b, 1975b, 1977), who drew an isoseismal map which was consistent with the aftershock patterns, and both of which were aligned parallel to New Britain. The effects of the earthquake were intense with intensity MM 8 extending from southern New Ireland to about midway along the southern coastline of New Britain. On the Gazelle Peninsula, there was further damage in places where there was damage suffered during the 14 July earthquake.

Another tsunami was generated in the Solomon Sea which had devastating effects in the southern Solomon Sea region, and noticeable on other coastlines. A "considerable disturbance" was observed on the sea surface by a pilot flying in the area between Nissan Island and southern New Ireland. A 5 m tsunami in Metlik harbour, southern New Ireland, destroyed all residential buildings and surged inland several hundred metres.

Ripper (1977) determined a nodal plane of the fault plane solution that dips to the northwest, with strike parallel to New Britain and plate boundary. Lay and Kanamori (1980) and Schwartz, Lay and Ruff, (1989) also analysed and described the source process.

Ripper (1992) documented that the bedrock accelerograph at Sulphur Creek in Rabaul recorded a maximum acceleration of 0.05g.

1972 April 28, 2332 UTC, Northern Solomon Sea M 6.9

The magnitude M 6.9 earthquake occurred deep at 409 km beneath northern Solomon Sea and was moderately felt in New Britain, New Ireland and Bougainville Island. Being at depth, it caused no noticeable damage.

At depth Ripper and Moihoi (1996c) determined that the earthquake occurred in a segment of Solomon Plate that has subducted in front of the advancing Pacific Plate.

1972 August 17, 2344 UTC, Central Solomon Sea, M 7.1

The magnitude M 7.1 earthquake, which occurred at a depth 10 km beneath the central Solomon Sea, was described by Everingham and Sheard (1980). The earthquake occurred remote from land and thus was moderately felt on New Britain, New Ireland and Bougainville Island. A tsunami that was generated effected New Britain coastlines and Buka passage, and was also noticed at Tabar Islands.

The Rabaul Observatory accelerograph recorded an acceleration of 0.01g (Ripper, 1992).

Everingham and Sheard (1980) determined that the fault plane solution was a normal fault, caused by extension in the Solomon Plate lithospheric slab as it bends downward towards the New Britain Trench.

1972 October 30, 1648 UTC, Eastern Solomon Sea, M 6.3

The magnitude M 6.3 earthquake occurred at depth 50 km beneath the eastern Solomon Sea near the central Bougainville Island coast. Everingham and Sheard (1980) described the earthquake.

On Bougainville damage included water tanks at Kieta and at Piva, near Torokina. Bougainville Copper Ltd also reported that a ground acceleration of 0.3g was recorded at Panguna.

1973 January 18, 0928 UTC, Northwestern Solomon Sea, M 6.6

The magnitude M 6.6 earthquake occurred at a depth of 43 km beneath northwestern Solomon Sea, south of New Britain. The only damage on New Britain was reported from Kimbe, where water tanks were cracked, and Numundo near Kimbe, which reported landslides. Garaina in the Papuan Peninsula southwest of the epicentre also reported some landslides.

1976 June 03, 1644, UTC, Northern Solomon Sea, M 6.5

The magnitude M 6.5 earthquake occurred at depth 88 km beneath northern Solomon Sea. At least ten water tanks were damaged on Duke of York Island during strong shaking and the earthquake was felt strongly in Gazelle Peninsula, southern New Ireland, and northern Bougainville Island, intensity MM5 and 6.

McCue (1981b) determined an overthrust focal mechanism solution and presented the isoseismal map, both trending parallel to the plate margin.

1981 July 29, 0144 UTC, Northeastern Solomon Sea, M 5.6

A magnitude M 5.6 earthquake occurred at a depth of 112 km beneath northeastern Solomon Sea and was strongly felt around the northern Solomon Sea. Damage was reported in Pomio on eastern New Britain where an overhead water tank moved on its stand.

An acceleration of 0.027g was recorded at the Warangoi Police Station accelerograph. Ripper (1992) compares this with the recorded 0.125g on the Warangoi Hydro site recorder during the close shallow magnitude 5.8 earthquake on 3 December 1978 (McCue, GNS report 1982/4).

1983 March 18, 0905 UTC, Northern Solomon Sea, M 7.6

The magnitude M 7.6 earthquake occurred at 89 km depth beneath the northern Solomon Sea and was felt through PNG, from close to the western border and felt in the Solomon Islands.

It was felt in ships near the epicentre as heavy vibrations. It created a tsunami in the northern Solomon Sea, observed at Feni Island, Muliama on New Ireland, Rabaul (25 cm measurement) and possibly also at Sideia in the Milne Bay Province.

Damage included collapse of concrete pier at Muliama on New Ireland, and wharf damage at Ulu on Duke of York Islands, and at Buka Passage. There was widespread damage to water tanks. Some damage to semi-permanent and village houses occurred.

Ripper (1992) reported accelerations of 0.13g, 0.015g, and 0.13g that were recorded at Rabaul Observatory, Rabaul Wanliss Street and Warangoi Police Station respectively. At Panguna Bougainville the bedrock acceleration was 0.03g, and an isoseismal map was produced (McCue, 1984. Seismic Risk at Panguna, BCL Report).

Harvard/USGS determined an overthrust fault plane solution striking northwest-southeast in the trend of the New Ireland - Bougainville Pacific Plate front, consistent with subduction of the Solomon Plate beneath the Pacific Plate margin.

1987 October 16, 2048 UTC, Northwestern Solomon Sea, M 7.4

The magnitude M 7.4 earthquake occurred at a depth of 48 km beneath the northwestern Solomon Sea near the Arawe Islands of southwestern New Britain. It has been described by Anton (1992).

A small government wharf at Kandrian was demolished and two jetties cracked. Further damage included five bush material houses and about 30 water tanks, and more water tanks were broken in the Hoskins - Kimbe area on northern New Britain.

Tsunami waves were noted at Kandrian, and the tide gauge at Rabaul recorded a 13 cm tsunami.

The accelerograph at Hoskins recorded an acceleration of 0.033g (Ripper, 1992).

The fault plane solution determined by Harvard/USGS is an overthrust on a west-east strike, approximately parallel to the coastline and plate margin.

1988 August 06, 0626 UTC, Western Solomon Sea, M 6.0

The magnitude M 6.0 earthquake occurred at depth 25 km beneath the central western Solomon Sea. The earthquake was felt at moderate strength around the Solomon Sea margins, at highest Intensity MM5, and a small landslide was reported on Fergusson Island, Milne Bay Province (Ripper, 1991).

The Harvard University fault plane solution is an overthrust, which is not understood as the earthquake occurred in a region where normal faulting would be expected.

2000 November 16, 0742 UTC, South of New Ireland, Mw 7.8

This was the second large earthquake, having magnitude values Ms 7.8 and Mw 7.8, which occurred offshore south of New Ireland less than three hours after the first earthquake of southern New Ireland-eastern Bismarck Sea, at 0454 UTC on 16 November.

This earthquake may have been caused by the changes in the stress field caused by the 16 November Earthquake (Geist and Parsons, 2005) specifically by static stress changes within the tectonic regime involved. Maximum left-lateral displacement observed along the Weitin Fault was 5.5 metres (Itikarai and Tregoning, 2003; Anton and McKee, 2005a).

3.2.2 Eastern Solomon Sea - Bougainville region

The shallow seismicity beneath Bougainville Island is sparse except in the southwestern corner, but the island regularly experiences strong earthquakes from the subduction of the eastern edge of the Solomon Plate.

As two magnitude 7.8 earthquakes have already occurred in the zone, and considering the rupture length of any future event can be large, the maximum credible earthquake magnitude is at least 8.5.

1939 January 30, 0218 UTC, Eastern Solomon Sea, M 7.8

The magnitude M 7.8 earthquake occurred at shallow depth beneath the eastern Solomon Sea, and was felt as far away as central New Ireland and the Trobriand Islands. It was felt at sea by passengers and crew of the MV Malaita near Kieta, off the eastern coast of Bougainville Island.

Six people were killed at Buin, and village houses suffered considerable damage, and fissures opened in many places along the coastline where a foot (0.3 metre) of subsidence was noted. A tsunami damaged a wharf at Faissi Island near the northern tip of Bougainville (Everingham, 1977).

1975 July 20, 1437 UTC, Bougainville, M 7.6

The magnitude M 7.6 earthquake occurred at depth 49 km beneath southwestern Bougainville coast, Solomon Sea, and was described in detail by Everingham, Gaull and Dent (1977), and presented an isoseismal map, map of aftershocks, and focal mechanism solution.

There was extensive damage on Bougainville where intensity was greatest on the southwest (MM8), and intensity MM8 also experienced at Manetai on the eastern coast, where small cracks opened in the ground and a house was moved off its stumps. Further damage included that to over 500 village houses on southwestern Bougainville, where wood and brick masonry were damaged, and bridges moved on their foundations, and cracks appeared in the ground.

A two-metre tsunami swept through Torokina village and PTC station on the western coast. An aftershock tsunami occurred while officials were examining tsunami damage at Torokina PTC station.

The focal mechanism solution is an overthrust striking northwest-southeast and parallel to the plate margin.

1995 August 16, 1027 UTC, Northeastern Solomon Sea, 7.8

The magnitude M 7.8 earthquake occurred at 30 km depth beneath the northeastern Solomon Sea, east of the two magnitude 8 earthquakes of 1971. The earthquake was strongly felt on Gazelle Peninsula, where landslides blocked the Rabaul-Kokopo road, and some houses suffered minor damage, such as being knocked off the stumps. One house suffered a sheared water pipe and water tanks were ruptured. Landslides occurred on Mt. Balbi volcano, Bougainville, and shaking was strong enough that people fell over, and many could not stand without support.

A tsunami about one metre peak to peak occurred in Rabaul harbour.

A magnitude 7.0 aftershock followed 13 hours later at 2310 UTC.

Both Harvard/USGS fault plane solutions are overthrusts on a northwest-southeast strike, parallel to the seismic zone and plate margin.

1995 June 24, 0658 UTC, Feni Island, M 7.0

The magnitude 7.0 earthquake occurred deep, at 386 km depth, beneath Feni Island. Being deep, it was only moderately felt in the New Britain New Ireland region, and therefore no damage resulted.

The Harvard/USGS fault plane solution is a normal fault on a virtually north-south strike. At depth, the earthquake probably is an evidence of stretching of the subducting Solomon Plate lithospheric slab.

1996 April 29, 1440 UTC, Bougainville, M 7.5

The magnitude M 7.5 earthquake occurred at depth 44 km beneath western Bougainville near Motupena Point.

Damage was caused included the collapse or sink of the sand bank, resulting in people being evacuated inland to dry land. Fourteen mostly permanent houses were damaged in the Konga area. An elderly woman collapsed and later died in hospital at Tokaino north of Buin, while a man was injured by a collapsing house at Konga. In total, the cost of damage was reported to be about K80,000, an amount equivalent of Aus$30,000 in recent times.

The Harvard/USGS fault plane solution is overthrust on a northwest-southeast strike, parallel to the plate margin.

3.2.3 Solomon Islands/Woodlark

The seismicity of the Solomon Islands is dominantly caused by the interaction of the India-Australia and Pacific Plates. To the northwest in PNG, the interaction is between the Solomon and Pacific Plates. In the Woodlark Basin the interaction is between the India-Australia and Solomon Plates.

Eleven magnitude 6 earthquakes have occurred in the zone since 1964, scattered along its length.

A magnitude 7.2 earthquake has occurred in the zone, butt maximum credible earthquake would be at least magnitude 7.8.

1926, Eastern Woodlark Basin, M 7.2

A magnitude 7.2 earthquake occurred in 1926 in the eastern Woodlark Basin near the New Georgia Islands, on 25 January at 0036 UTC.

1926, New Georgia, Mw 7.1

A magnitude Mw 7.1 occurred near New Georgia, in the Solomon Islands on 27 March at 1048 UTC.

1960, Woodlark Island, M 6.7and M 6.4

In addition, magnitude 6.7 and 6.4 earthquakes occurred close to Woodlark Island in 1960, on 11 June at 1514 UTC and on 11 June at 1637 UTC (aftershock).

1974 February 01, 0312 UTC, Southern Bougainville, Mw 7.4

The magnitude M 7.1 earthquake occurred at a depth of 40 km beneath southern Bougainville in the Solomon Islands

Damage included split water tanks in Buin on southern Bougainville. A small tsunami swept inland flooding a small village near Torokina on western Bougainville. McCue (1984) produced an isoseismal map of the combined felt reports of the January and February earthquakes.

2007 April 01, 2039 UTC, Georgia, Solomon islands, Mw 8.1

The magnitude Mw 8.1 earthquake occurred at 24 km depth beneath the Georgia Group Islands in the Western Solomon Island Province, and generated a tsunami that was experienced within the group of islands, and caused damage to homes and property. The tsunami caused panic throughout the southwest Pacific region.

3.2.4 New Britain

New Britain regularly experiences damaging magnitude 7 earthquakes. In western New Britain, the seismic hazard is a result of highly intense subduction seismicity of the area.

Two earthquakes of magnitude 7.8 have occurred since 1900 in the total of 21 above magnitude 7.0. The maximum credible earthquake may then be 8.5.

1906 September 14, 1604 UTC, Western Solomon Sea, Mw 8.0

A magnitude earthquake 7.5 (Mw 8.0) occurred in the western Solomon Sea, near western New Britain. The earthquake caused devastation along shorelines of northern Papuan Peninsula and neighbouring regions near Lae, and a devastating tsunami was experienced on coastlines west and northwest of the western Solomon Sea.

1923 November 04, 0004 UTC, Eastern New Britain, M 7.1

The magnitude M 7.1 earthquake occurred at shallow depth beneath Wide Bay, eastern New Britain. The earthquake caused damage on the eastern coast of Bougainville Island, and was felt as far away as Morobe on the Huon Gulf.

1945 December 28, 1748 UTC, Central New Britain, M 7.7

This magnitude 7.7 earthquake occurred under central New Britain.

1953 August 25, 0204 UTC, Eastern New Britain, M 7.0

This magnitude 7.0 occurred close to the coast of eastern New Britain, beneath the Solomon Sea.

1956 March 19, 1736 UTC, Central New Britain, M 6.4

The magnitude M 6.4 earthquake occurred at 33 km, probably deeper, beneath central New Britain. The intensities were extracted from Rabaul Observatory monthly volcanological reports by Everingham (1979).

The earthquake was felt MM7 at Kandrian indicated by broken water tanks. As with most earthquakes from that region, the earthquake was widely felt, including in the Popondetta region of the Papuan Peninsula, and at Rabaul (Ripper and Moihoi, 1996a).

1964 November 17, 0815 UTC, Central New Britain, M 7.0

The magnitude M 7.0 occurred at depth 45 km beneath central New Britain and was felt strongly on eastern New Britain. The earthquake was strongly felt in the Pomio region, with intensity 7 reported from Drina indicated by minor damage, including water tanks (Ripper and Moihoi, 1996a). Ripper (1975) determined the focal mechanism solution, which was an overthrust with strike approximately east-west, parallel to the plate margin.

1966 February 22, 0502 UTC, Pomio, New Britain, M 6.8

The magnitude M 6.8 earthquake occurred at depth 59 km beneath the Pomio, eastern New Britain and was very strongly felt in this area, with an intensity of MM 7-8 reported from Drina, near Palmalmal, with some damage to well constructed buildings.

The earthquake was also felt at Torokina on Bougainville.

Ripper (1975) determined the focal mechanism solution, which is an overthrust with northeast-southwest strike, parallel to the plate margin.

1967 October 04, 1721 UTC, Northeastern Solomon Sea, M 7.2

The earthquake was of magnitude 7.2, occurred beneath the northeastern Solomon Sea, and was strongly felt in eastern New Britain, southern New Ireland and Bougainville (Denham, 1971).

1967 December 25, 0123 UTC, Eastern New Britain, M 7.2

The magnitude M 7.2 earthquake occurred at depth 64 km beneath eastern New Britain and was felt in many areas around the northern Solomon Sea, including western New Britain, New Ireland and Bougainville Island, and at Losuia. Minor damage, cracked water tanks and cement, occurred at Hanahan on Buka Island and at Namatanai, New Ireland.

Denham (1971) reported the earthquake. Ripper (1975) reported a poorly defined overthrust focal mechanism solution, striking approximately northwest-southeast.

1968 February 12, 0544 UTC, Northern Solomon Sea, M 7.2

This magnitude 7.2 earthquake occurred in the northern Solomon Sea, and was felt as far away as Port Moresby.

1968 September 16, 1355 UTC, Off Southwestern New Britain, M 6.4

The magnitude M 6.4 earthquake occurred at 59 km depth just off the coast of southwestern New Britain, west of the Arawe Islands. An isoseismal map of the earthquake was prepared by Denham (1974).

Damage occurred to wharves at Kandrian and Amulut in New Britain and at Ablugul Island. At Kandrian 35 water tanks were damaged.

The earthquake was moderately felt as far away as Port Moresby.

The submarine SEACOM Cable joining Madang and Cairns was severed by turbidity currents in the New Britain trench, generated by the earthquake (Krause *et al.*, 1970).

An acceleration of 0.009g was recorded by the accelerograph at Yonki.

Ripper (1975) determined an overthrust focal mechanism solution striking approximately east-west, parallel to the plate boundary. He reported an acceleration of 0.009g recorded by the accelerograph on lake sediments at Yonki (Ripper, 1992)..

1970 October 03, 1034 UTC, Southern New Britain, M 5.5

The magnitude M 5.5 earthquake occurred at 23 km depth beneath southern New Britain and was felt moderately over most of New Britain. Minor damage was reported at Fulterton (MM 7) near the epicentre.

The earthquake was reported in Ripper (1980a).

1971 July 19, 1537 UTC, Northern New Britain, M 6.2

The magnitude M 6.2 earthquake occurred at depth 33 km beneath Hoskins, northern New Britain and was strongly felt in a small area near Hoskins.

Damage occurred to 140 village houses from Mora Mora in the west to Rapuri in the east, including damage at Mora Mora Vocational School and damage occurred to the road along the coast. Landslides occurred on Mt Lollo and Mt Bango (Pago), and liquefaction caused subsidence, sand volcanoes and sink holes along the coastal region and at the base of Mt Bango (Pago).

A normal fault focal mechanism solution was determined and report by Ripper (1977).

1978 January 25, 2318 UTC, Eastern New Britain, ML 6.4

The magnitude ML 6.4 earthquake occurred at depth 44 km beneath Mt Yeno on eastern New Britain. The earthquake was strongly felt in eastern New Britain. Damage was reported only at Kokopo, where water tanks were cracked.

McCue (1982) presented an isoseismal map. An overthrust fault plane solution on a WNW-ESE strike, not consistent with the southwest-northeast strike of the plate boundary, was determined.

Ripper (1992) reported that an acceleration of 0.063g was recorded at Rabaul Volcano Observatory.

1980 February 27, 2117 UTC, Southern New Britain, M 6.5

The magnitude M 6.5 earthquake occurred at 53 km depth, 50 km south of Kimbe, southern New Britain. The only damage reported was to three water tanks at Kimbe.

Maximum accelerations of the event and two aftershocks at 2121 and 2135 UTC recorded at Hoskins were 0.035g, 0.013g and 0.020g respectively (Ripper, 1992).

1980 June 18, 0918 UTC, Eastern New Britain, M 6.5

The magnitude M 6.5 earthquake occurred at depth 61 km beneath Wide Bay in eastern New Britain. Damage included 15 water tanks at Malabunga, south of Rabaul, and minor landslides occurred on the Gazelle Peninsula.

Maximum accelerations were recorded at Rabaul Observatory, 0.060g; Rabaul Wanliss Street, 0.015g; and Warangoi Police Station, 0.11g (Ripper, 1992).

1981 February 24, 1617 UTC, Southwestern New Britain, M 6.2

The magnitude M 6.2 earthquake occurred beneath Islands, southwestern New Britain and was strongly felt in the Arawe Islands region and on Umboi Island. Village buildings were knocked off their stumps, and permanent buildings walls were cracked, at Siassi on Umboi Island. Damage was also reported at Amulet on Arawe Islands, southwestern New Britain, where house stumps were cracked and plumbing fittings broken.

1981 May 28, 2218 UTC, Eastern New Britain, M 6.8

The magnitude M 6.8 earthquake occurred at depth 71 km beneath Palmalmal on Jacquinot Bay in eastern New Britain, and was felt strongly around the shores of the Bay. At least ten water tanks were ruptured at Palmalmal and at Pomio the cement stumps of the District Officers house were damage.

Accelerographs at Rabaul Volcano Observatory and Warangoi recorded accelerations of 0.043g and 0.079g respectively (Ripper, 1992).

1981 August 07, 1135 UTC, Eastern New Britain, M 6.3

The magnitude M 6.3 earthquake occurred at depth 66 km beneath eastern New Britain and was strongly felt in the eastern New Britain region. Damage was minor and included broken water tanks at Palmalmal and road slides at Uvol in southern New Britain.

Accelerations recorded at Rabaul Observatory, Warangoi Police Station and Warangoi were of 0.049g, 0.061g and 0.12g respectively, Ripper (1992).

The Harvard/USGS fault plane solution is an overthrust oriented east-west.

1982 June 09, 0308 UTC, Central New Britain, M 6.1

The magnitude M 6.1 earthquake occurred at a depth of 84 km beneath central New Britain and was most strongly felt at Bialla, on the northern coast of New Britain immediately north of the epicentre. No damage was reported, but people had difficulty walking.

The Harvard/USGS fault plane solution is an overthrust oriented WSW-ENE, parallel to the local New Britain Solomon Sea Plate boundary, indicating a typical subduction earthquake.

1984 May 30, 0749 UTC, Eastern New Britain, M 6.8

The magnitude M 6.8 earthquake occurred at depth 174 km beneath Open Bay, eastern New Britain and has been described by Anton (1993). It was felt strongly along the southern coast of New Britain, rupturing water tanks at Pomio and cracking a concrete floor at Uvol. A tsunami effect was observed at Marunga in Wide Bay. A louvre window was reported broken as far away as Esa'Ala on Normanby Island.

Ripper (1992) reported an acceleration of 0.047g recorded by the accelerograph at Warangoi Police Station, Warangoi. Anton (1993) documented an overthrust, striking northeast-southwest, fault plane solution by Harvard/USGS, which is consistent with the trend of the plate boundary.

1984 August 11, 0120 UTC, Eastern New Britain, M 5.9

The magnitude M 5.9 earthquake occurred at depth 40 km beneath the southern or Wide Bay coastline of the Gazelle Peninsula, eastern New Britain. The earthquake was felt strongly across the Gazelle Peninsula.

Ripper (1992) reported accelerations of 0.019g and 0.054g recorded at Rabaul Observatory and Warangoi Police Station, Warangoi, respectively.

The Harvard/USGS fault plane solution is an overthrust striking WSW-ENE (Anton, 1993), and reflects the upward/forward rebound of the New Britain margin of the South Bismarck Plate towards the New Britain Trench.

1985 May 10, 1535 UTC, Central New Britain, M 7.1

The magnitude M 7.1 earthquake occurred at a depth of 27 km beneath the Nakanai Mountains, central New Britain. The effects of the earthquake have been described by King and Loveday (1985); King (1986); King, Loveday and Schuster (1987); Mori, McKee and Letz (1987) and Anton (1996d).

The earthquake caused massive landslides and damming of rivers in central New Britain, resulting in extensive damage. The bridge over the Ivule River on the north coast was washed away. Also on the northern coast at Bialla, about 300 water tanks, 250 village houses and 16 other buildings were damaged. As well, cracks formed in roads and in the wharf causeway.

The south flowing Bairaman River was dammed inland by debris flow at the earthquake epicentre, forming a large lake formed behind the dam. King, Loveday, and Schuster (1987) reported on the dam blown by explosives on 11 September 1986, and breached by way of shovels to commence water overflow by early on 12 September when a wall of water and debris was released into the valley. The evacuated and deserted Bairaman Village near the mouth of the river was washed out to sea. Other damage on the southern coast included the destruction of the school science laboratory by fire at Palmalmal High School, and the damage and the subsequent demolition of a 300 m long concrete bridge under construction over the nearby Drina River.

Mori, McKee and Letz (1987) interpreted the focal mechanism solution by Harvard/USGS as suggesting that the arc is under tension. The fault plane solution by Harvard/USGS is strike-slip with the tension axis orthogonal to the plate margin.

An acceleration of 0.05g was recorded by the accelerograph at Hoskins, Ripper (1992).

1988 July 05, 2032 UTC, Southwestern New Britain, M 6.6

The magnitude M 6.6 earthquake occurred at depth 53 km beneath southwestern New Britain near Arawe Islands. The earthquake was reported by Ripper (1991), who documented that a foreshock of magnitude 5.1 preceded the mainshock by five seconds.

Damage included one cracked water tank at Pileo Island of the Arawe Island Group. A tsunami was generated and observed to have "swept through Maklo Village" but caused no damage. Two water tanks were damaged at Kandrian (Intensity MM 6), and 5 at Gigina Village, inland, north of the Arawe Islands, while four bush material houses were damaged at Sara Village between Kandrian and Arawe Islands.

The earthquake was felt strongly in west New Britain, including Kimbe on the north coast and widely throughout New Britain, intensity MM6 at Lassul Bay and Marunga on the north and south coasts of the Gazelle Peninsula, respectively, and moderately in Rabaul. The earthquake was felt at Popondetta on the north coast of the Papuan Peninsula, felling off minor articles falling from shelves, and was moderately felt as farther afield as Bulolo in the Morobe Province, and on Unea Island in the Bismarck Sea north of New Britain. The earthquake was felt in Port Moresby, on upper floors of multistorey buildings.

The Harvard/USGS focal mechanism solution is an overthrust on a west-east strike parallel to the plate margin.

1990 December 30, 1914 UTC, Northern New Britain, M 7.1

The magnitude M 7.1 earthquake occurred at depth 179 km beneath Bialla, northern New Britain and was widely felt moderately. At a depth of 179 km the intensity of shaking was attenuated and thus assisted to mitigate the effects. The strongest shaking was reported farther at Lae, where articles fell off from shelves.

The accelerograph at Bialla recorded an acceleration of 0.061g (Ripper, 1992).

The dip-slip and strike-slip components of motion (Harvard/USGS) may indicate distortion or partial melting of subduction slap at this depth, with neither pressure nor tension axis paralleling the Wadati-Benioff seismic zone nor plate boundary.

1991 September 08, 2026 UTC, Central New Britain, M 6.2

The magnitude M 6.2 earthquake occurred at depth 28 km beneath southern coast of central New Britain and was felt over most of New Britain. The only damage reported was cracked water tanks near the epicentre at Palmalmal.

The Harvard/USGS fault plane solution is overthrust, striking parallel to New Britain and the plate margin.

1992 October 06, 1028 UTC, Central New Britain, M 6.1

The magnitude M 6.1 earthquake occurred at depth 50 km beneath Nakanai Mountains, central New Britain and caused landslides in the epicentral region of the Nakanai Mountains. Old water tanks were cracked in Bialla.

The focal mechanism solution by Harvard/USGS is an overthrust striking northeast-southwest, parallel to the local trend of New Britain front of the plate margin.

2000 November 17, 2101 UTC, Eastern New Britain, Mw 7.8

This was the third large earthquake in a series, having magnitude values Ms 8.0 and Mw 7.8. It occurred near Pomio eastern New Britain forty hours after the first earthquake of southern New Ireland-eastern Bismarck Sea, at 0454 UTC on 16 November.

The aftershock sequence, significant numbers of which were felt, continued for weeks and caused unrest and anxiety.

3.2.5 Gazelle Peninsula – southern New Ireland

A magnitude 7.1 earthquake that occurred in September 1900 has been erroneously positioned in the central Bismarck Sea north of Umboi Island in the catalogues of Abe and Noguchi (1983) and Ripper and Letz (1991). It can be correlated with a strong earthquake and tsunami effects in the St Georges Channel region, reported by Everingham (1977), and its location was probably beneath St Georges Channel.

Prior to the 16 November 2000 magnitude 8.0 earthquake, the largest earthquake was of magnitude 7.2 and occurred in 1985, Mori (1989). However this high level of seismicity does not extend to central New Ireland. Seismicity in the Bismarck Sea does come close to the faults in the southwest and there is ongoing seismicity between Lihir Island and New Ireland on the northeast. Hence central New Ireland in the vicinity of these Quaternary faults could be the site of future large earthquakes, the most recent being the 16 November 2000, accounts of reported by Itikarai and Tregoning, 2003; Tregoning and McQueen, 2004; Anton and McKee, 2005a).

1916 January 01, 1329 UTC, Northern Solomon Sea, M 7.8

The magnitude 7.8 earthquake occurred in the northern Solomon Sea near New Ireland, and generated a strong tsunami in Rabaul.

1941 January 13, 1627 UTC, Central Gazelle Peninsula, M 7.0

The magnitude M7.0 earthquake occurred at shallow depth beneath central Gazelle Peninsula (Gutenberg and Richter, 1954) and caused extensive devastation in the period just prior to the Japanese invasion of Rabaul in 1941. Fisher (1944) described the earthquake in detail.

Rabaul Volcanological Observatory recordings of the earthquake indicated that it came from the southwest and, practically, all the aftershocks as well. Fisher (1944) determined from the distribution of intensities and the isoseismal map of the event that the earthquake came from a then unknown northwest-southeast trending fault system, now recognised as the Baining Fault (Macnab, 1970).

Damage occurred to about 15 residences of European style (about MM8), one child was killed, and many severe landslides occurred (MM8).

A tsunami was observed in Rabaul Harbour.

Since the 1941 earthquake, there has been virtually no shallow earthquakes on the Mediva or Baining Fault, most earthquakes occurring at greater depth on the subduction zone.

1944 May 19, 0019 UTC and 1944 May 25 1258 UTC, Lihir Island, M 7.2, 7.5

This magnitude 7.2 earthquake and the following magnitude 7.5 earthquake occurred beneath northern Solomon Sea and north of Lihir Island (northeast of New Ireland, well away from subduction zones of the northern Solomon Sea or the Bismarck Sea seismic zone) respectively. It may be badly mislocated.

1953 April, 23; 1624 UTC, Northern Solomon Sea, M 7.5

A magnitude 7.5 earthquake occurred beneath the northern Solomon Sea, near New Ireland and was strongly felt in Rabaul (Intensity 7). The earthquake caused cracks in tanks, split a concrete floor, caused landslides which blocked roads, damaged power lines, and caused unusual rising and falling of tides which lifted and dumped four ships in Rabaul Harbour onto a reef (Ripper and Letz, 1991).

1967 August 13, 1654 UTC, St Georges Channel, Ms 5.7

The magnitude Ms 5.7 earthquake that occurred at depth 33 km beneath St. Georges' Channel was described by Heming (1967), Skinner and Denham (1967) and Denham (1971).

The damage caused by this earthquake was hard to tell as it was masked by greater damage caused by the magnitude 6.1 earthquake 5 hours later that morning. Hence intensity 6 at Kokopo may well be intensity 7. It was reported that some water tanks were broken in Rabaul, and landslides occurred and blocked the Rabaul - Kokopo Road near Rabaul, and water pipes were broken at Kerevat.

1967 August 13, 2215 UTC, St Georges Channel, M 6.1

This was the magnitude M 6.1 earthquake, which occurred at 33 km depth beneath the St. Georges Channel, following the Ms5.7 earthquake. The earthquake occurred closer to Kokopo, and resulted in higher intensity there. The earthquake has been described by Heming (1967), Skinner and Denham (1967) and Denham (1971). Then, the total damage to buildings was estimated as Aus$172,000 in those days.

The most severe damage occurred at Kabaleo/Vunapau Missions, about 3km south of the Kokopo-Vunapope area. Buildings here were moved off their foundations or concrete piles (Ripper and Moihoi, 1996a). A tsunami of only a few centimetres was recorded in Rabaul harbour.

1969 August 03, 0022 UTC, New Ireland, M 5.9

The magnitude M 5.9 earthquake occurred at 65 km depth beneath southern New Ireland and was strongly felt in the Rabaul region on Gazelle Peninsula, and on southern New Ireland. Damage was minor, including just a few cracks here and there.

Ripper (1992) determined an acceleration of 0.022g, recorded by the accelerograph at Rabaul Sulphur Creek.

1972 May 05, 2316 UTC, Southwestern New Ireland, M 6.5

The magnitude M 6.5 earthquake occurred at depth 32 km beneath southwestern New Ireland and has been described by Everingham and Sheard (1980).

The earthquake was moderately felt in the southern New Ireland and northeastern Gazelle Peninsula regions. A few water tanks were cracked in the Kokopo Taliligap area, and a cement stump was reported to be cracked at Taliligap (Ripper and Moihoi, 1996c).

Ripper (1992) reported an acceleration of 0.15g recorded by the accelerograph at Rabaul Observatory.

1976 July 17, 2106 UTC, Southern New Ireland, M 6.6

The magnitude M 6.6 earthquake occurred at 53 km depth beneath southern New Ireland near St Georges Channel. Its' effects were relatively mild, and include a ruptured water tank on Duke of York Island, and minor damage to the Siarmanga Catholic church when three statues broke off their shelf and crashed through the wall of the church (Ripper and Moihoi, 1996c).

In the Rabaul-Kokopo-Kerevat region of Gazelle Peninsula, the intensity was generally MM6. Wanliss Street accelerograph recorded an acceleration of 0.043g, and while Rabaul Observatory on hilly topography recorded 0.21g, an increase of five times (Ripper, 1992).

McCue (1981b) prepared a focal mechanism solution which is essentially strike-slip, and suggested that if the nodal plane striking northwest-southeast parallel to the local fault system is the fault plane, then the motion is dextral, opposite to the expected sense.

1978 July 22, 1151 UTC, Southern New Ireland, M 6.4

The magnitude M 6.4 earthquake occurred at depth 43 km beneath southern New Ireland and was strongly felt in the Gazelle Peninsula.

Only minor damage occurred and included water tanks cracked at Boisen and Malabunga (Ripper and Moihoi, 1996c).

McCue (1982) prepared an isoseismal map and a fault plane solution. The fault plane solution is essentially an east-west trending vertical nodal plane and an almost horizontal nodal plane dipping to the west, neither plane easily interpreted as the fault plane.

Ripper (1992) reported a maximum acceleration of 0.20g recorded by the accelerograph at Rabaul Observatory.

1978 December 03, 1218 UTC, Gazelle Peninsula, M 5.8

The magnitude M 5.8 earthquake occurred at depth 33 km beneath the eastern coastline of the Gazelle Peninsula near its northeastern tip.

At Tapo Catholic Mission several village houses collapsed and water tanks were ruptured. Cement piles of houses cracked and the ground subsided around them. Some small landslides occurred. Some trees fell down.

McCue (1982) prepared an isoseismal map and a fault plane solution. The earthquake involved motion on either a vertical or almost horizontal plane.

Maximum acceleration at Warangoi Police Station was 0.103g while the accelerograph at Rabaul Wanliss Street recorded an acceleration of 0.010g (Ripper, 1992) or 0.125g (McCue, 1982).

1982 August 12, 0213 UTC, Eastern New Ireland, M 6.5

The magnitude M 6.5 earthquake occurred at depth 45 km beneath Cape Mimias, off the eastern most tip of New Ireland.

The earthquake was strongly felt on Duke of York Island and northeastern Gazelle Peninsula where damage included a cracked wharf at Hilhila on Duke of York Island. At Makarapau village near Kokopo, the earthquake caused landslides and toppled a water tank.

Ripper (1992) reported accelerations of 0.21g and 0.015g recorded at Rabaul Observatory and Wanliss Street seismic station in Rabaul, and 0.09g for Warangoi Police Station.

The Harvard/USGS fault-plane solution is northwest-southeast sinistral strike-slip, in the trend of the Weitin Fault.

1983 March 18, 0905 UTC, Northern Solomon Sea, M 7.1

A magnitude 7.1 earthquake occurred in the northern Solomon Sea, near southeastern New Ireland. Minor damage occurred on southeastern New Ireland including the collapse of a jetty constructed of cement-filled oil drum piles at Muliama, and rupturing of water tanks through southern New Ireland.

Landslides occurred on Feni Island and a mild tsunami was recorded in Rabaul Harbour.

1983 May 10, 1827 UTC, St Georges Channel, M 6.3

The magnitude M 6.3 earthquake occurred at 72 km depth beneath the southern end of St. Georges Channel and was felt throughout eastern New Britain, New Ireland and Bougainville.

Minor damage was reported and included minor holes in water tanks at Malabunga High School near Rabaul.

The Harvard/USGS fault plane solution is an overthrust striking east-west.

1985 July 03, 0436 UTC, Southern New Ireland, M 7.2

The magnitude M 7.2 earthquake occurred at depth 33 km beneath Verron Range, southern New Ireland. The effects of the earthquake were described by Buleka (1985) and the fault plane solution and aftershocks by Mori (1989).

The worst landsliding was on the southwest side of the Verron Range where up to 60% of vegetation was locally stripped. Village houses were damaged on the west coast including some destroyed at Kait village, while water tanks and more village houses were destroyed at Lamassa Station and Putput logging camp. Village houses and more water tanks were damaged at Manga and Silur Missions on the east coast, while water tanks were damaged in Rabaul.

A 1.3m wave tsunami was observed in Rabaul Harbour.

An overthrust focal mechanism solution striking NNW-SSE (Mori, 1989), suggests that the earthquake is associated with subduction of the Solomon Plate beneath the Bougainville arc.

Accelerations recorded included 0.31g at Rabaul Observatory, 0.19g at Warangoi Police Station and 0.049g at Bialla (Ripper, 1992).

1989 March 10, 1414 UTC, Southern New Ireland, M 6.0

The magnitude M 6.0 earthquake occurred at depth 33 km beneath central southern New Ireland. The earthquake was reported by Moihoi (1996). It was strongly felt in Rabaul where it caused minor cracking and some water tanks damaged. A woman was killed when a cliff-face landslide fell onto a house, burying her.

Ripper (1992) determined accelerations of 0.035g and 0.036g recorded at Kerevat Lowlands and Vunapope respectively.

The focal mechanism by Harvard University is strike-slip, dextral, and contrary to expected motion if the northwest-southeast trending plane parallel to the Weitin Fault is the fault plane.

2000 November 16, 0454 UTC, East Bismarck Sea, Mw 8.0

A magnitude 8.2 (Mw 8.0) occurred at shallow depth, and was one of the large earthquakes in the recorded history of PNG and was felt strongly in the eastern Bismarck Sea-New Ireland region. The large separation distance (110 km) between the hypocenter in the eastern Bismarck Sea and the centroid in southern New Ireland, and the length of the aftershock distribution field, indicated a rupture length of more than 200 km, from the eastern Bismarck Sea through southern New Ireland to the northern Solomon Sea. The earthquake focal mechanism indicated left-lateral strike-slip movement, consistent with observed left-lateral strike-slip ground displacement in the fault-controlled Weitin Valley of southern New Ireland.

The earthquake rupture involved huge stress release locally and the consequent change to the stress pattern triggered other large earthquakes on neighbouring structures.

Geist and Parsons (2005) pointed out the similarity of the tectonic regime, basically an offshore accommodation structure – here within the New Britain Trench and subduction zone, compared with other known regions in which tsunamis caused by thrust aftershocks can be triggered by large strike-slip earthquakes.

Results from the study of the 16 November 2000 earthquake and previous stress modelling studies suggest that the likelihood of local tsunamis in these regions may significantly increase after a great strike-slip earthquake (Geist and Parsons, 2005).

3.2.6 Huon Peninsula – Huon Gulf

Seismic activity of the Ramu-Markham, Huon Peninsula and Finisterre Range regions is very intense.

The Ramu-Markham lineament marks the southern border of the very seismically active Finisterre Huon Peninsula region.

The largest earthquake of the region was a magnitude 7.5 which occurred beneath the Vitiaz Strait on 12 May 1938. It was reported by The Pacific Islands Monthly that the whole of the New Guinea mainland shook severely. Damage included loss of houses at villages on the southern edge of the zone at Salamaua on the north coast of the Papuan Peninsula. Adding to this, a tsunami swept into the low-lying parts of the town (Everingham, 1977). Reliable sources report the earthquake being actually felt as far distant as Darwin in Australia's Northern Territory.

A slightly lower size magnitude (7.4) earthquake occurred in the same area on 08 February 1987, and caused extensive landsliding and damage.

Two magnitude 7.0 earthquakes occurred at shallow depths beneath the Finisterre Range in 1993, the first on 13 October and the second on 25 October respectively. The 13 October earthquake was the main event responsible for the second event and many smaller aftershocks. Extensive landsliding occurred in the area of the epicentre and caused damage to infrastructure, including village houses, road links and bridges

In the region, three magnitude 7 earthquakes have occurred at depths greater than 100 km within the sinking Solomon Plate. As a magnitude Mw 7.8 has occurred within the zone, beneath Vitiaz Strait and north of Huon Peninsula, the maximum credible earthquake then must be at least of magnitude 8.0.

1959 November 19, 1108 UTC, Finisterre Mountains, M 7.0

The deep magnitude M 7.0 earthquake occurred at a depth of 115 km beneath Finisterre Mountains, Huon Peninsula.

Everingham (1979) documented considerable damage at Alexishafen and Madang. Damage included reinforced concrete wharf extensively cracked, the bishop's single storey fibro-cement house flattened and water tanks thrown down at Alexishafen northwest of Madang. While at Madang, three permanent buildings were seriously damaged, power supply was cut, the airport runway was cracked in places, and water tanks were ruptured (Ripper and Moihoi, 1996a).

The earthquake was felt in Lae at intensity MM 6-7, indicating minor damage, and as far distant as Losuia, Trobriand Islands, in the Solomon Sea.

1962 March 09, 2207 UTC, Huon Peninsula, M 6.7

The magnitude M 6.7 occurred at depth 76 km beneath Saidor on the northern coast of Huon Peninsula and was moderately felt through the Huon Peninsula and Ramu-Markham regions. There were no reports of damage.

1966 December 23, 1550 UTC, Huon Gulf, M 7.2

The magnitude M 7.2 earthquake occurred at depth 46 km offshore in the Huon Gulf and caused no damage on land, but damaged the newly installed Madang-Cairns section of the SEACOM cable. The cable break was caused by turbidity currents in the West New Britain Trench following the earthquake (Krause et al., 1970).

An intensity map for the earthquake has been produced by Denham, Byrne and Wilkie (1968).

The focal mechanism solution is an overthrust striking northeast-southwest (Ripper, 1975), parallel to the plate boundary.

1968 May 11, 1533 UTC, Huon Peninsula, M 5.8

The magnitude M 5.8 earthquake occurred at depth 76 km beneath the Huon Peninsula and was felt strongly on the Huon Peninsula and in the Bulolo-Lae-Goroka area. The earthquake caused no damage. The earthquake was reported by Denham (1974).

The accelerograph at Yonki recorded an acceleration of 0.025g.

Ripper (1975) determined an overthrust focal mechanism solution striking northwest-southeast, in the trend of the Ramu-Markham Valley and plate boundary.

1971 February 02, 1906 UTC, Huon Peninsula, M 6.0

The magnitude M 6.0 earthquake occurred at intermediate depth 113 km beneath the Huon Peninsula and was felt moderately along the Ramu-Markham Valley and in the Highlands. Damage was minor including cracked walls at Watubung, near Goroka, Wantoat, at the epicentre, and Sio on the north coast of the Huon Peninsula.

The earthquake was caused by the northwestward subducting Solomon Plate and occurred in the crest of the plate arch where it plunges to the northwest beneath the Ramu-Markham Valley (Ripper and Letz, 1991).

1977 October 29, 2015 UTC, Saruwaget Range, M 6.4

The magnitude M 6.4 earthquake occurred at depth 106 km beneath the Sarawaget Range, Huon Peninsula.

Damage was minor including at Arau where a house was shifted on its stumps, and two water tanks ruptured at Kabwum.

Both an isoseismal map for the earthquake and a fault plane solution were presented by McCue (1979). The focal mechanism solution indicated left-lateral strike-slip motion, in the trend of and approximately paralleling the Ramu-Markham fault zone.

Measured maximum accelerations at Lae included on soft alluvium soil foundation of 0.041g and on firm rock foundation at Mt Lunaman of 0.016g (Ripper, 1992).

1978 October 10, 2347 UTC, Huon Peninsula, M 5.8

The magnitude M 5.8 earthquake occurred at 98 km depth beneath Huon Peninsula and was only moderately felt. Damage was minor and included cracked water tanks and windows at Etep on the northern coast of the Huon Peninsula.

McCue (1982) prepared an isoseismal map of the earthquake.

Measured maximum acceleration at Lae of 0.012g was recorded on firm rock foundation at Mt Lunaman (Ripper, 1992).

1982 August 05, 0728 UTC, Huon Peninsula, M 5.6

The magnitude M 5.6 occurred at depth 113 km beneath the northern coast of the Huon Peninsula, near Saidor and was felt only weakly. The energy appeared to be channelled south and southwest beneath the Huon Peninsula, Ramu Markham Valley and the Highlands.

The accelerograph at Yonki recorded an acceleration of 0.01g (Ripper, 1992).

The earthquake occurred within the subducted Solomon Plate, which is sinking as an arch beneath the Huon Peninsula.

1983 March 11, 0310 UTC, Huon Gulf, M 6.0

The magnitude M 6.0 earthquake occurred at depth 62 km beneath the Huon Gulf between Lae and Finschhafen. Minor damage occurred at Finschhafen where cracks appeared in the brick walls of a classroom, and some old water tanks developed leaks at Siassi.

Accelerations recorded at Lae included 0.012g on soft alluvium at Lae Botany, 0.015g on firm rock foundation at Mt Lunaman and 0.03g on soft soil at Laetech (Ripper, 1992).

The earthquake occurred in the arch of the Solomon Plate where it subducts north beneath the Huon Peninsula. A mainly strike-slip with some component of overthrust fault plane solution was determined by Harvard/USGS.

1987 February 8, 1833 UTC, Huon Peninsula, Mw 7.3

The earthquake caused damage included landslides, collapse of village houses and destruction of most water tanks, and caused a wharf to fall off its' piers on Umboi and nearby islands. Extensive landsliding on Huon Peninsula resulted in three casualties (Ripper and Letz, 1993). King et al (1987) and Anton (1992) investigated the effects of the earthquake.

1989 March 17, 1338 UTC, Huon Peninsula, M 6.0

The magnitude M 6.0 earthquake occurred at depth 43 km beneath northern coast Huon Peninsula and was strongly felt at Teptep in the epicentral region, where plumbing fittings on a water tank were broken. At Umboi Island, a house was shifted on its stumps, while water tanks were damaged at Eseli on West New Britain.

The focal mechanism solution by Harvard University/USGS is an east-west striking overthrust, consistent with northward subduction of the Solomon Plate beneath Huon Peninsula.

1991 April 30, 1236 UTC, Huon Peninsula, M 5.7

The magnitude M 5.7 earthquake occurred at depth 59 km beneath the Huon Peninsula and was strongly felt in the Huon Peninsula and neighbouring regions. Damage was minor and included cracked plaster sheeting at Yonki.

The Harvard/USGS fault plane solution is essentially overthrust, oriented northeast-southwest, consistent with subduction of Solomon Plate beneath Huon Peninsula.

1992 February 27, 2005 UTC, Huon Peninsula, M 6.5

The magnitude M 6.5 earthquake occurred at depth 39 km beneath the northeastern Huon Peninsula. Damage caused included rupture of water tanks caused by shaking and landslides on the road between Sialum in the northeast and Finschhafen in the southeast and inland between Finschhafen and Pindiu. In the Pindiu region, two permanent material houses and many bush houses were damaged.

The earthquake was strongly felt in Lae, where goods were thrown from shelves, and water tanks were damaged. The earthquake was felt outdoors in Port Moresby.

The Harvard/USGS fault plane solution is overthrust, oriented approximately east-west in the trend of the plate boundary.

1992 May 15, 0705 UTC, Huon Peninsula, M 7.1

The magnitude M 7.1 earthquake occurred at depth 58 km beneath the northern coast Huon Peninsula. Minor damage occurred in Lae and the Huon Peninsula, a fallen wall of a building and cracked cement floors, and damage water tanks in Lae. At Pindiu Village houses were damaged and landslides occurred in the Pindiu/Finschhafen region.

Water tanks were damaged as far away as Mingende in the Simbu Province.

The Harvard/USGS fault plane solution is an overthrust striking north-south.

1995 April 25, 0615 UTC, Huon Peninsula, M 5.7

The magnitude M 5.7 earthquake occurred at depth 22 km beneath the northern coast Huon Peninsula and caused landslides to block rivers during a period of high rainfall which had flooded the Sepik and Ramu Valleys, temporarily.

Although strongly felt, the earthquake caused no damage.

The Harvard/USGS fault plane solution is an overthrust on a WNW-ESE strike.

1995 September 22, 0539 UTC, Finisterre Mountains, M 6.7

The magnitude M 6.7 earthquake occurred at depth 45 km beneath the Finisterre Mountains, Huon Peninsula and was moderately felt through the Markham Valley and the Highlands. Minor damage was report at Aiyura near Kainantu.

The Harvard/USGS fault plane solution shows motion on a horizontal plane, the top side moved to the southwest, consistent with the proposal by Milsom (1981) that the Huon Peninsula is sliding southward toward the Markham Valley on a shallow thrust.

1996 March 02, 0150 UTC, Finisterre Range, M 6.1

The magnitude M 6.1 earthquake occurred at depth 59 km beneath the Finisterre Range, Huon Peninsula and caused landslides at Teptep on the northern side of the Finisterre Range. The National Disaster Centre advised that one person was killed, one person injured and about 12 houses damaged by landslides.

The Harvard/USGS fault plane solution is an overthrust on a northwest-southeast strike, in the trend of the India-Australia South Bismarck Plates boundary.

1996 September 21, 0123 UTC, Finisterre Range, M 5.9

The magnitude M 5.9 earthquake occurred at depth 10 km beneath the Finisterre Range - Markham Valley, on the edge of the region devastated by the 1993 earthquakes and landslides. Three people at Dagwenda village in the epicentral region were reported to be injured by a landslide.

The Harvard/USGS fault plane solution is an overthrust on a WNW-ESE strike, parallel to the Markham Valley and in the trend of the plate boundary.

3.2.7 Ramu – Markham Valleys

The triple junction of the India-Australia, South Bismarck and Solomon Plates is situated beneath the headwaters region of the Ramu and Markham Valleys. The first observation of surface faulting following an earthquake on mainland PNG is in the Gusap Valley of the Finisterre Mountains following the M7.1 earthquake of 13 October 1993 (Tutton and Browne, 1994).

In 1970 a magnitude 7 earthquake occurred at shallow depth near Madang beneath the Adelbert Range north of Madang. The earthquake was described by Everingham (1973a; 1973b; 1975a), ACSEE (1973) and Ripper (1980b). Damage and casualties included fifteen people killed, and an estimated 800 buildings collapsed, mostly bush material houses. Widespread and extensive landslides occurred in the epicentral region (Intensity MM 9), and both the Cairns and Guam sections of the SEACOM telecommunications cable were severed in Astrolabe Bay near Madang. The earthquake was felt as far away as Port Moresby.

A magnitude 7.2 earthquake occurred beneath the Sepik Valley in 1986 and caused damage in the Highlands and northern PNG coast regions. Near Madang in the Astrolabe Bay, both the Guam and Cairns sections of the SEACOM telecommunications cable were extensively severed.

Ripper and Letz (1993) suggested a maximum credible earthquake magnitude of at least 7.5 or even 7.8 as the largest earthquake recorded so far is of magnitude 7.3.

1916 August 03, 0130 UTC, Markham Valley, M 7.2

The magnitude M 7.2 earthquake possibly occurred at intermediate depth beneath the Markham Valley region. The earthquake was given a location by Duda (1965) on the north coast near Wewak, but the earthquake was felt at intensity 6 at Kerema on the south coast as well as Madang on the north coast. It was felt at intensity 4 in Port Moresby. The north coast location would appear to be in error possibly due to the sparse global network and seismic station timing uncertainties.

The adopted location at intermediate depth beneath the Markham Valley replaces the Duda location given in Ripper and Letz (1991, 1993).

1962 March 24, 1259 UTC, Ramu Valley, M 6.4

The magnitude M 6.4 occurred at depth 98 km beneath the Ramu Valley and was widely felt, from the Sepik region in the northwest to Port Moresby in the southeast.

Minor damage was reported at Simbai in the Schrader Range adjacent to the Ramu Valley. The earthquake was moderately felt throughout the Highlands region.

1963 February 14, 2207 UTC, Ramu Valley, M 6.5

The magnitude M 6.5 earthquake occurred at depth 80 km beneath the lower Ramu Valley and was strongly felt (intensity 6) at Manam Island and Tung near the mouth of the Ramu River, but with slight damage.

1968 June 17, 1749 UTC, Ramu-Markham Valley, M 5.3

The magnitude M 5.3 earthquake occurred at depth 110 km beneath the Ramu-Markham Valley and Huon Peninsula, the earthquake was strongly felt through the Huon Peninsula and Highlands, without causing damage. It was felt as far away as Port Moresby, despite its low magnitude. The earthquake was reported by Denham (1974).

An acceleration of 0.038g was recorded on the Yonki accelerograph.

1969 August 02, 0430 UTC, Markham Valley, M 5.5

The magnitude M 5.5 occurred at depth 17 km beneath the Markham Valley about 20 km from Lae. The earthquake was felt strongly at Nasuapum near Lae where some cracking was reported in brick walls. At Bubia near Lae, it was reported as the "best" felt in 17 months.

At Afore near Popondetta, about 300 km from the epicentre, the earthquake was felt by everyone and slight ground waves were observed.

1971 September 25, 0436 UTC, Markham Valley, M 6.7

The magnitude M 6.7 earthquake occurred at depth 115 km beneath the Markham Valley only about 20 km from Lae, where it was felt strongly. Several water tanks were cracked, louvre windows were broken, and cracks appeared in river banks.

The fault plane solution determined by Ripper (1977) is a dip-slip normal fault, with the "Pressure" axis approximately vertical, consistent with the concept of the Solomon Plate sinking below the colliding South Bismarck and India-Australia Plates.

The accelerograph on alluvium foundation at Lae recorded an acceleration of 0.11g (Ripper, 1992).

1974 September 20, 2120 UTC, Markham Valley, M 6.3

1976 May 21, 0642 UTC, Ramu Valley, M 6.1

The magnitude M 6.1 earthquake occurred at depth 126 km beneath the Ramu Valley, typical of earthquakes which occur at depths of about 100 km and over in the sinking Solomon Plate beneath the Markham Ramu Valley and Sepik Valley region. The earthquake was moderately felt throughout Huon Peninsula and the Highlands, and landslides were reported near Pindiu on the Huon Peninsula.

An accelerograph on alluvium at Lae recorded an acceleration of 0.007g (Ripper, 1992). McCue (1981b) prepared both an isoseismal map and a focal mechanism plot. The focal mechanism is a normal fault with strike parallel to the Markham Ramu Valley and plate boundary.

1977 December 02, 0413 UTC, Ramu Valley, M 6.0

The magnitude M 6.0 earthquake occurred at depth 66 km beneath the Ramu Valley and was strongly felt through the Highlands and north coast regions. South of the epicentre at Chuave in the Highlands, water pipes were sheared. At Wabag, a water tank was cracked.

McCue (1979) prepared both an isoseismal map and a fault plane solution of the earthquake. The fault movement is strikeslip on a vertical plane. The nodal plane striking WNW-ESE is indicative sinistral movement, parallel the plate boundary.

1980 June 25, 1848 UTC, Markham Valley, M 5.9

The magnitude M 5.9 earthquake occurred at shallow depth (21 km) beneath Markham Valley, 25 km from Lae. In Lae, some water tanks cracked, and goods that fell from shelves in stores was valued at several thousand kina. At Sialum on the northern coast of the Huon Peninsula, several village houses were damaged.

Maximum accelerations at Lae included of 0.19g recorded on firm soil and 0.098g on soft alluvium and 0.104g on firm rock foundation (Ripper, 1992).

Abers and McCaffrey (1994) determined a focal mechanism of an overthrust striking WNW-ESE, approximately parallel to the plate boundary.

1989 December 07, 1338 UTC, Markham Valley, M 6.3

The magnitude M 6.3 earthquake occurred at depth 104 km beneath the Markham Valley and was felt from near the western international border with Papua, Indonesia, to Bialla in northeastern New Britain.

The earthquake caused landslides near the epicentre at Kup, and cracked a brick wall of a building at Yonki and damaged a water tank at Gogme. In Lae, goods fell from shop shelves.

Accelerations at Lae included 0.018g recorded on firm rock foundation and 0.075g recorded on firm alluvium (Ripper, 1992).

The earthquake occurred in the sinking Solomon Plate. Harvard/USGS determined a strike-slip fault plane solution.

1991 November 05, 0656 UTC, Markham Valley, M 6.0

The magnitude M 6.0 earthquake occurred at depth 105 km beneath the Markham Valley and may have had its effects mitigated at depth. Minor damage reported was of cracked plaster at Wau. The earthquake was widely felt, as far away as Port Moresby and Terapo on the Gulf of Papua.

The Harvard/USGS fault plane solution is strike-slip and occurred within the sinking Solomon Plate.

3.2.8 Eastern New Guinea

Earthquakes of great depth beneath Long Island, eastern New Guinea are usually widely felt through the Highlands, some strong enough to cause damage. Typically of deep earthquakes from this region, the energy apparently channelled up through the Solomon lithospheric plate slab southwest into the Highlands, as suggested by Denham (1971). The slab is part of the Solomon Plate, which is subducting beneath the New Britain Volcanic Arc. Some of these earthquakes have been significant and are described herewith, in this section.

1967 September 01, 0331 UTC, Long Island, M 6.0

The magnitude M 6.0 earthquake occurred deep beneath Long Island at depth 182 km, north of the Huon Peninsula, and was felt most strongly in the Kainantu region, 150 km to the southwest, where it initiated landslides in road cuttings near Kompiri.

Denham (1971) suggested that the energy from this earthquake is transmitted up the lithospheric slab, from beneath Long Island towards the south or southwest.

1967 November 14, 0528 UTC, Long Island, M 6.0

The M 6.0 earthquake occurred at depth 201 km deep beneath Long Island and was strongly felt through the Highlands but without causing any damage. It was typical of deep earthquakes from the Long Island region, the energy apparently channelled up the Solomon lithospheric plate southwest into the Highlands, as suggested by Denham (1971), who reported the earthquake. The accelerograph at Yonki recorded an acceleration of 0.048g. The earthquake was an overthrust with strike approximately east-west (Ripper, 1975), probably caused by partial melting and break-off of the sinking slab.

1969 March 10, 0654 UTC, Vitiaz Strait, M 6.4

The magnitude M 6.4 earthquake occurred deep beneath Vitiaz Strait, near Long Island, at depth 206 km. Typical of deep earthquakes which occur beneath Long Island, the earthquake was moderately felt throughout the Ramu-Markham Valley and Highlands regions, and even as far away as Port Moresby. Damage included the cracking of two concrete posts at Ino-onka near Kainantu.

An acceleration of 0.036g was recorded on the Yonki accelerograph.

Ripper (1977) determined an overthrust focal mechanism solution, striking approximately east-west.

1969 June 24, 0329 UTC, Huon Peninsula, M 5.9

The magnitude M 5.9 earthquake occurred at depth 113 km deep beneath the northern coast, Huon Peninsula. Typical of intermediate depth shocks beneath the Huon Peninsula and Vitiaz Strait, the earthquake was moderately felt up the Ramu-Markham Valley and in the Highlands. Cracks appeared in the new cement floor of a classroom and cement brick walls of a house at Chevasing Primary School in the Markham Valley. Typical of deep earthquakes of the region, the seismic energy appeared to have been channelled from the hypocentre 113km deep beneath the north coast, diagonally upwards towards the south into the Markham Valley.

The accelerograph at Yonki recorded an acceleration of 0.059g.

Ripper (1977) determined the focal mechanism solution, which is a left lateral strike-slip; the motion is sinistral, northeast side moving northwest.

1972 November 05, 2008 UTC, Long Island, M 6.0

The magnitude M 6.0 earthquake occurred at depth 230 km deep beneath Long Island. The earthquake has been described by Everingham and Sheard (1980). Typical of deep earthquakes beneath the Long Island region, it was felt throughout the Markham-Ramu and Highlands regions. The felt intensity was greatest at Garaina on the Papuan Peninsula, intensity MM7.

Ripper (1992) reported accelerations of 0.017g and 0.018g recorded at Lae on firm soils.

It is suggested that the earthquake occurred in a segment of Solomon Plate, which has subducted beneath the South Bismarck Volcanic Arc (Ripper and Moihoi, 1996c).

1981 March 21, 2252 UTC, Vitiaz Strait, M 6.1

The magnitude M 6.1 earthquake occurred at depth 227 km beneath Vitiaz Strait between Long Island and Huon Peninsula, and was strongly felt throughout the Huon Peninsula, Markham Valley and Highlands. In Lae, vehicles stopped as the earthquake was felt by drivers. People ran from houses. Visible ground waves were observed (Ripper and Moihoi, 1996b).

Accelerographs at Lae recorded accelerations of 0.028g and 0.020g, while the accelerograph at Yonki recorded 0.005g, all on firm soil and rock foundations (Ripper, 1992).

1983 January 16, 2210 UTC, Long Island, M 6.3

The magnitude M 6.3 earthquake occurred at depth 235 km beneath Long Island and was felt strongly throughout the Highlands, but caused slight damage. A few small landslides occurred near Ambulla in the Western Highlands Province and Okapa in the Eastern Highlands Province. Cables suspended in the Postal and Telecommunications building at Lae frayed and disrupted telephone communications.

Accelerations recorded at the Lae on firm soil foundations were 0.034g and 0.031g while those recorded at Yonki on rock foundations were 0.041g and 0.011g (Ripper, 1992).

The Harvard/USGS fault-plane solution is an overthrust striking WNW-ESE, parallel to the local trend of the Wadati-Benioff Zone.

1987 February 08, 1833 UTC, Vitiaz Strait, M 7.4

The magnitude M 7.4 earthquake occurred at depth 55 km beneath Vitiaz Strait and has been described by King, Letz and Buleka (1987) and Anton (1992). The earthquake caused damage to "permanent" fibro buildings at the government centre of Samo on Umboi (Siassi) Island, and ruptured fourteen water tanks on the station. The nearby wharf at Gizarum collapsed and a small vehicular wooden bridge on a plantation on the northeast of the island was damaged. There was extensive landsliding at Samo. In all 327 village houses were damaged on Umboi Island of which sixty were damaged at the village of Tarawe near Samo.

Damage also occurred on Huon Peninsula, as far southwest as Mindik, near Pindui in central Huon Peninsula. Road slides occurred as far away as the road between Kundiawa and Diruima in the Highlands. A total of 374 village houses were damaged on the mainland. Three people, a woman and two children, were killed by a landslide on the Yalumet River near Kabwum on Huon Peninsula.

Accelerations of 0.030g and 0.024g were recorded at Lae on firm soil and rock foundations respectively (Ripper, 1992).

The Harvard/USGS determined a strike-slip fault plane solution, with motion dextral on a north-south plane. Anton (1992) determined that the fault plane diagrams of a foreshock at 1157 UTC and the aftershock sequence are similar. The aftershock pattern approximates a line trending SSW-NNE, from Lae through Umboi Island. More than 1900 earthquakes were recorded by the PNG seismic network (Anton, 1992). Abers and McCaffrey (1994) also studied the earthquake and aftershock sequence, and indicated the earthquake and sequence as one occurring on one of those cross-arc fault systems.

1990 April 03, 0733 UTC, Vitiaz Strait, M 6.0

The magnitude M 6.0 earthquake occurred at depth 88 km beneath Vitiaz Strait. The earthquake was strongly felt on the Huon Peninsula and neighbouring regions, with the only damage reportedly caused to a water tank at Wasu on the Huon Peninsula.

Ripper (1992) reported that an acceleration of 0.012g was recorded at Lae on firm soil foundation. The Harvard/USGS fault plane solution is mainly overthrust (Anton, 1995). The earthquake occurred in the subducting Solomon Plate.

1992 August 16, 1023 UTC, Long Island, M 6.2

The magnitude M 6.2 earthquake occurred at depth 215 km beneath Long Island and was widely felt through the Highlands and northern coast of PNG mainland regions. The Harvard/USGS fault plane solution is essentially overthrust.

1993 October 13, 0206 UTC, Finisterre Mountains, M 7.1

The magnitude M7.1 earthquake occurred at depth 24 km beneath the Finisterre Mountains, and was the first of a three-month earthquake sequence which included a second magnitude 7 earthquake. During this earthquake, 37 lives were lost, the highest number of casualties during any earthquake in PNG since the 1935 Torricelli Mountains earthquake. About three thousand aftershocks occurred during the first month, as recorded by the Yonki seismograph.

Damage caused by the earthquake series has been described by Tutton and Browne (1994). The landsliding caused by the earthquake extended about 60 km through the Finisterre Mountains on a northwest-southeast azimuth parallel to the Ramu-Markham lineament, causing damage to the Matak airstrip by cracking and subsidence. Many villages were left in a critical condition by the landslides to be later destroyed by the aftershocks. Nineteen casualties were from Mataya village, killed by landslides.

The Yonki Hydroelectric Power Plant situated about 40 km to the south of the epicentre, built to earthquake resistant specifications was not damaged. Minor damage in the township included ruptured water tanks, intensity MM 7.

The Harvard/USGS fault plane solution is an overthrust on a WNW-ESE strike, indicative of consistency with the hypothesis proposed by Milsom (1981) that the Huon Peninsula is sliding south on a shallow thrust, or the interpretation accorded the earthquakes by Stevens *et al.* (1997) that they occurred on a shallow (20 km) thrust, ramping to shallow depth below the Markham Valley.

1993 October 25, 1027 UTC, Finisterre Mountains, M 7.0

The magnitude M7.0 earthquake occurred at depth 30km beneath the Finisterre Mountains. The earthquake was the largest of the aftershock sequence of the 13 October magnitude 7.1 earthquake described by Tutton and Browne (1994). No villages were completely destroyed in the first earthquake, but after the 25 October shock, three villages had been completely destroyed and more than 50 sufficiently damaged to require the evacuation of their 8000 inhabitants. Cracks occurred in the airstrip at Matak (Ripper and Moihoi, 1996b).

Tutton and Browne (1994) reported on massive landslides causing extensive damage as a result of major blockages in all major rivers flowing southward from the Finisterre Mountain range. Damage was catastrophic and included breached dams destroying two major bridges along the Lae-Madang Highway, and that irrevocably altered the form of many of the valleys and rivers draining into the Markham and Ramu valleys. Damage occurred at Yonki, to block-work brick walls of at least one house.

The Harvard/USGS fault plane solution is an overthrust on a plane dipping gently to the NNE, similar to the 13 October earthquake.

Ripper and Moihoi (1996b) documented that in the aftershock series, intense landsliding (MM 9) occurred in the crest region of the Finisterre Mountains on 29 October from a magnitude 5.6 aftershock and at MM 8 on the southern side of the ridge on 5 January 1994 from a magnitude 5.0.

3.2.9 Sepik Valley – northern PNG

The seismicity north and northwest of the Sepik River is intense. The largest earthquake occurred at a depth of about 130 km beneath the Sepik Valley in 1943. Shallow earthquakes are scattered about the zone, nine having actually occurred. The 1935 magnitude 7.9 Torricelli Mountain earthquake is the largest earthquake to have occurred in this seismic zone. Massive landsliding occurred as a result thus dislodging debris transported and deposited offshore (Marshall, 1937). The earthquake was experienced by pioneer geologist S.W. Carey who reported (Carey, 1990) that, "shallow focus was not far below us. My terrified survey labourers were thrown down, rose, to be thrown down again, and again. The acceleration locally exceeded g because objects left the ground. Trees were falling all about. Ridges were splitting and roaring down like avalanches. The survey station I had just left was buried tens of metres deep as the cliffs above erupted over it". Stanley et al, (1935), Marshall (1937) and Carey (1990) reported extensive damage and casualties from breached dammed rivers. McCarthy (1963) and Everingham (1977) reported a tsunami that flooded low-lying coastal sections.

In 1968, a magnitude 7 earthquake was the largest in a series of earthquakes that damaged the Wewak area. Damage caused occurred mainly in the Dagua region, 40 km west of Wewak, and damage caused by the foreshocks was centred around Maprik, 60 km southwest of Wewak, and at Wewak (Ripper and Letz, 1993). Landslides dammed rivers and streams.

The most recent large earthquakes that occurred in the region of northern New Guinea including the 1996 Biak magnitude 8.2 (Mw) earthquake and, the 1998 Aitape magnitude 7.0 (Mw) earthquake and the 2002 Wewak magnitude 7.6 (Mw) earthquake.

As magnitude 7.9 and 7.7 earthquakes have occurred in the region, the maximum credible earthquake, or largest earthquake ever likely to occur, is of magnitude 8.0 at least.

1931 August 07, 0211 UTC, Sepik River, M 7.2

The magnitude M 7.2 earthquake occurred at shallow depth north of the Sepik River probably further north, closer to the north coast. It was reported that the beach east of Aitape was fissured, and that an "ingress of water" occurred. Many villages were completely wrecked, while many landslides occurred (Ripper and Moihoi, 1996a). The earthquake was felt as far southeast as Madang.

1935 September 20, 0146 UTC, Torricelli Mountains, M 7.9

The magnitude M 7.9 was largest for a while. It occurred at shallow depth (possibly 30 km) beneath the Torricelli Mountains, north of the Sepik River.

Chief Geologist then, S.W. Carey and a geological survey party, experienced first hand the intense shaking while mapping in the Sibi River region of the southern Torricelli Mountains (Stanley, et al., 1935; Carey, 1990). Reports were that rocks left the ground, which suggests an acceleration exceeding 1g, and massive landslide dams created huge lakes in the Gweinif and Kaufangi Rivers area.

Stanley *et al.* (1935) documented reports of damage at Aitape, which was slight cracking of concrete, shifting of houses on foundations, overthrowing of water tanks and all movable objects. There was minor landsliding at Wewak with no damage.

Marshall (1937) documented extensive denudation of whole mountains in the Torricelli Mountains inland from Aitape.

Damage was also reported from the Fly River region, Oroville Camp, near the Kiunga Township, where a severe disturbance "uprooted large trees near the camp", assisted by minor landslips which occurred in the hills or by the river banks indicative of intensity MM 6.

1961 January 05, 1554 UTC, Sepik Valley, M 7.1

The magnitude M 7.1 earthquake occurred deep at depth 131 km beneath the Sepik Valley and was widely felt, with the highest intensities, MM 6, reported from the Southern Highlands, south of the Sepik Valley.

1962 April 01, 1211 UTC, Sepik Valley, M 6.3

The magnitude M6.3 earthquake occurred at depth 80km beneath the Sepik Valley and was strongly felt in the Sepik Valley and western Highlands region (intensity 6), without any appreciable damage.

1962 July 30, 1716 UTC, Wewak, M 7.0

The magnitude M 7.0 earthquake occurred at depth 25 km beneath the northern coast, at the intersection of the Bismarck Sea Seismic Zone with the northern coast zone of New Guinea, near Wewak (Ripper and Moihoi, 1996a).

The earthquake was felt strongly at Wewak, at intensity MM 6, but damage reported was minor, and was reported from as far north as Alison Island, in the Ninigo Group, westnorthwest of Manus Island.

1962 August 01, 0436 UTC, Wewak, 6.7 Aftershock

An aftershock of the 30 July earthquake, the magnitude M 6.7 earthquake occurred at shallow depth beneath the northern coast near Wewak and was strongly felt in Wewak, with slight damage caused. The earthquake was felt in the Highlands, with a report of moderate intensity (MM 4) at Mt Hagen.

1968 September 08, 1512 UTC, Maprik, M 6.2

The magnitude M 6.2 earthquake occurred at shallow depth (29 km) near Maprik, beneath the Prince Alexander Mountain Ranges north of the Sepik River. Damage caused by the earthquake has been described by Denham (1974), and included the cost of repairs in Maprik alone estimated at Aus$20,000.00 involving mostly that to the conventional European-style houses, three experimental adobe houses indicative of intensity MM 8. Nearby villages and missions stations suffered and road slides occurred. The damage indicated intensity 8 in Maprik and nearby localities. Landslides dammed the Misuam River. The earthquake was felt at Komo in the Southern Highlands, and as far away as Kelanoa on the Huon Peninsula. This earthquake was the beginning of a series that would include a magnitude 7 earthquake (23 October) and extend into November (Ripper and Moihoi, 1996a).

Ripper (1975) determined an overthrust focal mechanism solution, striking approximately northwest-southeast parallel to the coastline and plate boundary.

1968 September 27, 1906 UTC, Prince Alexander Mountains, M 6.4

The magnitude M 6.4 earthquake occurred at depth 13 km beneath the Prince Alexander Mountains, northern New Guinea, about 50 km west of Wewak, or probably closer. The earthquake and another of magnitude 5.7 on 29 September at 2154 UTC caused damage at Wewak, the 29 September aftershock appears to have caused the most damage. The damage has been described and photographs presented by Denham (1974).

Damage included destruction to a bridge foundation at Boram near Wewak, at intensity MM8, over 70 water tanks were damaged and brick walls collapsed (MM7), and cracks appeared in brickwork. Damage to houses included cracked piers supports and broken plumbing. At Boram three large storage sheds were damaged by the toppling of brick walls and movement of brick walls on their damp courses. At Moem Army Barracks, roof beams in a three-storey dormitory separated from the walls. At Passam, south of Wewak, the unsupported internal wall of a low cost cement brick house was damaged (Ripper and Moihoi, 1996a).

The focal mechanism solution is an overthrust striking northwest-southeast, approximately parallel to the coastline and plate boundary (Ripper, 1975).

1968 October 23, 2104 UTC, Price Alexander Mountains, M 7.0

The magnitude M 7.0 earthquake occurred at depth 12 km beneath northern New Guinea, north of the Prince Alexander Mountains, and was the largest of the series that occurred during September and October 1968 in the Maprik-Wewak region of northern New Guinea. It occurred after about a three-week lull in the aftershock series, and the earthquakes had appeared to be finished. Damage has been described by Denham (1974).

One taxiway was closed as a result of cracks developed in the main runway of Wewak airstrip at Boram. Buildings damaged at Dagua on the coast and at Muschu Island, due to subsidence. On Muschu Island, a small dam backing up water to form a swimming pool cracked.

Buildings and water tanks were damaged at Hawain River Technical College about 15km west of Wewak, between Wewak and Dagua.

The focal mechanism of the earthquake is strike-slip, with nodal planes approximately NNE-SSW and WNW-ESE. Ripper (1975) proposed that if the latter nodal plane is the fault plane, the motion is sinistral, north side moving west.

1970 October 13, 1853 UTC, Sepik Valley, M 5.9

The magnitude M 5.9 earthquake occurred at depth 120 km, deep beneath the Sepik Valley. It is postulated that at this depth the earthquake is evidence of the existence of lithosphere, either as a horizontal plate or as fragments, sinking into or being assimilated into the mantle (Denham, 1975), the sunken lithosphere originally being part of a major Solomon Plate (Ripper and Letz, 1991; Ripper, Letz and Anton, 1996).

Damage included three houses at Amboin in the Sepik Valley and at Ialibu 200km south of the epicentre in the Highlands, where a bulk fuel tank was fractured. Several water tanks were damaged at Mendi, and a water tank fell over at Koroba. Many small landslides occur in road cuttings.

The earthquake was reported by Ripper (1980b). The focal mechanism is an overthrust striking east-west (Ripper, 1977; 1980a).

1970 October 31, 1753 UTC, Adelbert Range, ML 7.0

The magnitude M 7.0 earthquake occurred at depth 42 km beneath the Adelbert Range, northern New Guinea and caused intense landsliding in the Adelbert Mountains near Madang, and killed 15 people, damaged bridges, broke the submarine SEACOM Cable near Madang in four places, and caused considerable damage in the town of Madang.

The effects have been extensively described, in particular by Everingham (1973a, 1973b, 1975a), Baker, Berg and Wight (1973) and Clifton-Bass (1973) in ACSEE (1973), Ripper (1980b), and Pain (1972) who described the intense landsliding.

Ripper (1977) for the earthquake was an overthrust on a northwest-southeast strike, but the aftershock series is elongated to the northeast and Karkar Island (Everingham, 1975a). The aftershock sequence is consistent with sinistral strike-slip focal mechanism solution determined by Abers and McCaffrey (1994), an indicative of movement on a cross-fault system.

Yonki recorded an acceleration of 0.079g and the recorded period of shaking exceeded a minute.

1970 November 28, 2022 UTC, Sepik Valley, M 6.4

The magnitude M 6.4 earthquake occurred and intermediate depth (114 km) beneath the Sepik Valley and was moderately felt from Wewak in the north to Lake Kutubu in the south. It was strongest at Tari and Tigibi where it damaged some water tanks.

Ripper (1977) determined a focal mechanism which is an overthrust striking WNW-ESE. At this depth, the earthquake is evidence of activity in a sunken section of the Solomon Plate, which extends westward beneath the Ramu-Markham and Sepik Valleys.

1972 January 18, 2155 UTC, Ramu Valley, M 6.5

The magnitude M 6.5 earthquake occurred at shallow depth beneath the Ramu Valley side of the Adelbert Mountains, and was followed 13 minutes and 17 hours later by magnitude 6.0 aftershocks. These earthquakes were described by Everingham and Sheard (1980), which were strongly felt at intensity MM 6 within 100 km of the epicentre. Damage included leaks to two water tanks at Kamba near Madang, and some minor damage was reported from Serang, on the northern coast near Manam Island. The earthquake was felt as far away at Garaina in the Bowutu Mountains, where the main shock stopped a pendulum clock.

Ripper (1992) determined an acceleration of 0.028g recorded at Yonki.

1973 August 13, 0828 UTC, Sepik Valley, M 6.3

The magnitude M 6.3 earthquake occurred deep beneath the Sepik Valley at 112 km depth and was strongly felt in the north coast, Sepik and Highlands regions. Damage occurred to several water tanks, and two trees were knocked down in Wewak. In the Western Highlands a landslide occurred. The earthquake was felt strongly at Goroka.

Ripper (1992) determined accelerations on firm foundations at Yonki 0.027g, and Lae Mt Lunaman, 0.008g.

The earthquake occurred within a section of the westward-subducted Solomon Plate (Ripper and Letz, 1991), and at depth the effects were mitigated locally and felt strongly farther a-field in the PNG highlands seismic energy having channelled up sinking lithospheric slab.

1975 December 25, 2322 UTC, Sepik Valley, M 6.9

The magnitude M 6.9 earthquake occurred at depth 115 km, typical of intermediate depth earthquakes beneath the Sepik Valley, and caused minor damage in the surrounding region. Six water tanks were broken and minor landslides occurred at Ambunti. Other damage included that to a prefabricated temporary accommodation cubicle at Tabubil and waters tanks at Green River.

Ripper (1992) determined an acceleration of 0.23g recorded at Frieda River, at an epicentral distance of 68 km.

At this depth, the earthquake occurred in a segment of Solomon Plate, which has sunk beneath the Sepik Valley (Ripper and Letz, 1991).

1977 April 26, 0359 UTC, Madang, M 5.4

The magnitude M 5.4 earthquake occurred at depth 87 km near Madang where it was strongly felt, knocking goods off shelves in shops. The Madang-Cairns section of the SEACOM Cable was ruptured 4.2 km from Madang 15 minutes after the earthquake, presumably by a submarine slide.

1979 June 25, 0529 UTC, Adelbert Range, M 6.6

The magnitude M 6.6 earthquake occurred at depth 189 km beneath the Adelbert Range near Madang, and this depth mitigated damaging effects in the epicentral region. Only two brick houses were damaged at Halopa close to the epicentre. Damage occurred to water tanks along the highlands from Wapenamanda to Kundiawa, and to a concrete floor at Okapa. The Madang-Cairns section of the Seacom Cable ruptured for the fifth time (by earthquakes) since its installation in 1966. Three breaks along the section 30 minutes after the earthquake, at 16 km east of Madang, and again 39 km east of Madang in Astrolabe Bay, and four hours after the earthquake, 32 km east of Madang.

Ripper (1992) measured maximum accelerations of 0.14g and 0.13g on firm foundations at Yonki, and 0.016g on firm foundation at Lae Mt Lunaman, and 0.016g, 0.032g, 0.019g and 0.021g on firm soil foundations at Lae.

1980 July 16, 1956 UTC, Sepik Valley, M 6.8

The magnitude M 6.8 earthquake occurred at depth 84 km deep beneath the Sepik Valley and caused considerable damage to village communities along the Sepik River and tributaries in the epicentral region.

The village of Kapaimari near Ambunti was devastated having a total of its 60-70 bush material buildings flattened, and more damaged. "Big waves" were seen on the Sepik River, and fish were thrown onto the sand along tributaries. More houses were damaged at Kundima on the Yuat River (19), at Kambrindo, on the Sepik River(60), Oksapmin in the Central Highlands west of Lake Kupiano (6 low cost permanent material houses) and at Komo in the Southern Highlands (one permanent material).

Ripper (1992) determined accelerations of 0.003g and 0.004g from the Frieda River accelerograph and the Yonki Machine Hall accelerograph respectively.

1980 September 26, 1520 UTC, Aitape/Torricelli Mountains, M 6.5

The magnitude M 6.5 occurred at shallow depth (33 km) beneath Aitape/Torricelli Mountains, northern New Guinea. The earthquake was strongly felt in Aitape and in a small surrounding area. It was said to be "the strongest tremor felt in Aitape since the tremor in September 1935".

Bush material houses collapsed and water tanks were ruptured at Aitape, and at Tumleo Island, near Aitape, at Afua and Yakamul to the southeast of Aitape. A permanent house on 1m concrete stumps at Paup moved. A bridge approach at Waipo Inlet subsided and was cracked (Ripper and Moihoi, 1996b).

1981 October 17, 1208 UTC, Torricelli Mountains, M 5.9

The magnitude M 5.9 earthquake occurred at depth 26 km beneath Torricelli Mountains, northern New Guinea near the northern coastal town of Aitape. Some damage occurred in Aitape including water tanks, and cracks to semi-permanent buildings, several motorists reported difficulty in controlling their vehicles. One motorist sitting in his parked vehicle was under the impression that he had been hit by another car.

1981 November 06, 1647 UTC, Wewak, M 6.6

The magnitude M 6.6 earthquake occurred beneath northern New Guinea coastline, near Wewak. Significant effects of the earthquake occurred west of Wewak, inland between Wewak and Aitape. Hence the probable earthquake centre is beneath the Prince Alexander Mountains west of Wewak. Landslides occurred at Lumi, near Aitape, and Yangoru, near Wewak and village houses were damaged at Lemieng, near Aitape.

Maximum accelerations of 0.18g and 0.11g were recorded two nearby sites at Wewak on firm soil foundations.

The Harvard/USGS focal mechanism is an overthrust aligned parallel to the coastline and plate boundary, indicative of the forced collision of the North Bismarck Plate with the India-Australia Plate.

1981 November 25, 0936 UTC, Aitape, M 5.5

The magnitude M 5.5 earthquake occurred at 24 km depth beneath the northern New Guinea coastline near Aitape. Damage included ruptured water tanks at Pes village near Aitape. People found it difficult to stand in the epicentral region, and also at Sassoga Mission near Wewak.

1983 October 08, 2233 UTC, Astrolabe Bay, M 5.6

The magnitude M 5.6 earthquake occurred at depth 59 km beneath Cape Rigny, Astrolabe Bay and was strongly felt in the Madang region without causing any damage.

Ripper (1992) determined accelerations of 0.1g and 0.055g recorded at Madang, on firm coral foundation and firm soil foundation.

The Harvard/USGS fault plane solution is an overthrust parallel to the coastline and the local South Bismarck/India-Australia Plate boundary.

1984 March 27, 2006 UTC, Karkar Island, M 6.5

The earthquake was described by Anton (1993). The magnitude M 6.5 earthquake occurred at depth 28 km beneath Isumrud Strait, west of Karkar Island. Eleven people were reported injured and considerable damage was caused in the government District Office area of Miak, northwest Karkar Island, and to schools in the north of Karkar Island. The government station reported that about twenty brick residences were damaged. School classrooms in the region were also badly damaged. Landslides occurred on the sides of the mountain. The wharf and causeway at Kinim were damaged.

An acceleration of 0.026g was recorded in Madang of firm soil foundation (Ripper, 1992).

The earthquake occurred on a seismic zone, which seems to trend from the coastline, the margin of the South Bismarck and India-Australia plates, northeastward through Karkar Island. As such, it would involve internal deformation of South Bismarck Plate. The Harvard/USGS fault plane solution is strikeslip (Anton, 1993). If the southwest-northeast trending nodal plane is the fault plane, the motion is sinistral, northwest side moving southwest. The solution is similar to that of the 31 October 1970 Adelbert Range earthquake (Abers and McCaffrey, 1994).

1985 January 17, 2133 UTC, Sepik Valley, M 5.8

The magnitude M 5.8 earthquake occurred at 34 km depth beneath the Sepik Valley, and was followed by another magnitude 5.8 earthquake which occurred at the same location eleven minutes later, at 2144 UTC. Water tanks were damaged at Aitape, Lumi and Nuku, and a roadslide occurred at Meiwaute. The Harvard University/USGS fault plane solution is strike-slip.

1985 April 16, 2238 UTC, Wewak, M 5.3

The magnitude M 5.3 earthquake occurred at depth 25 km beneath the northern New Guinea coastline near Wewak. Minor house cracks in Wewak, and a village house moved on its stumps at But Community School close to the epicentre, and a tree fell down at Hawain Community School.

The Harvard fault plane solution published by USGS is an overthrust parallel to the coastline and the plate margin.

1986 June 24, 0311 UTC, Sepik Valley, M 7.1

The magnitude M 7.1 earthquake was described by Anton (1994). The earthquake occurred at depth 102 km beneath the Sepik Valley and was felt throughout the PNG mainland, and as far southeast as Port Moresby. Both the Madang-Guam and Madang-Cairns submarine SEACOM cables run in Astrolabe Bay were ruptured, consequently not repaired and were abandoned. Sixty-eight village houses were damaged in the village of Wom in the Sepik Valley, in the epicentral region near Angoram. The Anagram PTC microwave station was disabled temporarily as equipment fell from racks. The Mt Hagen squash court was damaged, and there was damage to a bridge-approach, to water tank and road throughout the Highlands.

Ripper (1992) reported accelerations recorded at Madang Cable Station on firm coral foundation, 0.072g; Madang Frieda Office on firm soil, 0.094g; Wewak on firm soil, 0.056g; Wewak Post Office on firm soil, 0.060g; and at Tabubil on rock foundation, 0.014g.

The Harvard/USGS fault plane solution is an overthrust striking northwest-southeast, with vertical tension axis (Ripper and Moihoi, 1996b).

1990 March 27, 2004 UTC, Astrolabe, M 5.5

The magnitude M 5.5 earthquake occurred at 82 km beneath Astrolobe Madang and at depth although only of magnitude 5.5, the earthquake was strongly felt along the northern coast and Highlands. Damage to water tanks at Wasu on the Huon Peninsula was the only reported.

Ripper (1992) reported an acceleration of 0.030g recorded at on firm soil foundation at Laetech, Lae.

Anton (1995) reported the earthquake and documented a strike-slip focal mechanism solution determined by Harvard/USGS. The earthquake occurred in the Solomon Plate subducting beneath the Bismarck Volcanic Arc.

1990 November 23, 0056 UTC, Karkar Island, M 5.7

The magnitude M 5.7 earthquake occurred at depth 62 km beneath the northern coastline of the PNG mainland, between Madang and Karkar Island, and was strongly felt on Karkar Island with some damage. A landslide blocked off the coastal road at Kavailo Village and houses were damaged. At Biabi Plantation buildings were damaged, and classrooms and water tanks were damaged at Kavailo and Abesan schools.

The strike-slip Harvard/USGS fault plane solution was reported by Anton (1995). The plane orthogonal to the plate margin is the fault plane, indicating sinistral motion, the northwest side moving southwest. Similar mechanisms were obtained for the 31 October 1970 Adelbert Range earthquake (Abers and McCaffrey, 1994), and 27 March 1984 earthquake described by Anton (1993).

1991 May 17, 0231 UTC, Sepik Valley, M 6.0

The magnitude M 6.0 earthquake occurred at depth 59 km beneath the Sepik Valley and was felt strongly in the epicentral region. Only minor damage resulted. Water tanks cracked and few cracks in cement, and at Angoram on the Sepik River, a seiche motion was observed on the river.

The Harvard/USGS fault plane solution is strikeslip.

1993 June 15, 1306 UTC, Adelbert Range, M 5.8

The magnitude M 5.8 earthquake occurred deep at 227 km beneath the Adelbert Range, northern New Guinea and was strongly felt along the Highlands, with landslides occurring in the Simbu Province.

The Harvard/USGS fault plane solution is mainly strikeslip, with northwest-southeast and northeast-southwest trending nodal planes, with the northwest-southeast plane in the strike of the boundary.

1998 July 17, 0949 UTC, Aitape, Mw 7.0

The Aitape Tsunami of 17 July 1998 closely followed a magnitude 7.1 earthquake, and may have been caused by an earthquake-induced submarine slump (Ripper, Anton et al., 2000; Sweet et al., 1999; Sweet and Silver, 2003; Synolakis et al., 2002; Tappin et al., 1999; Tappin et al., 2001; Tappin et al., 2008).

The tsunami was extensively studied, for example Borrero (2001), Davies et al. (2003), Okal (1999), Okal and Synolakis (2001), Imamura and Hashi (2003). The tsunami killed more then 2,000 people and injured 1,000 and left thousands homeless (Davies, 1998).

2002 September 08, 1844 UTC, Wewak, Ms 7.8

The magnitude Ms 7.8 Wewak Earthquake of 2002 September 8 (Anton and McKee, 2005b) was one of the largest earthquakes ever recorded from the northwestern part of mainland Papua New Guinea. The earthquake occurred at shallow depth, just offshore and about 90 km west-northwest of Wewak. It caused serious damage to numerous houses and water tanks, triggered many landslides and created ground cracks. Uplift of as much as 30-40 cm occurred at the "Wewak Islands", Tarawai, Walis, Kerasau, Kairiru and Muschu.

A moderate tsunami, having maximum amplitude of 3-4 m, was generated at the same time as, or soon after, the earthquake.

3.2.10 PNG Highlands

The zone southwest of the Ramu Valley is a region of very weak seismicity. Two magnitude 5 earthquakes have occurred on or near the zone since 1964, in 1973 and 1993. However, the earthquake activity indicates that a large earthquake could occur in the Schrader and Bismarck Mountains on the northern margin of the Western Highlands.

Seismicity in the Asaro region is relatively quiet however, since 1964, a magnitude 5 earthquake has occurred in June 1975, felt intensity 5 at Goroka.

In the future the town at greatest risk from such an earthquake or greater would be Goroka.

The level of shallow earthquake activity is low. The region lies between the strong north coast and Papuan Fold Belt zones, through the Star Mountains just north of the Papuan Fold Belt seismic zone.

Two magnitude 5 earthquakes occurred in April and May 1985 near Porgera and Laiagam in the Enga Province.

A magnitude 5.7 earthquake occurred near Pangia in the Southern Highlands Province in November 1975. It was felt in Pangia intensity 5.

1964 April 24, 0556 UTC, Schrader Range, M 6.8

The magnitude M 6.8 earthquake occurred at 106 km depth beneath the Schrader Range in the Western Highlands Province and was strongly felt throughout the Highlands and Sepik regions, and from the northern to southern coasts. Felt intensities reached MM 8 at Lai, near Baiyer River where trees were uprooted, and Minj, where the cement columns and steel supports of the new steel frame house were badly damaged. Intensity MM 7 was reported over a broad area of the Highlands and Sepik regions, including Nuku, Angoram, Tari, Mendi, Goroka, Kainantu, Mt. Hagen, and Kompiam. Damage was mainly to houses and water tanks.

Ripper (1975) determined the nodal planes of the focal mechanism solution are vertical, striking approximately north-south, and approximately horizontal. At intermediate depth in this area, the earthquake may have occurred within the southern limb of the sinking Solomon Plate lithospheric slab.

1966 December 14, 2107 UTC, Schrader Range, M 6.4

The magnitude M 6.4 earthquake occurred at depth 70 km beneath the Schrader Range, Western Highlands Province and was strongly felt throughout the Highlands and northern coast without causing any appreciable damage (Intensity MM 6). An isoseismal map for the earthquake was produced by Denham, Byrne and Wilkie (1968).

1971 July 10, 1156 UTC, Mt Hagen, M 5.5

The magnitude M 5.5 earthquake occurred at depth 68 km beneath Mt. Hagen, central Highlands, on a zone which plunges northward from the Southern Highlands or Papuan Fold Belt Zone beneath Mt. Hagen to seemingly link with the intermediate depth zone beneath the Ramu Valley (Ripper and Moihoi, 1996c). Most located earthquakes on this zone occurred in the two year period mid 1971 to mid 1973. These earthquakes, and in particular this zone has been described by Ripper and McCue (1981b, 1983).

Twenty water tanks were damaged in Mt. Hagen where the earthquake was strongly felt, and at Okapa 100 km away, where trees were knocked down and cracks appeared in the ground.

1979 March 27, 1007 UTC, Western Highlands, M 5.4

The magnitude M 5.4 earthquake occurred at depth 65 km beneath Mt Kubor, Western Highlands, on the zone of earthquakes that dips northward from the shallow zone of the Papuan Fold Belt beneath Mt Hagen to intersect the intermediate depth zone beneath the Ramu Markham Valley (Ripper and McCue, 1981b). The earthquake was felt strongly in Mt Hagen, where the only damage was to goods falling off from supermarket shelves. Nearby at Kundiawa, some landslide occurred at MM 8.

1980 October 19, 1503 UTC, Goroka, M 6.1

The magnitude M 6.1 earthquake occurred at depth 125 km beneath Goroka, Eastern Highlands, in the section of Solomon Plate that has sunk beneath the Ramu-Markham Valley and Highlands. The earthquake was felt strongly in the Highlands, and caused only minor damage to a few water tanks and cracks, and was also felt strongly at Siassi on Umboi Island.

The accelerograph at Yonki on firm rock foundation recorded an acceleration of 0.006g (Ripper, 1992).

1995 September 27, 0127 UTC, Kratke Range, M 5.3

The magnitude M 5.3 earthquake occurred at intermediate depth beneath the Kratke Range of the Highlands. Minor damage in the Highlands region included a cracked water tank at Namta, and broken louvres in Mt. Hagen.

The Ripper and Moihoi (1996b) interpretation is that the earthquake occurred on the southwestern edge of the Highlands zone of intermediate depth earthquakes associated with the sinking Solomon Plate.

3.2.11 Papuan Fold Belt

The Main Frontal Thrust or Hegigio Fault follows the Fold Belt seismic zone, although earthquakes occur both in front of and behind the thrust.

No earthquakes have occurred southwest of the Main Frontal Thrust, but some small earthquakes are positioned on the northwest extension.

The location given by Everingham (1974) for the 1922 magnitude 7.5 earthquakes was 143°E, 7°S, but the location was only an estimate.

No earthquakes are located anywhere near the Fly River and Mt Bosavi, the nearest being north of Mt Bosavi on the Papuan Fold Belt seismic zone.

The main Papuan Fold Belt Frontal Thrust is in an apparently aseismic region southwest of the main seismic zone in the Gulf and Fly Provinces. Also the Fly River and Bosavi systems are well away from the recognised seismic zone. However the magnitude 7 earthquake of 1922 January 19, which was strongly felt on the south coast, may have occurred in this region to the southwest of the main seismic zone.

The maximum credible earthquake must be of at least magnitude 7.5, an earthquake of about this magnitude having already occurred on the zone.

1922 January 19, 2158 UTC, Papuan Fold Belt, M 7.5

The magnitude M 7.5 earthquake occurred at shallow depth beneath the Papuan Fold Belt, the location and magnitude of which were determined by Everingham (1974), the Papuan Fold Belt location being the closest possible source to the effected areas.

At Sumai Village on Kiwai Island in the Fly Estuary, and at Mabadauan on the southern coast tsunami effects were reported. Everingham (1977) reported that one big wave of about six feet high came right into the village and then receded, felling one house.

The earthquake shook the houses at Sumai Village violently and broke off some of the coconut trees.

1954 March 03, 0602 UTC, Papuan Fold Belt, M 7.0

The magnitude M 7.0 earthquake occurred at shallow depth near Tari, on the Papuan Fold Belt. Dent (1974) and Everingham (1979) reported "considerable damage" at Tari. The force at Mt. Hagen was described as "quite considerable", but damage was minor only to glassware and crockery. The earthquake was felt from Wewak on the northern coast to Daru on the southern coast (MM3). Everingham (1979) presented an isoseismal map of the earthquake.

1968 September 05, 1702 UTC, Komo, Papuan Fold Belt, M 5.6

Denham (1974) reported the magnitude M 5.6 earthquake that occurred at shallow depth 31 km, near Komo on the Papuan Fold Belt. Slight damage occurred to two bush material buildings at Komo.

The earthquake was felt at Kiunga (MM 5) and at Obsobip (MM 4) near the border with Papua, Indonesia.

1977 September 06, 0852 UTC, Papuan Peninsula, M 5.5

The magnitude M 5.5 earthquake occurred at shallow depth beneath the Papuan Peninsula, Southern Highlands. The earthquake was strongly felt at Margarima close to the epicentre where cracks appeared in the ground, where some landslides occurred, water tanks were ruptured and people had difficulty standing. McCue (1979) reported the earthquake and aftershocks, which continued for more than two weeks.

1990 December 10, 0934 UTC, Papuan Fold Belt, M 5.8

The magnitude M 5.8 earthquake occurred at depth 32 km beneath the Papuan Fold Belt and was sharply felt at the Ketu Rigsite where drilling mud sloshed out of the drilling pit, and felt strongly also at Porgera and Mendi.

Anton (1995) documented the Harvard/USGS fault plane solution, which is an overthrust consistent with southwest compression perpendicular to the trend of the Fold Belt seismic zone.

1992 October 21, 1211 UTC, Papuan Fold Belt, M 6.1

The magnitude M 6.1 earthquake occurred at depth 19 km beneath the Papuan Fold Belt north of Kikori. Damage was minor at Middletown near the epicentre, and was slight north of the Fold Belt, to old bush material houses in the Mt Hagen region.

The Harvard/USGS fault plane solution is an overthrust on the trend approximately parallel to the strike of the Papuan Fold Belt.

1993 August 20, 0506 UTC, Papuan Fold Belt, M 6.2

The magnitude M 6.2 earthquake occurred at depth 15 km (Anton, McKee and Abers, 2001) beneath the Papuan Fold Belt about 15 km southwest of the Hides Gas field. Minor damage occurred at the Hides Gas plant installation, constructed to earthquake specifications MM 8, and air conditioning units "flew" out of their slots on walls. Landslips occurred at the Hides 2 Wellhead ridge-top as well as ground fracturing. Downstream to the southeast from Hides, landslides blocked the Tagari River.

Ripper and Moihoi (1996b) reported heavy damage occurred at both Tari and Komo at intensity MM 8, 35 km northeast and 25 km southeast of the epicentre respectively. At Komo, a bailey bridge was destroyed. More than twelve permanent houses and more than 100 village houses were lost. At Tari, four permanent buildings collapsed and several others were damaged.

The Harvard/USGS fault plane solution is an overthrust on a NNW-SSE azimuth in the trend of the fold-and-thrust belt. Anton, McKee and Abers (2001) interpreted the earthquake to have occurred on a structure within or penetrating basement rocks, evidence of thick-skinned thrusting within the fold-and-thrust belt.

Although many aftershocks were felt locally for a few weeks, none were large enough to be located.

2000 March 03, 2222 UTC, Southern Highlands, Ms 6.7

A broad area of the south-central part of mainland Papua New Guinea (PNG) was strongly shaken by a moderate-large (Ms 6.7) earthquake at 0822 local time on 4 March 2000. The epicentre of the earthquake was in the Gobe area of the Southern Highlands Province hence the earthquake was named the Gobe Earthquake (Anton, McKee and Abers, 2001; see Figure 2.3.8).

3.2.12 Papuan Peninsula

A magnitude 6.0 earthquake occurred within the graben in October 1972 and struck Wau hard but only for a few seconds. A (presumed stationary) car reportedly jumped off the ground.

Most of the Papuan Peninsula length has experienced magnitude 6 earthquakes, but not magnitude 7. The central part of the Owen Stanley Range closest to Port Moresby is an apparent gap in the seismicity, but could experience a major earthquake.

The southern side of the Papuan Peninsula also contains Quaternary fault systems. Faulting at Cape Possession, between Kerema and Port Moresby, is associated with the Aure Fold Trough. East and southeast of Port Moresby, the Southern Fall and Kemp Welsh fault systems could cause damaging earthquakes in Port Moresby. The 1979 magnitude 6.2 earthquake occurred in this region but in the lower crust at a depth greater than 40 km.

Magnitude 4 earthquakes have occurred near Cape Possession, about 40 km to the northwest.

Earthquakes have occurred along the whole length of the Owen Stanley Range, but in the midway region only scattered magnitude 4 earthquakes have occurred. This is the section of the fault system closest to Port Moresby.

In the northwest section, which reaches the Huon Gulf in the vicinity of Salamaua, magnitude 5 earthquakes are common but there have been no recorded magnitude 6 earthquakes.

In the southeast section southwest of Mt Victory including the Musa River region, several magnitude 5 and one magnitude 6 earthquakes have been recorded. The magnitude 6.2 earthquake occurred on 1976 September 16, the first anniversary of PNG Independence. It was moderately felt in Port Moresby (Ripper and Moihoi, 1996c).

In this southeastern Papuan Peninsula area, it is virtually aseismic. Instead, the seismicity is occurring to the north in the Goodenough Bay and Goodenough Island regions. Magnitude 6 earthquakes could occur in the aseismic Abau Sheet area of the Papuan Peninsula.

No earthquakes have occurred close to the southern side of the Owen Stanley Ranges. However, several very small earthquakes have occurred there. More significantly, the magnitude 6.2 earthquake, which shook Port Moresby strongly on 9 March 1979, occurred at depth 46 km in the Southern Fall region. Its occurrence at depth 46 km could indicate that the Quaternary fault systems of the Papuan Peninsula, including the Owen Stanley Fault System, extend deep into the crust. The earthquake has been described by Ripper, McCue and Wolter (1980), Ripper and McCue (1981a), and Ripper and Moihoi (1996c).

Large earthquakes can be expected to occur again in the southern Owen Stanley Range. Seismic activity of the Owen Stanley Range as a whole is ongoing, but the largest recorded earthquakes are only of magnitude 6.2. An earthquake of magnitude 7 on the Owen Stanley Range would not be unexpected.

Two other magnitude 7 earthquakes occurred beneath Menyamya, a magnitude 7.2 in 1951 at depth 180 km and a magnitude 7.3 in 1963 at depth 171 km. No other magnitude 7 earthquakes have occurred in the Papuan Peninsula since 1900, but since 1964 five magnitude 6 earthquakes have occurred; a magnitude 6.0 in 1972, a 6.2 in 1976, a 6.0 in 1978, a 6.2 in 1979, and a magnitude 6.2 in 1999.

Two of the magnitude 6 earthquakes occurred within 100 km of Port Moresby and strongly shook the city. The 1979 earthquake occurred only 90 km from Port Moresby and has been described by Ripper, McCue and Wolter (1980) and Ripper and McCue (1981a). During the earthquake, several "well-built" reasonably new buildings suffered slight damage such as cracks along construction joints. It was further documented that the most spectacular damage was the buckling of several heavy concrete slabs in the suspension roof of the National Museum.

For the Papuan Menyamya zone, the maximum credible earthquake magnitude would be at least 7.5, as magnitude 7.3 and 7.2 earthquakes have already occurred.

From the known historical record of earthquakes, the maximum recorded magnitude that occurred in the Papuan Peninsula region is 7.3. Closer to Port Moresby the suggested maximum credible earthquake magnitude would be of about 6.7. But, for the region and since magnitude 7.3 and 7.2 earthquakes have occurred in the Wadati-Benioff zone even in the intermediate depth pocket, it cannot be assumed that they could not happen elsewhere in the zone (Ripper and Letz, 1993). Because of this, the maximum credible earthquake magnitude could thus be at least 7.3 or even 7.5.

1962 February 15, 0056 UTC, Owen Stanley Range, mb 4.1

The magnitude mb 4.1 earthquake occurred at 60 km beneath the Owen Stanley Range, Papuan Peninsula and was moderately felt along the Papuan Peninsula region. In Port Moresby the earthquake shaking lasted several seconds duration and was sufficiently intense to displace small objects, intensity MM 5. At Sogeri, a full 1000-gallon water tank was seen to rock up off its stand, and cement paving was cracked at Hisiu.

The magnitude, mb 4.1, is probably too low as intensity MM 5 at an epicentral distance of about 80 km is more akin to a magnitude of about 5.0 (Gaull, 1979).

1963 February 26, 2014 UTC, Menyamya, M 7.3

The magnitude M 7.3 earthquake occurred at 171 km depth beneath Menyamya, northwestern Papuan Peninsula. The central location of the earthquake and its high magnitude caused it to be felt from Wewak, Ambunti and Tari in the west to Rabaul and Trobriand Islands in the east. However, the intermediate depth mitigated its damaging effects locally. At depth, the energy radiating out may have been guided up the lithospheric slab towards the northeast from a focus within the slab. The slab is a section of oceanic Solomon Plate, no longer actively subducting, which dips southwest beneath the Papuan Peninsula (Ripper, 1982; Davies, Symonds and Ripper, 1984).

In the Owen Stanley Mountains the earthquake was felt strongly at intensity MM 7, in particular at Yodda, and at Lae damage was caused to water tanks. Farther away, highest intensities (MM 6-7) were reported in the Lae-Markham-Huon Peninsula and Popondetta-Kokoda regions. Ripper (1975) determined that the focal mechanism solution could represent either horizontal sliding, top side east, or vertical motion, east side up.

1967 September 03, 0123 UTC, Garaina, M 5.5

The magnitude M 5.5 earthquakes occurred at depth 139 km beneath the Papuan Peninsula, near Garaina and was felt sharply in the Tapini-Woitape region, duration uncertain (reports from 5 seconds to 1 minute), and was sufficiently strong to knock objects to the floor. The earthquake was reported by Denham (1971).

1967 September 18, 1533 UTC, Huon Peninsula, M 6.2

The magnitude M 6.2 earthquake occurred at 39 km depth beneath the northern coast of Huon Peninsula and was moderately felt throughout the Highlands and northern coast, with maximum intensity, MM 6, slight damage, at Boana near the epicentre. The earthquake has been described by Denham (1971).

1967 September 24, 0748 UTC, Huon Peninsula, M 5.3

The magnitude M 5.3 earthquake occurred at depth 84 km beneath the Huon Peninsula and was felt in the Highlands between Mt Hagen and Wau, and on the northern coast and Huon Peninsula. No damage was reported. It was described by Denham (1971).

1968 January 04, 1027 UTC, Owen Stanley Range, M 5.8

The magnitude M 5.8 earthquake occurred at depth 19 km beneath the Owen Stanley Range, Papuan Peninsula and was moderately felt, but without causing any damage. It was reported by Denham (1974).

1972 September 16, 0415 UTC, Musa River Dam, M 5.0

The magnitude M 5.0 earthquake occurred at very shallow depth of 4 km beneath southeastern Papuan Peninsula and occurred only a few kilometres from two accelerograph installations at the Musa River dam site. Gaull (1974, 1976) reported the acceleration recordings, on hilltop weathered rock site of 0.19g, and on a hard rock site 200 metres lower of 0.04g.

1972 October 28, 0227 UTC, Bowutu Mountains, M 6.0

The magnitude M 6.0 earthquake occurred at very shallow depth of 2 km beneath Bowutu Mountains near Wau and struck Wau hard, but only for a few seconds. It was reported that a car presumably stationary, jumped off the ground (Everingham and Sheard, 1980). Twelve foreshocks and over 50 aftershocks were recorded at Lae, and maximum felt intensities in Port Moresby reached MM 3.

The accelerograph at Mt Lunaman, on firm rock foundation at Lae, recorded a maximum ground acceleration of 0.053g (Ripper, 1992).

1976 September 16, 1126 UTC, Owen Stanley Range, M 6.2

The magnitude M 6.2 earthquake occurred shallow at depth 15 km beneath the Papuan Peninsula, Owen Stanley Range approximately 100 km east of Port Moresby. A ship in Port Moresby harbour was thumped and it was though that the ship had run aground. Near the epicentre a house at Afore was moved out of plumb, and stove and refrigerator moved. Cracks in the ground were left at the base of the piers.

Focal mechanism solutions have been computed by Ripper (1980a, 1982) and McCue (1981b). Both solutions have an almost horizontal nodal plane dipping to the north. Both solutions have a vertical nodal plane, but striking NNE (Ripper, 1980b) and ENE (McCue, 1981b).

1978 April 11, 0241 UTC, Owen Stanley Range, M 5.9

The magnitude M 5.9 earthquake occurred at shallow depth 13 km beneath Mt Suckling, Owen Stanley Range and was felt particularly strongly on the northern coast of the Papuan Peninsula at Wanagela and Uiaku. Two village houses were knocked down at Wanagela Village, and three village houses and some trees were knocked down at Uiaku. Landslides also occurred.

McCue (1982) presented both an isoseismal map and fault plane solution, and preferred a strikeslip solution, with motion on either a north-south or east-west vertical fault plane.

1979 March 09, 0126 UTC, Owen Stanley Range, M 6.2

The magnitude M 6.2 earthquake occurred at depth 46 km beneath the Owen Stanley Range, 90 km east of Port Moresby and was strongly felt in Port Moresby. Effects were no more serious in the epicentral region except possibly for a few landslides. The earthquake was described by Ripper, McCue and Wolter (1980), who produced both an isoseismal map and fault plane solution, and by Ripper and McCue (1981a). Damage occurred in many Port Moresby suburbs, including the most spectacular and probably the most expensive of the buckling of the "floating" concrete slab roof of the National Museum at Waigani. It was reported that cracks formed in many buildings and ceiling slabs fell. In downtown Port Moresby, electric power failed causing panic in multi-storey buildings. Outside of Port Moresby at Kwikila, near the epicentre two village houses were reported damaged, but a number of water tanks were ruptured. A possible tsunami effect was reported at Hula village, the water receding from the beach and then slowly returning.

The fault plane solution is a combination of strike-slip and overthrust, with the nodal plane striking northwest-southeast parallel to the Owen Stanley Range and plate boundary being the fault plane.

1984 October 12, 0329 UTC, Owen Stanley Range, M 5.4

The magnitude M 5.4 earthquake occurred at 117 km depth beneath the Owen Stanley Range 120 km north of Port Moresby. It was felt in Port Moresby, but only by those under favourable conditions such as in high-rise buildings. No damage was reported, the earthquake being felt only to intensity MM 5.

Anton (1993) documented the Harvard/USGS fault plane solution which is motion either on a vertical fault striking NNW-SSE, west side down, or motion on an almost horizontal fault, top side east. At depth, the earthquake occurred within the seismic zone which dips southwest beneath the Papuan Peninsula and indicates the presence of a sloping lithospheric slab (Ripper, 1982; Davies, Symonds and Ripper, 1984).

1992 January 24, 1209 UTC, Mt Victory, M 5.2

The magnitude M 5.2 earthquake occurred at depth 35 km beneath Mt Victory, Papuan Peninsula and was felt in Port Moresby at intensity MM 3. It was felt strongest at

Wanigela, near the epicentre, but even so, only intensity MM 5, with the fall of pictures from walls (Ripper and Moihoi, 1996b).

The Harvard/USGS focal mechanism solution is a normal fault parallel to the trend of the peninsula. The earthquake is evidence of the extended rifting into continental margin, further west of the region of crustal extension in the Woodlark Basin, with the epicentre under the peninsula about 100 km WNW of Goodenough Bay. In an area of overthrust earthquakes Ripper (1982) suggested that the solution indicates that the zone of extension that extends from the Woodlark Basin into Goodenough Bay may have penetrated further WNW up the Papuan Peninsula (Ripper and Moihoi, 1996b).

1999 June 29, 0550 UTC, East of Port Moresby, Mw 5.7

A magnitude 5.7 earthquake occurred in a similar location to the 1979 earthquake in 1999 and was felt strongly in parts of Port Moresby.

3.2.13 Milne Bay

A low level of seismicity does occur in the region of Goodenough and Fergusson Islands, but the seismicity does not appear to follow the trend of the faults. However the D'Entrecasteaux region is highly seismically active, with the Woodlark Basin spreading system passing through the islands into Goodenough Bay. Magnitude 6 earthquakes have straddled the region, and minor damage has been caused by earthquakes of magnitude as low as 4. In view of the high level of current seismicity, a damaging magnitude 7 earthquake would not be unexpected.

Since 1964, no significant earthquakes have occurred onshore at Woodlark Island. However the island is located on a zone of seismicity that follows the Woodlark Ridge towards Bougainville Island. Two magnitude 6 earthquakes occurred close to Woodlark Island in 1960 and a magnitude 5.9 in 1992. The existence of the seismicity in the region on Woodlark Island however indicates that a magnitude 6 or higher (perhaps 7.5) earthquake could occur near Woodlark Island itself.

In the Solomon Sea, Misima Island appears to be on a gap between west and east Woodlark Basin seismicity. Woodlark Island lies on a seismic zone.

Magnitude 5 earthquakes which occurred about 40 km WNW of the island are the largest close significant earthquakes. Four magnitude 7 earthquakes have occurred in the region, one being the "great" 1906 earthquake. Mechanisms would involve both subduction rebound overthrust at the interface with the South Bismarck Plate margin, and intraplate extension in the top of the Solomon Sea crust where it bends downward.

Maximum credible earthquake magnitude is at least 8.3, an earthquake of magnitude 7.8 having occurred in the zone and the rupture length being possible.

1955 July 07, 0230 UTC and 0314 UTC, D'Entrecasteaux Islands, M ~ 4.5

The earthquakes occurred in Dawson Strait between Normanby and Fergusson Islands, D'Entrecasteaux Islands. Reynolds (1956) described the earthquakes, and provided an isoseismal map of the 0230 UTC shock. The earthquakes were accompanied by both foreshocks and a long aftershock series.

Ripper and Moihoi (1996a) documented the effects of the two main earthquakes that were just recorded at Rabaul and Brisbane, indicating a magnitude of about 4.5. The earthquakes caused landsliding in Oiau Crater near Gomwa Bay, Fergusson Island, and in the Du'una area "inland from the Salamo Mission" on Fergusson Island, intensity MM7. Damage occurred to a wharf at Sebulugomwa, Fergusson Island, and several places suffered cracking in cement buildings, posts and paving

3.2.14 Bismarck Sea

Three magnitude 7 earthquakes were listed for the zone, for the period prior to 1945. However, Ripper and Moihoi (1996a) maintained from speculations by Everingham (1974) that some of the magnitude 7 earthquakes assigned to the West Melanesian Arc zone in the period 1906-1918 may have occurred on the West Bismarck zone, including the magnitude 7.5 earthquake of 13 May 1920 which may have occurred in the Ramu-Markham Valley.

Only earthquakes smaller than magnitude 6.5 have occurred in the zone since 1946, the largest magnitude of 6.5 for an earthquake in 1977, and two magnitude 6.4 earthquakes have occurred in 1989 and 1990.

Since magnitude 7.5 earthquake has already occurred on the zone, the maximum credible earthquake is at least of magnitude 7.5, may well be higher as 7.8

Two other earthquakes which may have locations of in error by hundreds of kilometres includes a magnitude 7 earthquake which occurred in 1906, and a 1956 magnitude 7.2 earthquake which occurred at a depth of 380 km on the New Britain Wadati-Benioff Zone extension beneath the Bismarck Sea.

3.2.15 West Melanesian Trench

Only scattered weak seismicity exists throughout the Manus Island region. However, the existence of Quaternary faulting on Manus and Los Negros Islands indicates that these islands of the Admiralty group could experience a magnitude 6 or even 7 earthquake. Elsewhere in the general north Bismarck Sea region, magnitude 7 earthquakes have occurred.

3.2.16 Other PNG Earthquakes

Two earthquakes of magnitude 7.2 and 7.5 occurred in May 1944, 90 km north of the Lihir Island. The general accuracy of the locations were verified by the then Australia Bureau of Mineral Resources, restructured and renamed Australian Geological Survey Organisation and now Geoscience Australian, using the original International Seismological Summary data.

On 24 December 1930, some islands of the Hermit Islands in the Ninigo Group were shaken by a severe earthquake and then immediately inundated by a tsunami that drowned five people (Everingham, 1977). As the effects were localised, the earthquake would not have been particularly large, but still large enough to generate that tsunami.

Other earthquakes of the region include:

(1) a magnitude 6.5 earthquake in 1964 close to Mussau Island

(2) a magnitude 6.5 earthquake in 1975 100 km southwest of Manus Island,

(3) magnitude 6.2 and 6.1 earthquakes in 1983 100 km south of the Hermit Islands, and

(4) a magnitude 6.0 earthquake in 1974 60 km south of Kavieng in New Ireland.

As the largest earthquake recorded magnitude is 7.5, the maximum credible earthquake magnitude is at least 7.5.

3.2.17 Papua Province, Indonesia

1971 January 10, 0717 UTC, Southwest of Jayapura, M 7.9

The magnitude M 7.9 earthquake occurred at 41 km depth beneath the highlands of Papua, southwest of Jayapura, Indonesia, about 140 km west of the border with PNG. Along the border at Green River, nine water tanks were damaged and that at least one landslide occurred in the nearby Iuri Mountains. The earthquake was felt as far south as Daru. This was the first of 3 great earthquakes in the PNG region in 1971.

The focal mechanism is an overthrust striking approximately northwest-southeast (Ripper, 1977).

1976 June 25, 1918 UTC, Irian Jaya, M 7.1

The magnitude M 7.1 earthquake occurred at shallow depth (33 km) beneath the highlands of Papua, Indonesia, about 100km west of the border with PNG. The earthquake was described by UNDRO (1976) and McCue (1981b). It was estimated that 420 people died in landslides, fifteen villages were reported to be completely destroyed, together with about 70% of village gardens in the epicentral area. Landslides devastated mountains and debris choked rivers. McCue (1981b) documented that landslides that occurred in PNG in the Mt Fubilan region near Tabubil and Ripper (1992) determined a maximum acceleration of 0.08g recorded at the "HongKong" accelerograph on Mt Fubilan, which was recorded about a minute after the shaking started.

McCue (1981b) determined a focal plane mechanism that is either a northwest strike, shallow southwest dip, movement topside southeast, or a northeast strike, vertical, movement northwest side down. The northwest-southeast strike is in the general trend of folds-and-thrusts in the region.

1976 October 29, 0251 UTC, Irian Jaya, M 7.1

The magnitude M 7.1 earthquake occurred at shallow depth in almost the same location as the magnitude 7.1 earthquake of four months earlier. The media and the USGS reported that 133 people were killed, including 47 at Langola (location uncertain Ripper and Moihoi, 1996c) and 32 at Bime. Among the casualties were some workers engaged in relief work after the June earthquake. The earthquake was strongly felt on the PNG side of the border (Ripper and Moihoi, 1996c).

McCue (1981b) determined that the focal mechanism solution is strikeslip, sinistral, north side west, if the WNW-ESE striking fault plane, parallel to the New Guinea spine, is the fault plane.

1996 February 17, 0559 UTC, Biak Island, Ms 8.1

On 17 February at 0559 UTC a magnitude Ms 8.1 earthquake occurred at shallow depth beneath Biak Island, Papua, Indonesia. The earthquake generated a tsunami measuring 7.7 metres that struck Biak Island. At least 108 people were killed, 423 injured, 58 missing, and 5,043 houses were destroyed or damaged in the epicentral area.

Extensive damage occurred on Biak Island and Supiori from the tsunami, which reached heights of 7 metres (USGS, 1996; 1997; Davies, 1999; Henry and Das, 2002). A 61 cm tsunami was observed at Rabaul Harbour, on eastern New Britain, about 1,800km away.

Chapter 4 Earthquake hazard and risk

Earthquake hazard assessment is an attempt to forecast the future occurrences of earthquakes and the effects earthquakes can have on the Earth and environment. The physical phenomena that cause the hazard may be the ground shaking, the fault movement or liquefaction. On the other hand, risk is the danger or likely occurrence of loss of human life and property from the hazard. Risk management may involve land-use planning, earthquake prediction and earthquake engineering (Yeats, Sieh and Allen, 1997). To properly address or evaluate the risk involved, there must be an understanding of the existing hazard. Further, there must be an acceptable understanding of the regional tectonics and distribution patterns of earthquakes before the hazard analysis can be attempted. For the PNG region Anton *et al.* (2008) proposes that the tectonic models used influence the earthquake hazard assessments.

In most places the greatest seismic hazard known is the ground shaking that directly results from earthquakes, and risk is the structural damage that results from this ground motion. Earthquake shaking is associated with the rupture of and movement along geological faults. Earthquake occurrences may cause apparent ground surface expressions. These include displacements and uplifts, which would normally indicate shallow earthquakes (point of initial rupture), while transitory effects (ground shaking) and permanent effects (surface deformation) both decrease with earthquake depth. The effects of intermediate and deep earthquakes are usually minimal, even near their epicentres, although these earthquakes may be felt at farther distances and at times quite strongly, but rarely causing severe damage. The highlands and southern regions of PNG are known to experience strong earthquake shaking from earthquakes occurring within zones of subducting lithospheric slabs, especially from intermediate depth earthquakes that are occurring beneath northeastern New Guinea and western New Britain.

Seismic wave energy generation originates within the crustal rocks in the immediate neighbourhood of fault zones under-going stress and strain, which after a long while of strain accumulation suddenly rupture. Consequently, seismic waves first propagate outwards from the point of initial rupture, then from other points as the rupture propagates along the fault. The greatest earthquake source motion occurs along crustal weaknesses of geological fault systems, although there is deformation within the three-dimensional volume surrounding the two-dimensional fault rupture. Strain accumulation between earthquakes can take tens to hundreds (or even thousands to millions) of years, the time being apparent from the period between the occurrence of current events and the last recent events, in particular the period between the occurrences of large earthquakes.

Attenuation

As well, it has been observed during investigations of large damaging earthquakes that the rate of decline of severity of shaking away from surface fault rupture, or epicentre, is due to energy dissipation. This is when the medium of energy propagation is heterogeneous as a result of the existing and dominating tectonic, and thus geologic, complexities, so the strength of shaking and therefore the hazard lessens with distance from the earthquake source. The attenuation functions are therefore varied with varying tectonic, and no one suits the whole region. It is imperative to obtain local data for proper determination of functions for specific application. Available raw data is too few and therefore not considered in this study, but it is the hope to embark on that in the next stage of the overall plan to expand this work.

Site Effects

The impact intensity depends on local geology and soil conditions. Where local soils include thick alluvial sediments, seismic shaking is amplified by resonance. However, also on soft strata, the seismic energy is attenuated thus losing energy rapidly with distance. On bedrock outcrops, this energy attenuation is small. If the medium of energy propagation is heterogeneous as a result of tectonic complexities, then the strength of shaking and therefore the hazard lessens with distance from the earthquake source.

Prior to the days of proper modern monitoring equipment, the site of greatest surface offset of the fault was taken as the best pick for the earthquake location. This was the way the location of the Great 1906 San Francisco Earthquake was determined (Bolt, 2006). As no sophisticated seismic equipment was in operation in those days, much of existing seismological results that emerged then and now ongoing depended very much on fair judgment - achievements quite ingenious.

Seismic cycle, based on seismic gap hypothesis, assumes that the probability of an imminent large earthquake is low after significant release of seismic energy and that danger increases only when tectonic plate motion accumulates strain sufficient enough for a new stronger event. This has been the method by which many long-term seismic hazard studies are based (Kagan and Jackson, 1999).

Omori (1894) on the other hand recognised then what was acknowledged as regional seismicity accompanying most large earthquakes, which peak immediately after and then fade away as a function of time. Although well recognised, the phenomenon is not well explained, and it is not certain whether dynamic stresses involved are induced by the passage of seismic waves.

It is suggested though, that near field earthquake prediction is enhanced by static stresses induced by fault offset. This is particularly important when earthquake forecasting is increasingly becoming a present day frequent concern (Parsons, 2005). Researches are concluding that periods of quiescence are being followed by occurrences of large earthquakes (Reasenberg and Mathews, 1988), and suggestions are that this is presently being the most reliable intermediate term precursor for large earthquakes (Wardlaw *et al.*, 1990).

Generally, historical seismicity patterns have made it practicable to predict probable future locations of damaging earthquakes. However, it is still not possible to forecast the times of occurrence, as earthquakes do not occur on regular schedules (Bolt, 1993).

Regardless of having warnings or not, for buildings and infrastructure to withstand shaking, the building code provisions have to be designed higher then the earthquake itself, and construction of highest quality. In stating the experiences learnt during the 07 December 1988 Armenian Earthquake, Bolt (2006) emphasized the importance of earthquake-resistant structures or structures with the best inbuilt earthquake provisions being the key to ensuring maximum safety in areas prone to seismic activity.

The experiences in PNG especially during the last number of decades have been to make-do with the building code developed in the 1970s, designed based on data and experiences from abroad, in particular New Zealand and Indonesia, with little input from locally obtained strong motion data. While the intensity of earthquake activity in these two countries may compare well with those in PNG, and thus the experiences during strong earthquake shaking, the region would benefit from proper approaches to addressing the issues including the use of the now available country and regional data. It is important to learn from the experiences of many countries and address the issues of proper building and construction, paying more attention to the seismic hazard. Some have experienced total destruction and even the loss of the entire national economy.

There is naturally the need of preservation of both life and property, and particularly the society's lifelines - essential services and infrastructure. Specifically, the constructing and building of infrastructure should include excavation of the weak top soil and adopting proper foundation systems such as involving the installation of wooden or concrete piles that reaches down to bedrock.

4.1 Previous earthquake hazard studies

Since the 1970s, seismic hazard analyses and studies have been undertaken for various sites in PNG, in locations of major national projects particularly dams, mines and petroleum facilities. However, these studies have been mainly based on the limited and imprecise earthquake catalogue, and even without detailed consideration of regional geology and geophysics (particularly gravity and magnetic data), and geodesy, to include vital details.

As the PNG region is essentially seismically active and large earthquakes are frequent, the hazard is very significant. On average, two earthquakes of magnitude 7 and above have occurred every year since 1900.

Brooks (1965) was the first to analyse seismic hazard of the PNG region. Ripper and Letz (1993) subdivided PNG into seismic zones and determined the hazard within respective zones, zones only based on seismicity.

In addition to this, seismic hazard was determined for cities and towns of Lae, Kokopo and Kimbe by Ripper and Anton (1995), Anton (1996a) and Anton (1996d) respectively, while Ripper and McCue (1981a, 1983) determined the seismic hazard of the Papuan Fold Belt. Seismic hazard at projects sites at Yonki (Anton, 1997) and Lihir Island (Anton and Ripper, 1999; Luo, 2004) were also determined. These studies and others have been based on limited data and there was no consideration of regional geology and tectonics.

The previous investigations outlined below are in need for review, as there now exist better data and improved methods for determining the earthquake hazard for regional as well as specific sites. An important input is the use of regional geology and geophysics (gravity, magnetic, etc), as well as seismicity. The thesis includes the revision of the earthquake hazard and determined that for specific sites, and, iteratively, established the basis for the revision of the seismic (earthquake) zoning for building construction in PNG.

4.1.1 First seismic hazard estimates

In the first earthquake risk maps, Brooks (1965) contoured the expected number of earthquakes of high magnitudes per square degree per century, and from these, developed maps of expected highest Modified Mercalli intensity for 100, 50 and 25 year periods. This was the first ever attempt to quantify earthquake hazard in PNG. A Modified Mercalli earthquake intensity scale for PNG (Ripper, 1979) is given in Appendix 3 and a quick reference version in Appendix 4.

4.1.2 Relating New Guinea earthquakes to tectonics

Denham (1969) improved on the identification and defining of the seismic source zones of the New Guinea region, and virtually interpreted seismicity in terms of plate tectonics. Defining seismic source zones and thus tectonic plate boundaries have consequently been improved as data became available from both the local and regional seismic networks, especially in the last 30 years. Zones of deforming plate fronts have also been identified, the most significant being the zone of the Papuan Fold Belt in the southern PNG Highlands, now proposed as the northern boundary of the India-Australia Plate (Anton *et al.*, 2008).

4.1.3 Seismic risk at principal towns of PNG

Gaull (1979) investigated the seismic risk at 20 principal towns of PNG, obtaining return periods of intensity and peak ground acceleration. An example of work that needs a review of its results utilising current data, this study was based on very scanty data of any kind; be it earthquake hypocentres, intensities or even strong motion.

4.1.4 Earthquake building (code) seismic zones

The seismic zoning for building construction in PNG was introduced in 1971 (PNG Statutory Instrument No. 44 of 1971), which included peak ground acceleration maps for a recurrence interval of 20 years, and a seismic zonation map based on these estimates. Based on the occurrences of earthquake intensity 8, the studies involved were undertaken to support building codes for earthquake design of bridges (Beca *et al.*, 1976), and for buildings (Jury *et al.*, 1982). The seismic zoning was later revised when the PNG National Standards Council and Department of Works, in consultation with various PNG authorities, commissioned engineering consultants Beca, Carter, Hollings and Ferner Ltd to develop a seismic zoning map. The development of the seismic zoning map was reported by Jury *et al.* (1982) and PNG National Standards Council (1983). The map is shown in Figure 21.

It has been recognized for some time that this map of seismic zones is in need of revision. Adequate local acceleration attenuation data was not available at the time when the seismic zoning map was developed, which led to use of data from Indonesia and New Zealand in the development of the map. The zoning was also criticized (McCue, 1984) because it has no correlation with the seismotectonic framework of PNG.

The seismicity of PNG has been studied in detail for over 30 years, and is now reasonably understood. Seismicity map of PNG show shallow earthquakes occur either on or near plate boundaries, and in regions of crustal deformation. Seismic activity is greatest in the area of the northern Solomon Sea (Zone 1, Figure 21), while the area of lowest seismic activity is in the south and southwest of PNG (Zone 4, Figure 21).

Comparing the seismic zoning maps, the well recognized plate boundaries and seismic zones of the Bismarck and Solomon Seas are not well reflected in the seismic zoning map. The seismic zone of the Papuan Fold Belt (southern highlands of PNG) which coincides with a broad zone of Pliocene/Quaternary faulting and folding caused by collision of the South Bismarck and India-Australia Plates is also not reflected in the seismic zoning map. This seismic zone should appear as a separate feature, being separated by 200 km from the active zone of northern coast PNG mainland. A third main concern is that Seismic Zones 3 and 4 of mainland PNG should be in better agreement with the seismicity and geology/tectonics of the western part of the Solomon Plate.

Frequency of occurrence of earthquakes of given magnitude per square degree were contoured to show the relative levels of activity throughout PNG (Beca *et al.*, 1976; Jury *et al.*, 1982). The Building Construction Seismic Zones are shown in Figure 21.

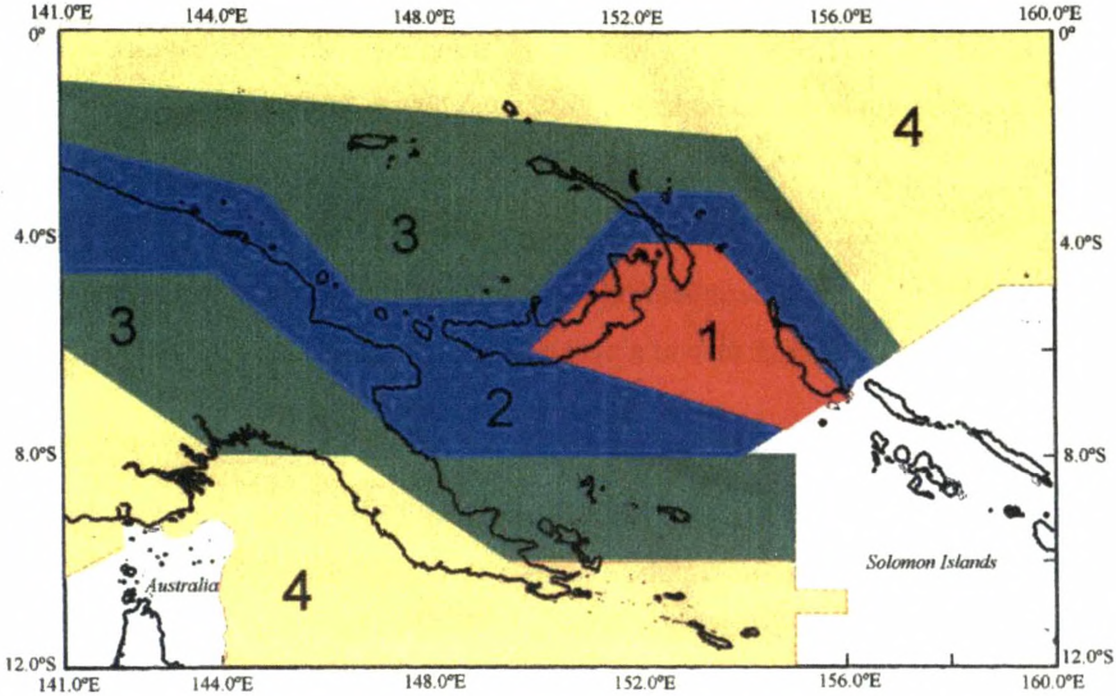

Figure 21: Seismic zones for building construction in PNG.

Zone 1 required design for accelerations of 0.68g or greater, zone 2 accelerations of 0.54g – 0.68g, zone 3 accelerations of 0.4g-0.54g and zone 4 accelerations less than 0.4g (modified from Jury et al., 1982).

4.1.5 Papuan Fold Belt seismic risk

Ripper and McCue (1981a, 1983) examined the seismic risk (or more correctly, hazard) in the Papuan Fold Belt, using the Type 1 Gumbel Extreme Magnitude Distribution method of Epstein and Lomnitz (1966) and Lomnitz (1974). The study lead to the determination of the earthquake hazard in this zone, and included some of the first interpretations of the seismicity and tectonics that is involved.

4.1.6 Maximum ground accelerations of PNG

The Australian Bureau of Mineral Resources (renamed Australian Geological Survey Organisation (AGSO) and now Geoscience Australia) through the Port Moresby

Geophysical Observatory, commenced deployment of a network of accelerographs throughout PNG in 1967. The maximum ground accelerations for the period 1967-1990 were determined and listed by Ripper (1992).

4.1.7 Global Seismic Hazard Assessment Project (GSHAP)

Denham and Smith (1993) gave a review of earthquake risk in the Southwest Pacific region, including PNG, in the Technical Planning Volume for the Global Seismic Hazard Assessment Project (GSHAP) undertaken for the United Nations International Decade of Natural Disaster Reduction (IDNDR).

McCue (1999) used available ground motion recurrence calculations to contour the map incorporated into the GSHAP map of global hazard.

4.1.8 Large earthquake return periods and probabilities of occurrence

Using the extreme earthquake magnitude method of Epstein and Lomnitz (1966) and Lomnitz (1974) large earthquake return periods and probabilities of occurrence of large earthquakes were calculated for the regions of PNG (Ripper and Letz, 1993). Return periods and probabilities of occurrence of magnitude 7.0 earthquakes were determined for normalized 10,000 km^2 areas of PNG. The return periods calculated for magnitude 7.0 earthquakes for Bougainville Island, New Britain, Huon, West Bismarck, North Sepik and Ramu seismic zones were 37, 60, 81, 88, 125 and 125 years respectively.

This study was based seismicity and wasn't constrained utilising regional geological and geophysical data for the determination of seismic zones. More importantly, seismicity wasn't constrained for depth ranges.

4.1.9 Lae seismic hazard

The seismic hazard of Lae City was determined using the method of Epstein and Lomnitz (1966) and Lomnitz (1974) utilising limited earthquake data, especially of maximum earthquake magnitude since 1964, and found to be significant (Ripper and Anton, 1995).

4.1.10 Kokopo seismic hazard

The same was done for Kokopo Town after the Rabaul Volcanic eruptions to assist in the settlement of the township. The seismic hazard was determined to be very significant, in fact higher than that for Lae City (Ripper and Anton, 1995), as Kokopo is located within the most seismically active zone in the region (Anton, 1996a).

4.1.11 Kimbe seismic hazard

The same was conducted for Kimbe Town in West New Britain Province, New Britain. The hazard was determined to be very significant (Anton, 1996d), higher than Lae City (Ripper and Anton, 1995), and similar to that of Kokopo (Anton, 1996a) on eastern New Britain.

4.1.12 Yonki seismic hazard

For the interest of a major national project, the seismic hazard of Yonki Township hosting the Yonki Hydroelectricity project was determined as significant (Anton, 1997), again utilising maximum magnitude earthquake data since 1964, comparable to that of Lae City (Ripper and Anton, 1995).

4.1.13 Lihir seismic hazard

Also based on limited data, the seismic hazard of Lihir Island was determined to assist in the Lihir Mining geotechnical efforts there on the island mine. Again using data consisting of maximum earthquake magnitudes annually since 1964, the seismic hazard for Lihir Island was determined to be of some significance (Anton and Ripper, 1999).

Luo (2004) recorded and located activity associated with local faults and geothermal activity, and used the data to calibrate earthquake hazard models proposed (Zhao *et al.*, 1997), and which can be adopted for Lihir.

4.2 Large damaging earthquakes

Accounts of past damaging earthquakes are mostly post 1900. The most damaging earthquakes have mostly been shallow. Earthquake catalogues include few events prior to this date, but some data exists that has been collated from earlier years by explorers and missionary workers, for example Neuhauss (1911) and Sieberg (1910).

In each seismic zone, a maximum credible earthquake magnitude has been adopted. The adoption of this can be somewhat subjective. The method proposed by Ripper and Letz (1993) was the magnitude must be at least that of any earthquakes that have previously occurred in the zone. There is a strong possibility that many of the estimates made using this method will be unconservative.

Another "rule-of-thumb" suggestion was that a magnitude level 0.5 greater than the largest magnitude earthquake that has previously occurred in the zone might be assumed. This method will give some estimates of the maximum credible earthquake that are conservative, and others that are unconservative.

The method employed in this work considers several factors. Firstly, the historical seismicity is considered, but recognising that the recurrence periods of large earthquakes in many seismic zones may be tens to hundreds, or thousands of years, while the earthquake catalogue for the region may cover only a small fraction of this interval. Secondly, consideration of the tectonic environment will provide a constraint. For example, along a subduction zone there is likelihood of a large rupture (large both in depth and length) giving an earthquake of magnitude Mw 8.3 to 9.0 or larger. A large tectonic fault that is associated with the plate boundary but not on a deep subduction zone may give a maximum credible earthquake of Mw 8.0 to 8.5. Away from the plate boundary, the magnitudes of intraplate earthquakes are usually limited by the relatively thin seismogenic zone and a limited fault rupture length, usually to a value in the range from Mw 7.0 to 7.5, or larger if earthquakes occur to greater depths than for most continental earthquakes.

Shallow earthquakes are significant if they occur locally, regardless of the sizes. In the PNG region many shallow earthquakes occur at sea, beneath the zones defining the plate boundaries in the northern Solomon Sea, and across the seismic zones of the Solomon (Woodlark Basin) and the Bismarck Seas.

However there are significant shallow earthquake zones on land, including the southern New Guinea highlands, the Papuan Fold Belt in PNG and Irian Jaya Fold Belt in eastern Papua Province, Indonesia, and beneath the north-eastern New Guinea region.

4.2.1 North of the Sepik River

Ripper and McCue (1982) referred to the seismicity of the region as the North Sepik Shallow Zone and described it as strong. The earthquakes here are the westward continuation of the shallow earthquakes that crosses the Bismarck Sea, linking southern New Ireland and northern New Guinea near Wewak. The zone then continues west-northwestward beneath the mountain ranges of Prince Alexander, Torricelli and Bewani.

Ripper and Letz (1993) and Ripper, Letz and Anton (1996) consider that the Pacific Plate is underplating the India-Australia Plate in a WSW direction. The collision is forced and oblique thus causing intense seismicity, a consequent of deformation of the leading edge of the India-Australia Plate as it is dragged westwards. The region is the site of oblique collision of the Pacific and India-Australia Plates. The collision rate determined by Chase (1978) is approximately 13 cm/yr on azimuth 072°. In the region the existence of the North Bismarck Plate was debated and Tregoning (2002) confirm from GPS measurements its existence. Ripper (1992) suggested that the region of scattered seismicity north of the Bismarck Sea seismic lineation might be considered to be the leading edge of the Pacific Plate. Earthquakes are also scattered southward linking the shallow seismicity complex of Papua Province, Indonesia.

Large shallow earthquakes that have occurred in the region include:

1935 September 20, 0146 UTC, magnitude 7.9, Torricelli Mountains

The earthquake killed many people, caused massive landslides on the mountains, and rivers were dammed with rubble, creating huge lakes. The dams were unstable and later burst, killing more people in the floodwaters.

1968 October 23, 2104 UTC, magnitude 7.0, coastal region near Wewak

Damage was in mainly the Dagua region northwest of Wewak. Village houses collapsed, and water tanks ruptured. Some damage was caused by the subsidence of filled-in bomb craters beneath buildings.

1998 July 17, 0949 UTC, magnitude 7.1, offshore Sissano Lagoon

This earthquake generated a tsunami that killed more than 2000 people and devastated a narrow 10 km of coastline, although the effects of the tsunami were experienced along a 45 km stretch of coastline. The findings as to the cause of the tsunami have been controversial, and either earthquake dislocation or submarine slump has been attributed as being the major cause. It is possible a huge volume of sediments slumped as a result of earthquake, either by violent shaking or fault dislocation.

2002 September 08, 1844 UTC, the magnitude 7.8 (Ms), coastal Wewak region

This is one of the largest earthquakes ever recorded from the northwestern part of mainland PNG. The earthquake was shallow and was located just offshore and about 90 km west-northwest of Wewak. The strong shaking caused serious damage to numerous houses and water tanks, triggered many landslides and created ground cracks. Uplift of as much as 30-40 cm occurred at the "Wewak Islands", Tarawai, Walis, Kerasau, Kairiru and Muschu. A moderate tsunami, having maximum amplitude of 3-4 m, was generated at the same time as, or soon after, the earthquake (Anton and McKee, 2005b).

4.2.2 North of the Ramu – Markham Fault

Ripper and McCue (1982) termed this the Northern Shallow Zone and described it as strong, having had some of the strongest earthquakes occurred there. Ripper (1992) pointed out that the seismic zone is approximately the southwestern margin of the region of shallow earthquakes beneath the Adelbert and Finisterre Mountains and the Huon Peninsula. Ramu Valley on the other hand represents the plate boundary of the South Bismarck Plate and the India-Australia Plate. Further, and shown quite well by shallow seismicity, the southeastern part of the region is possibly the location of the triple junction of the South Bismarck, India-Australia and Solomon Plates.

Ripper (1992) proposed, and later re-affirmed by Ripper, Letz and Anton (1996) that the shallow seismicity of the Adelbert Mountains is partly caused by shallow fracturing of the South Bismarck Plate front. This may be the development of a separate Adelbert block.

The earthquakes here include the intermediate depth earthquakes beneath the region, and those related to the volcanic arc to the north. These earthquakes are associated with the sinking of the Solomon Plate beneath the collision zone, and may be sinking further west then 142° East, possibly to 135° East (Ripper, Letz and Anton, 1996).

Large damaging earthquakes that have occurred in the region include:

1970 October 31, 1753 UT, magnitude 7.0, Adelbert Mountains

Fifteen people were killed and there were widespread landslides in the epicentral region. An estimated 80 buildings collapsed, mainly village houses. Damage occurred in Madang Town. Both the Cairns and Guam sections of the SEACOM submarine cable were severed in Astrolabe Bay, offshore near Madang. A 3 metre high tsunami was generated.

The 1970 magnitude 7.0 earthquake was strikeslip with the "pressure" axis orthogonal to the Ramu Valley, and the arc. The aftershock sequence analysed by Abers and McCaffrey (1994) was consistent with the strikeslip mechanism of the main earthquake, and in support of the fracture being a cross-arc feature.

1986 June 24, 0311 UTC, M7.1, depth 102km deep beneath the Sepik Valley

The earthquake has been described by Anton (1994), and Ripper and Moihoi (1996b). The earthquake occurred at intermediate depth, and was felt at greater epicentral distances throughout the PNG mainland, and as far southeast at Port Moresby.

Damage that occurred in the epicentral region was extensive, including many damage houses in the Sepik Valley, 68 at Wom near Angoram. Breakages occurred to both the Madang-Guam and Madang-Cairns submarine SEACOM cables in Astrolabe Bay, which were subsequently not repaired and abandoned.

Many village houses were damaged in the Sepik Valley epicentral region near Angoram, the most being 68 in the village of Wom. The microwave station at Anagram also suffered damage. Farther afield at Mt Hagen there was damage, and throughout the PNG Highlands bridge approach damages, road damages and water tank fractures occurred.

1987, February 08, 1833 UT, magnitude 7.4, Vitiaz Strait

The earthquake was investigated and the devastating effects of it described by King, Letz and Buleka (1987) and Anton (1992). On Umboi Island 327 village houses were damage, and sixty were damaged at the village of Tarawe near Samo. A landslide on the Huon

Peninsula killed three people, and more damage on Umboi Island included extensive landsliding, collapse or partial collapse of old or weak buildings including village houses, and destruction of most water tanks. The earthquake was also described by Ripper (1992), while Abers and McCaffrey (1994) interpreted the aftershock sequence and mechanism of the earthquake rupture.

1993, October 13, 0206 UT, magnitude 7.0, Finisterre Mountains

The landslides resulted in massive denudation of whole mountain slopes, burying villages, gardens and causing deaths. Thirty-seven people were killed by landslides or rockfalls. The aftershock series included a second magnitude 7 earthquake that caused surface rupture, but there were no further fatalities.

4.2.3 Papuan Fold and thrust Belt

The Papuan Fold and thrust Belt seismic zone was called the Southern Highlands Seismic Zone, and seismicity in the zone was first described by Ripper and McCue (1981a, 1983). The shallow earthquake zone extends from the Gulf of Papua northwest through the Star Mountains into Papua in Indonesia, linking up with the Irian Jaya Fold Belt. Although mostly shallow, the seismicity extends deep into or below the crust, at least to depth of 45 km (Abers and McCaffrey, 1988). The intraplate seismicity represents the fracturing of the India-Australia Plate front from its collision with the South Bismarck Plate (Ripper and McCue, 1981a, 1983; Ripper, Letz and Anton, 1996). This seismic zone could well be the southern boundary of a separate New Guinea Highlands block (Wallace *et al.*, 2004; Anton, Gibson and McCue, 2008).

Ripper and McCue (1982; Ripper and Letz (1993) described the seismicity on the Papua Fold Belt as being strong.

Large earthquakes, which have occurred on the zone, include:

1922 January 19, 2158 UT, magnitude 7.5, Papuan Fold Belt

The earthquake occurred to the north of Daru (Everingham, 1974). Tsunami effects were observed on the south coast, probably in the Fly River delta (Everingham, 1977).

1931 November 02, 1702 UT, magnitude 6.5, Kerema

The Gulf of Papua earthquake was documented by the Resident Magistrate of Kerema Town who reported that a number of village houses collapsed.

1954 March 03, 0602 UT, magnitude 7.0, Papuan Fold Belt

The earthquake occurred near Tari on the Papuan Fold Belt, southern Highlands of PNG. At the epicentre, damage was extensive. The earthquake was felt as far away as Wewak on the north coast and Daru on the south coast.

1993 August 20, 0506 UT, magnitude 6.2, Papuan Fold Belt

The earthquake occurred near Hides and Tari where damage was considerable at the Hides Gas plant. The "Hides Earthquake" (Anton, McKee and Abers, 2001) occurred at about 15 km depth, under the eastern part of the Muller Anticline. This event also appears to have occurred on a structure within or penetrating basement, along strike of the northwest trending structural fabric.

2000 March 3, 2222 UTC, magnitude Ms 6.7, Papuan Fold Belt

The earthquake occurred beneath southeastern part of the Papuan Fold Belt and strongly shook a broad area of the south-central part of mainland PNG. The epicentre of the earthquake was in the Gobe area of the Southern Highlands Province of PNG, hence the name "Gobe Earthquake" (Anton, McKee and Abers, 2001).

The focal mechanism was an overthrust event that occurred at a mid-crustal depth (13 km) within basement. The earthquake occurred within the southeastern part of a northwest-trending seismic zone 900 km long and 150 km wide, extending from Kerema at the head of the Gulf of Papua into Indonesia's Papua Province, to about 139°E. This zone of shallow (<50 km deep) earthquakes, the Southern Highlands Seismic zone (Ripper and McCue, 1981a; 1983), is related to folding and northeast-dipping thrusting of the Papuan Fold Belt.

4.2.4 Papuan Peninsula

The seismicity along the Papuan Peninsula is viewed as the current boundary between the Solomon and India-Australia Plates (Ripper, 1982). The Papuan Peninsula seismicity includes two clusters of earthquakes. The first is in the north of the Peninsula, south of Huon Gulf. The second is in the southeast of the Peninsula, extending through Goodenough Bay and D'Entrecasteaux Islands into the western Woodlark Basin.

Ripper (1992) suggested that the apparent gap in seismicity could be a temporary phenomenon based on the relatively short recording interval.

No magnitude 7 earthquakes have occurred in the peninsula since 1900 but numerous magnitude 6 earthquakes, including the magnitude 6.2 earthquake that occurred 46 km depth near Kwikila in 1979 and which caused damage in Port Moresby.

4.2.5 New Britain

The earthquakes beneath New Britain at depths beyond 40 km northward across the island show seismicity in the form of the Wadati-Benioff Zone. Ripper (1992) proposed that the earthquakes represent two tectonic regions. The seismicity of southern coast of New Britain is the top of the Wadati-Benioff Zone.

Earthquake fault plane solutions are generally overthrust, typical subduction type earthquake mechanism.

Central and north coast New Britain seismicity occurs in the extensional environment that extends north-south across New Britain (Mori, McKee and Letz, 1987; Ripper, 1992; Ripper, Letz and Anton, 1996). Earthquake fault plane solutions tend to have a horizontal "Tension" axis orthogonal to the New Britain arc trend and plate boundary, either normal faulting or strikeslip.

Major shallow New Britain earthquakes include:

1985 May 10, 1535 UT, magnitude 7.1, Central New Britain

The earthquake occurred beneath central New Britain. Its effects have been described by King and Loveday (1985), King (1986), King, Loveday and Schuster (1987), Mori, McKee and Letz (1987) and Anton (1996d). It caused damage to bridges, houses and properties on both north and south coasts, and massive landsliding in central New Britain.

The Harvard/USGS fault plane solution is strikeslip with the tension axis orthogonal to the plate margin, suggesting that the arc is under tension (Mori, McKee and Letz, 1987).

2000 November 17, 2101 UTC, magnitude Mw 7.8, southeastern New Britain

This was the third largest earthquake in the sequence which started on the 16 November at 0444 UTC earthquake (next section 4.2.6). The earthquake had magnitude values Ms 8.0 and Mw 7.8 and occurred near Pomio, beneath eastern New Britain forty hours after the first earthquake (Anton and McKee, 2005a).

4.2.6 Southern New Ireland – Northern Solomon Sea

The shallow seismicity of the southern New Ireland region is the result of the triple junction of the Pacific, South Bismarck and Solomon Plates. The seismicity of the zone extends in depth to more than 500 km.

Shallow depth seismicity forms the link between the shallow earthquakes of the northern Solomon Sea where the Solomon Plate bends downward beneath New Britain and the Bougainville margin, and the shallow earthquakes of the eastern Bismarck Sea.

Large southern New Ireland earthquakes include:

1971 July 14, 1406 UTC, magnitude 8.0, northern Solomon Sea/NW Bougainville

Both the earthquake and a tsunami generated by the earthquake had devastating effects along eastern New Britain, southern New Ireland and western Bougainville, as described by Everingham (1973b, 1975b, 1977), Ripper (1977, 1992), Lay and Kanamori (1980) and Schwartz, Lay and Ruff, (1989).

1971 July 26, 0123 UTC, magnitude 8.1, northern Solomon Sea/south of New Ireland

The doublet of the July 14 earthquake, the earthquake and a tsunami generated were again devastating along eastern New Britain, southern New Ireland and western Bougainville region as described by Everingham (1973b, 1975b, 1977), Ripper (1977, 1992), Lay and Kanamori (1980) and Schwartz, Lay and Ruff, (1989).

1985 July 03, 0436 UTC, magnitude 7.2, southern New Ireland

This earthquake occurred on the northwest trending Sapom Fault. Damage included severe landslides, the collapse of village houses and water tanks, and a large timber frame house. The fault plane solution is an overthrust on a northwest-southeast azimuth (Mori, 1989).

2000 November 16, 0445 UTC, magnitude 8.0, southern New Ireland

The earthquake occurred beneath the eastern Bismarck Sea but the area of intense shaking and damage included southern New Ireland and Gazelle Peninsula. Both this and linked events, and associated significant aftershock sequences have been described by Anton and McKee (2005a). Evidence of fault movement along the Weitin Fault were observed and documented by the Rabaul Volcanological Observatory (Itikarai and Tregoning, 2003; Anton and McKee, 2005a).

2000 November 16, 0742 UTC, magnitude 7.8, northern Solomon Sea

This was the second main earthquake that occurred beneath the northern Solomon Sea, which shook up Gazelle Peninsula and southern New Ireland very strongly (Anton and McKee, 2005a).

4.2.7 Bougainville Island

The seismicity in the region of Bougainville Island is associated with the subduction of the Solomon Plate at Bougainville Island, and is mainly offshore in the Solomon Sea. It encroaches onto Bougainville only in the southwest corner of the island.

Large earthquakes, which in the past have devastated parts of Bougainville, have occurred offshore in the Solomon Sea.

4.2.8 Solomon Islands

The seismicity of the Solomon Islands is a result of the collision and northeastward subduction of the India-Australia Plate beneath the southwestward approach of the Pacific Plate. The subduction zone spans from about the region of the Woodlark Basin in PNG and southeastward.

Numerous large earthquakes have occurred within the Solomon Islands including:

2007 April 01, 2039 UTC, magnitude 8.1, New Georgia Group of Island near Gizo

The largest of events to occur in the zone since 1900, the earthquake occurred at shallow depth (10 km) and was followed by an aftershock sequence that included a large magnitude of 6.2.

Casualties included fifty-two people while sixty were reported missing when a tsunami generated by the earthquake struck the Solomon Islands. The tsunami wiped out more then thirteen villages, and left thousands homeless. Damages were estimated in millions. The effects of the tsunami were experienced in South Choiseul where death toll increased with wave heights of 10 metres swept away villages, gardens and a hospital. About 900 homes were destroyed and 5000 people left homeless.

The tsunami was experienced as far away in Papua New Guinea, with a family of five reportedly missing from a remote island in Milne Bay Province, and at Woodlark Island where a 2 metre wave destroyed 17 houses and a church.

This earthquake occurred in the segment of the Bougainville-San Cristobal Trench where no earthquake of magnitude 7 or larger had occurred since the early 1900s. Uplift was observed at Ranongga where a landslide caused 2 casualties.

4.2.9 Papua Province, Indonesia

Although the seismicity of Papua is more diffused in comparison, the main seismic zones are somewhat recognisable. These have been the zones of large significant earthquakes. Especially in the New Guinea Highlands and Wamena Valley, the Mamberamo Range in the north, the Yapen-Sorong Fault system, and the shear zone accommodating most of oblique convergence in the region, along the Tarera-Aiduna and Lowland-Paniai Fault systems (Pebullier and Ego, 2002).

The large earthquakes of the Papua Province region have been many, including:

1976 June 25, 1918 UTC, magnitude 7.1, and October 29, 0251 UTC, magnitude 7.1.

These two earthquakes occurred inside the border with PNG and were responsible for the death of about 500 people (McCue, 1981b).

1996 February 17, 0559 UTC, magnitude 8.1, Biak Island, Papua Province

The magnitude MS8.1 earthquake occurred at depth 33 km beneath Biak Island and generated a tsunami measuring 7.7 metres which struck Biak Island, Irian Jaya, causing extensive damage and loss of 108 lives (USGS, 1997; Davies, 1999). A 61 cm tsunami was observed as far east as Rabaul Harbour.

4.3 Observed surface effects of earthquakes

Intense earthquake-induced landslides have been numerous in many mountains of the regions. Although otherwise a tectonically active region, only two fault scarps have been observed after the occurrence of two different earthquakes, while one earthquake (possibly two) has produced subsidence, three probable earthquake uplifts and one earthquake caused horizontal movement. A total of seven earthquakes have produced possible tectonic ground deformations. There may have been numerous more but the thick soil cover due to intense earthquake-induced and rain-induced landslides, and dense vegetation cover may have obscured evidence of any.

4.3.1 1907 December 15, 1735 UT, magnitude 7.0, northern New Guinea

The earthquake occurred beneath the region along the coastline adjacent to the Torricelli Mountains. Carey, in Stanley *et al.* (1935) reported subsidence along tens of kilometres of coastline occurred forming lakes and lagoons, and drowning local villages. Some of the damage was photographed by Neuhauss (1911).

Away from the region of intense activity however, westward towards Vanimo and eastward near Wewak considerable Quaternary uplift occurred (Norvick and Hutchison, 1980).

4.3.2 1920 February 02, 1122 UTC, magnitude 7.7, southern New Britain

Everingham (1977) extracted from government reports from Gasmata District Office that after the earthquake, the seawater rushed out of the main harbour entrance and did not return. This resulted with the high water mark being about 20 to 24 inches lower than previously. It was observed that reefs were left stranded, and Gasmata Island now joined to Abelle Island, both previously separated by water. Milsom (1974) pointed out that these observations are consistent with known Quaternary uplift of the southern New Britain coastal reef terraces, some of which are up to heights of 500 metres.

4.3.3 1935 September 20, 0146 UTC, M7.9, Torricelli Mountains

The earthquake was felt by a geological survey party, led by S.W. Carey, in the Sibi River region of the southern Torricelli Mountains, (Carey, in Stanley *et al.*, 1935; Carey, 1990). Carey reported having observed rocks having left the ground during the earthquake, defying gravity thus suggesting an acceleration exceeding 1g. Whole mountainsides became denuded during massive landslides (Marshall, 1937) dumping debris in to the Gweinif and Kaufangi Rivers. Dams were developed on both rivers, which created huge lakes.

There was light damage at Aitape and minor landslides at Wewak (Montgomery and Eve, in Stanley *et al.*, 1935).

Felt effects and damage were reported as far south as the Fly River region, Oroville Camp, which was located near the present Kiunga Township, where minor landslips occurred in the hills.

4.3.4 1941 January 13, 1626 UT, magnitude 7.0, Gazelle Peninsula

The earthquake occurred beneath the Gazelle Peninsula, on the northwest-southeast trending Baining Fault (Macnab, 1970), about 30 km southwest of Rabaul. Fisher (1944) described the earthquake in great detail.

Fisher in 1941 strongly suspected existence of a fault (Macnab, 1970), possibly linking from Ataliklikun Bay on the north through the Warangoi Valley southwards and further offshore to the south. It is now confirmed the earthquake occurred on the Baining Fault system. It has been known for sometime the presence of this fault system, based on geological and topographical evidence, and the origin of many tremors along the system (Fisher, 1944). Fisher noted that an actual fault scarp could be seen, observing a subsidence up to 3 feet took place along the west side of Ataliklikun Bay. Ripper (1992) documented other observations made by Fisher, including possible precursory seismicity on the fault. There were also rare precursory land tiltmeter readings at the Observatory. These observations were noted one month prior to the events, and immediately ceased after the shock.

4.3.5 1993 October 25, 1027 UT, magnitude 7.0, Finisterre Mountains

The earthquake occurred in the Finisterre Mountains, beneath the vicinity of the Solomon/Indo-Australia/South Bismarck triple junction. Tutton and Browne (1994) investigated the effects of the earthquake, and aftershock series. The magnitude 7.0 earthquake that preceded this earthquake on 13 October killed 37 people.

Tutton and Browne (1994) made observation of one dislocation believed to be a fault plane movement occurred on. This was in the Gusap valley where a released surface along a fault plane was responsible for the intense landslides. Evidence of lineaments of similar trends, were observed from both Landsat TM imagery and aerial photography. During this earthquake, a down throw of about 74 cm with a near vertical exposed face was observed and traced for several hundred metres.

4.3.6 2000 November 16, 0445 UT, magnitude 8.0, eastern Bismarck Sea

The earthquake was felt very strongly beneath southern New Ireland and Gazelle Peninsula. The earthquake, with linked events and have been documented by Anton and McKee (2005a) and evidence of horizontal fault movement by as much as 5.5 metres was observed and documented by the Rabaul Volcanological Observatory (Itikarai and Tregoning, 2003).

Tsunami waves that followed caused by possible sediment slides were damaging on southern New Ireland, Gazelle Peninsula, western Bougainville, and on Islands of the Milne Bay Province (Anton and McKee, 2005a). Geist and Parsons (2005) proposed that the associated large (Mw 7.8) earthquakes caused the resulting tsunami(s), and suggested that future local tsunamis are likely after great strike-slip earthquakes. Tregoning *et al.* (2005) interpreted the aftershock relocations and noted that the aftershocks cluster in the NE of Weitin Fault and did not necessarily define a linear feature that trend the fault system.

4.3.7 2002 September 08, 1844 UTC, magnitude Ms 7.8, Wewak

Anton and McKee (2005b) documented this as one of the largest earthquakes ever recorded from the northwestern part of mainland PNG. The earthquake was shallow and occurred offshore and about 90 km west-northwest of Wewak. The strong shaking caused serious damage to numerous houses and water tanks, triggered many landslides and created ground cracks. Uplift of as much as 30-40 cm occurred at the "Wewak Islands", Tarawai, Walis, Kerasau, Kairiru and Muschu. A moderate tsunami, having maximum amplitude of 3-4 m, was generated at the same time as, or soon after, the earthquake.

4.4 Significance of earthquake hazard analysis

Using data that is now available, seismic hazard maps are produced to cover the whole country to replace existing parameters and maps. The results achieved are envisaged to benefit many of our endeavours in PNG, especially those by the building industry and town planning country-wide.

4.4.1 Engineering aspects

Living on active plate margins does have many drawbacks, especially when countries are seeing rapid development in nationhood. This is what may be happening or if not yet, soon will be taking place in PNG – economically and socially. Issues that require full attention include those of earthquake magnitudes, isoseismal mapping, the attenuation of ground shaking, and the resulting damage from earthquake shaking. The problems of producing objective isoseismal maps have been tough, and unresolved (Ripper, 1979).

PNG has a database of earthquake intensity data based on the Modified Mercalli scale for PNG (Ripper, 1979; Appendices 3 and 4), but very few isoseismal maps have been produced for large earthquakes. Strong motion data was collected but instrumentation maintenance was not sustained due to lack of funding. In other countries, government funding supports the collection, analysis, storage and distribution of such data. In PNG it still has yet to be ensured that at least one of the three levels of government fund the collection of data, and that this is available for community use on a permanent basis. This requires the continuing attention of seismologists and engineers. Currently there exist very little data of any sort, as little success was achieved in the past to secure sustainable assistance. It requires a lot more effort and discussions to find ways of providing data suitable for earthquake risk mitigation.

It becomes apparent the need for instrumentations and the deployment of these strategically in locations in the region as seen from limited work done so far. The influence of soil and topography conditions on maximum earthquake accelerations for PNG conditions, and attenuation relationships have been discussed by Ripper (1992). It was determined that in general, a magnitude 6.0 earthquake occurring within 56 km radius would give rise to a maximum acceleration of about 0.1g, at about a 56 km radius. This would equate to about Intensity MM 7, causing landslides and damage to poorly built structures. A magnitude 7.0 earthquake occurring at this radius would give rise to a maximum acceleration of 0.2g or more (about Intensity 8), with damage to well-built structures.

Large earthquakes occurring further than 56 km away should generally only cause damage at Intensity 7 (damage to defective design and workmanship) to structures built in accordance with the building construction seismic loadings on normal foundations.

Spence (2007) stressed the importance of earthquake engineering, the significance of the protection of life, property and livelihoods from the destructive power of earthquakes. Emphasis must be placed on every type of action aimed at achieving, whether in the design of new buildings or civil engineering structures, or otherwise in the modification of existing ones or in setting up the human systems needed to create a society safe from earthquakes.

4.4.2 Earthquake hazard analysis method

The hazard maps were produced using the four-stage Cornell method. In the method involved, the first stage was when the development of the seismotectonic model. This is where attempts to anticipate the distribution of earthquakes over the next few tens of years were determined. This was largely based on the time and space distribution of past earthquakes, with additional constraint from geological and geophysical data. This usually involved division of the region into seismic source zones, and the identification of active faults. Normally the area or volume source zones and the active faults are each assumed to have uniform rates of seismicity. The zones were more detailed than used in past studies, and the seismotectonic model includes some tens of source zones.

In second stage the seismicity in each of the source zones were quantified, giving the rate of earthquake activity as a function of magnitude, with key parameters defining the relative numbers of small to large earthquakes (the seismological or Gutenberg-Richter b-value), and the maximum credible earthquake magnitude in each zone. Quantification considered earthquake clustering, and sequences including foreshocks and aftershocks were identified thus isolating only the independent main earthquakes for analysis.

The third stage involved the specification of ground motion from an earthquake as a function of distance, magnitude and other parameters. One or more attenuation functions are normally derived from empirical data. This requires considerable instrumentation that is not installed in most places, and is very limited in PNG. Attenuation functions derived using data from other places that are geologically and tectonically similar were applied but will be replaced when local data are available. The applicability of such functions was checked with any local data that is available. Local attenuation affects estimates of local earthquakes, especially smaller events, so the variations were expected to affect the magnitude estimates of the earthquakes in the catalogue, used in stage 1.

Stage four involved the computation of spectral ground motion recurrence by integrating the probabilities of motion from all earthquakes in space (longitude, latitude and depth), magnitude (from negligible to maximum credible), and frequency of motion. This is a complex integration requiring software such as the EZ-FRISK program. This computed the spectral ground motion recurrence at a point that took minutes to tens of minutes processing time per point depending on the complexity of the seismotectonic and attenuation models. To produce a hazard map, this was repeated at many points on a grid covering the region.

The first stage of the project was to compute spectral ground motion recurrence at a single point using a preliminary simplified seismotectonic model and attenuation function. It was planned that an important site such as Lae be chosen as a starting point.

The sensitivity of the results to the input parameters was assessed, and each of the four stages was further developed. It was expected that development of the three-dimensional seismotectonic model and evaluation of attenuation functions were the major problems.

An exceptionally accepted hazard map for PNG map was completed. The models used are to be developed further to produce improved hazard maps, of higher resolution, in an iterative process.

4.4.3 EZ-FRISK

Earthquake data for the PNG region from the International Seismological Centre (ISC) bulletin and from the Port Moresby Geophysical Observatory (PMGO) were utilized. The data include comprehensive earthquake hypocenter and intensity databases, as well as a collection of accelerograms recorded on medium or soft foundation. Some of these records have been analysed by the then Bureau of Mineral Resources, Geology and Geophysics (now Geoscience Australia) and others have been analysed by PMGO (Ripper, 1992), and kept at the Seismological Research Centre (SRC).

The analysis software is EZ-FRISK (McGuire, 1993), which is a commercial software program used by engineering seismologists and earthquake engineers, as well as expertise and facilities owned by SRC at the Environmental Systems and Services (ES&S). The facilities at ES&S in Melbourne include computer hardware and other software, apart from the analysis software.

4.5 Other geological hazards

4.5.1 Significant tsunamis

Historically, most damaging tsunamis in PNG were related to seismicity. PNG lies in one of the most seismically active regions of the world. The occurrence of large earthquakes having magnitude greater than 7 is relatively frequent, 200 have occurred in the period 1900-2008. A large number of these earthquakes were tsunamigenic. Less commonly, tsunamis were caused by volcano-related activities.

Listed here are tsunami events thought of as significant in relation to the mechanisms by which they were generated, the location of their sources. They are not necessarily the largest events.

There appear to have been several mechanisms of tsunami generation in PNG. While earthquake induced slumping seems to be the most common mechanism, the largest tsunamis probably are caused by large-scale slope failure at volcanic islands.

Earthquake focal mechanisms, major earthquake locations and aftershock patterns are important factors to consider when evaluating mechanisms for seismogenic tsunamis.

Results from the Aitape Tsunami offshore surveys will enhance regional and local tsunami studies which, hopefully, will help minimise loss that will result from future events. An immediate lesson from the 1998 Aitape Tsunami is that other coastlines of PNG may be considered highly vulnerable to tsunamis generated from offshore sediment slumping caused by earthquake shaking.

Ritter Island, 1888

A major tsunami was generated by rapid, large-scale slope failure at Ritter Island Volcano on 13 March 1888 (Johnson, 1987). Tsunami wave heights reached 15 metres along eastern New Guinea and western New Britain coastlines where native coastal villages disappeared and 3 metres at Rabaul 480 km away.

North coast PNG mainland, 1930

A severe earthquake shook the northern mainland coastal area on 24 December 1930 and was followed by a 7-8 metre tsunami on part of the northern mainland coast, and a 9-12 metre tsunami on Mal Island (Everingham, 1977).

Madang, 1970

On 01 November 1970 a magnitude 7.0 earthquake occurred onshore beneath the Adelbert Range, about 30 km north-northwest of Madang, and was followed by a 3 metre high tsunami near Madang. The Madang-Guam and Madang-Cairns SEACOM cables, on the seafloor east of Madang were severed at the same time.

Solomon Sea, 1971

On 14 July 1971 a magnitude 8.0 earthquake occurred beneath the northern Solomon Sea and was followed by a tsunami that was observed at areas of Bougainville (1-2 metres), Wide Bay (6-8 metres), Rabaul (2.4 metres) and at Pomio (1-2 metres). Twelve days later on 26 July, another magnitude 8.0 earthquake occurred in a different part of the Solomon Sea. An apparently related tsunami was observed at Rabaul Harbour (7 metres), southern New Ireland (4-5 metres), Pomio (3 metres), areas of Kavieng (1metre) and western New Britain (1 metre) (Everingham, 1977; Ripper and Letz, 1991).

Lae Voco Point, 1972

Unusual sea waves were noted at the Lae Harbour and waterfront, that the sea surged into the harbour, receded, and surged in again to a greater extent, sinking one boat and breaching another. This event, which occurred in August 1972, was not associated with an earthquake or volcanic eruption. It was a result of spontaneous submarine slumping.

Rabaul, 1994

Two metre high tsunami waves were generated during the September 1994 Rabaul volcanic eruptions. Tsunamis swept across the northern part of Matupit Island near the centre of Simpson Harbour damaging many houses, and affected near-shore properties at Rabaul Town in the northern part of the harbour (Anton, 1996b).

Biak Island, 1996

On 17 February at 0559 UTC a magnitude Ms8.1 earthquake occurred at shallow depth beneath Biak Island, Papua, Indonesia. The earthquake generated a tsunami measuring 7.7 metres, which struck Biak Island. At least 108 people were killed, 423 injured, 58 missing, and 5,043 homes were destroyed or damaged in the epicentral area on Biak Island and Supiori (USGS, 1996; 1997; Davies, 1999). A 61 cm tsunami was observed at Rabaul Harbour, on eastern New Britain, about 1,800 km away.

Aitape, 1998

The Aitape Tsunami of 17 July 1998 closely followed a magnitude 7.1 earthquake. The tsunami killed more then 2500 people and injured 1,000 and left thousands homeless (Sweet et al., 1999: Synolakis *et al.*, 2002; Tappin *et al.*, 1999; Tappin *et al.*, 2001).

Southern New Ireland, 2000

On 16 November 2000, a tsunami was generated soon after a magnitude Mw8.0 earthquake which occurred immediately offshore northwest of southern New Ireland. Tsunami waves damaged houses and property on southern New Ireland, Gazelle Peninsula, eastern New Britain, Trobriand Islands and Bougainville (Tregoning *et al.*, 2004; Geist and Parsons, 2004; Itikarai and Tregoning 2003; Anton and McKee, 2005a).

Wewak, 2002

A moderate tsunami of maximum amplitude of 3-4 m, was generated at the same time as, or soon after the shallow magnitude 7.8 Wewak Earthquake of 08 September 2002, at 1844 UTC (Anton and McKee, 2005b).

Shortland Island, 2007

A 9 m high tsunami struck the western Solomon Islands soon after the magnitude Mw8.1 earthquake of 1 April 2007 and washed away hundreds of homes, taking numerous lives. The tsunami waves were part of a so-called near-field or local tsunami that arrived within minutes after the earthquake, and flooded the coastal region including Gizo Township, and extended as far inland as 200 m.

Tsunami generation mechanisms

Volcano associated activity

The Ritter Island event of 1888 produced one of the most damaging tsunamis in PNG's recorded history. It appeared that no earthquakes or eruptive activity accompanied the event, and that tsunami waves were generated by the collapse of part of the volcano. The volume of the displaced part of the cone is estimated to be 4-5 km^3 (Johnson, 1987).

Pyroclastic flows from Vulcan cone are the probable cause of the tsunamis generated during the Rabaul volcanic eruption in 1994. The formation of the tsunamis was closely linked to the on-set of the initial plinian phase of Vulcan's eruption when voluminous pyroclastic flows were formed and entered the sea in an arc on the northern to eastern flank of Vulcan.

Submarine slumping

Earthquake-induced submarine slumping is considered to be a common cause of tsunamis in PNG. This mechanism is illustrated by the events of Madang 1970, Solomon Sea 1971, Lae's Voco Point 1972 and Aitape 1998.

Submarine sediment slumping was indicated as the causative mechanism for the Madang 1970 tsunami on the basis of the coincidental breakages of the seafloor telecommunications cables immediately east of Madang (Everingham, 1973a; 1973b; 1974; 1975a). The on-shore location of the earthquake linked to the Madang tsunami of 1970 would tend to rule out seafloor surface rupture as a possible cause of this tsunami.

In 1971 the two magnitude 8.0 northern Solomon Sea earthquakes were typical subduction earthquakes. Occurring at depths of 50km, these earthquakes were too deep to cause surface rupture. Thus the most probable mechanism for the tsunamis associated with these earthquakes is sediment slumping.

The 1972 event had no accompanying earthquake or volcanic eruption. Spontaneous submarine slumping within the Lae City Port or even in the Huon Gulf caused this event.

The 1998 Aitape Tsunami was generated by slumping, which was induced by a magnitude 7.1 earthquake. The focal mechanism and aftershock distribution indicate that the fault plane was near horizontal, strike 147° and dip 14°. Motion on the fault plane was bottom side movement landwards orthogonal to the coastline and plate boundary.

Surface rupture

The tsunami of 16 November 2000 may have been caused by large-scale surface rupture on a well-defined left-lateral strike-slip fault. There is on-shore evidence of both vertical and horizontal ground displacements of several metres along the fault. The length of rupture was several hundred kilometres, including offshore northwest and southeast of southern New Ireland.

The Solomon Island Tsunami of 1 April 2007 was caused by a 250 km NW rupture along the Bougainville-San Cristobal Trench (USGS, 2007), where the Woodlark Spreading Ridge is subducting ahead of the India-Australian Plate beneath the SW approaching Pacific Plate. It is determined that in the northwest the rupture length was restricted by the subduction of the Woodlark Rise.

4.5.2 Volcanic hazard

Studies are being conducted to assist better understand and confirm the origin and nature of the phenomena that lead to volcanic hazards in the region, and assist in revealing volcanic hazards by uncovering the extent of their recent past activities. Studies are being conducted to map, date and characterise offshore debris avalanche deposits, coastal tsunami deposits and other features (volcanic and sedimentary) and structures in volcanic arcs in PNG, the Bismarck/New Guinea Volcanic Arc being the dominant.

Amongst others the study carried out to uncover and properly assessing vulnerability of islands and coastlines to these hazards, and confirming and re-affirming the existing hazard. Offshore New Britain and eastern/northern New Guinea region that hosts the New Guinea/Bismarck Volcanic Arc, was recently studied in detail. The information now available will have great implications for understanding the volcanism, structure, and hazards of the volcanic arc (Silver *et al.*, 2004).

The study of volcanic hazard responsible for tsunami generation involved an in depth investigation of the debris avalanche associated with the 1888 collapse of Ritter Island. The avalanche was successfully mapped (using multi-beam bathymetry, side scan sonar and chirp seismic). The Ritter Island Volcano once stood approximately 800 m above sea level, but now its remnant is only about 150 m high. Witnesses at the time documented a tsunami that reached 12-15 m along the neighbouring islands and lesser heights farther away. The event was devastating, and resulted in damage and loss of life. It was experienced along most coastlines of New Britain, and on eastern and northern New Guinea.

A number of other presently active volcanoes show significant collapse scars. Evidence for older debris avalanches off Tolokiwa, Sakar, and Dakataua volcanoes were found and these are possible future sources for avalanches. Modelling and predictions of tsunamis generated from a debris field is identified. The Ritter collapse is especially useful because many of the details associated with it are still present and are even able to compare them with well-studied collapses of onshore volcanoes such as Mount St. Helens.

Onshore volcanoes

Onshore volcanoes dominate the entire New Britain Island, especially the northern coast, and Bougainville. Making up the New Guinea/Bismarck Volcanic Arc, the most active have been the Rabaul Volcanoes of Tavurvur and Vulcan in East New Britain, and Ulawun and Pago in West New Britain. On Bougainville, Bagana is also monitored as very active.

There exist a line a volcanoes that run from Papuan Peninsula to the central eastern Highlands of PNG. However, the most active volcano have been Mt Lamington along the central region of the Peninsula and Esa 'Ala further southeast in Milne Bay Province.

Experiences have been that the hazard from ash fall and lava flow from these volcanoes have caused and pose future threat to many village communities living on the fringes of these volcanoes. There are also threats from tsunamis generated as a result of activity from those volcanoes that are huge enough and located close to coastlines. Recent examples have been the Vulcan Volcano at the time of the twin 1994 Rabaul eruptions. Other volcanoes with potential threats of tsunami generation include Ulawun, Pago of west New

Britain; and Bagana, Baibi and Loloru of Bougainville; and Savo, Kavachi, and Cook Submarine Volcanoes of Guadalcanal (Solomon Islands) among many know.

Offshore volcanoes

Many undersea volcano mounds were revealed to exist in random positions within the area covering western New Britain-Bali/Vitu-Willaumez Peninsula-Kimbe Bay-Lolobau-Ulamona-Open Bay. These features co-exist with many islands off Langila-Kimbe-Ulamona and seem to be young in nature.

Several interesting features, including a possible debris avalanche to the north of Crown Island and a region of lava flows in this area were discovered. In the area of Bagabag Island, known to have a wide area of reefs surrounding it, several drowned terraces between 700 and 1000 m below sea level were found, giving a measure of the subsidence of the volcano over time. Detail information on these features was explored and search continued for a debris avalanche from the collapsed and drowning of Yomba Island, presently known only from legends.

Mapping the full extent of the collapse of Ritter Island, to distances of up to at least 60 km from the present location of the island, enable imagery of where the debris avalanche from the collapse rose several hundred meters along one wall of a canyon near Ritter before bending around a high ridge. This elevation constrains the velocity of the flow and indicates very high flow rates. Several very large blocks of the old island occur near the present island, and 25 km away discovered giant blocks of the underlying material that were torn up by the passing debris avalanche. The outer 30 km of the debris avalanche, much of the debris is composed of material torn up from the underlying sediments as the flow passed by.

A large number of offshore volcanoes have debris avalanche deposits. These include Sakar, Tolokiwa, Garove, Crown, Karkar, Manam and Bam. Some of these are major events and some are of lesser volumes, but they indicate that volcano collapse is a significant process in the New Guinea/Bismarck Volcanic Arc. A large amount of submarine volcanic activity occurs in this region, including seamounts, small cones, lava flows, and intrusive volcanic features.

Volcanoes on the bigger islands located northwest along the New Guinea/Bismarck Volcanic Arc, especially Karkar and Manam Islands are very active. The arc extends further northwest and includes the Schouten Island volcanoes. These volcanoes can emit debris that can cause seawater displacements, which potentially endanger coastlines of tsunamis that can be generated.

4.5.3 Earthquake-induced landslides

Landslides have been caused by earthquake induced shaking, slope instability induced by rain or spontaneously. Those occurring offshore have generated tsunamis while those onshore have had devastating effects on people, properly and infrastructure, economy and the environment. Floods have been caused by many resulting in much more devastation. Those that stood out, and of significant impact included the once described below.

1935 Torricelli Mountains

The largest earthquake associated with landsliding was the magnitude 7.9 which occurred in 1935 beneath the Torricelli Mountains, experienced and reported by pioneer geologist S.W. Carey (Carey, 1990). Stanley *et al.*, (1935) reported Carey's experiences as those terrifying. Labourers were thrown everywhere, and as objects left the ground the acceleration experienced locally must have exceeded g. Trees were falling all about, and ridges were splitting and roaring down like avalanches. The survey base station was buried tens of metres deep, covered by debris from the cliffs above it.

The earthquake denuded whole mountain slopes of their cover, carrying away village houses, killing many of the inhabitants. Rivers were dammed with rubble, forming huge lakes. Some dams later burst, killing more people in the floodwaters. Aitape and Wewak along the coast suffered only minor damage (Stanley *et al.*, 1935; Marshall, 1937; Carey, 1990). A tsunami flooded many hundreds of yards inshore in low-lying coastal sections (McCarthy, 1963; Everingham, 1977).

1968 Maprik Earthquake

The magnitude M 6.2 earthquake occurred shallow near Maprik, beneath the Prince Alexander Mountain Ranges. Denham (1974) reported on the damage including the cost of repairs estimated at $20,000. Nearby villages and missions stations suffered and road slides occurred. Landslides dammed the Misuam River.

1985 July 03, Central New Britain Earthquake

Massive landslides were caused by the 1985 earthquake of central/southern coast of New Britain. The earthquake occurred beneath the Nakanai Mountains and dislodged massive debris during shaking thus damming rivers flowing to the north and south coasts. Bridges and property were lost when dams were breached. Breaching was assisted by use of TNT on the Bairaman River, which washed away the Bairaman Village – luckily evacuated earlier. The Ivule River and others on the north coast washed away bridges, on the Kimbe-Bialla Road. The earthquake has been written about and described by Loveday (1985); King (1986); King, Loveday and Schuster (1987); Mori, McKee and Letz (1987); Ripper (1992) and Anton (1996).

1993 October 13, 25 Finisterre Range Earthquakes

Devastation was caused by massive landslides during the two shallow (Stevens et al., 1997) magnitude 7 earthquakes of October 1993. Landslides buried people, houses, gardens and property. Rivers were dammed and caused damaged to bridges when breached, mostly by overflowing (Tutton and Browne, 1994; Ripper and Moihoi, 1996c)

2000 March 3, Gobe Earthquake

A broad area of the south-central part of mainland Papua New Guinea (PNG) was strongly shaken by this magnitude (Ms 6.7) earthquake at 2222 UTC. Landslides were common within the epicentral area, especially in the vicinity of Mount Murray. Numerous landslides within the summit area of Mount Murray may indicate the proximity of the epicentre to Mount Murray. Dust clouds generated from landsliding on the flanks and crater walls of the neighbouring Mount Murray Volcano made the people afraid that the volcano was about to erupt. A number of small landslides along the roads constructed for petroleum company operations caused minor disruption (Anton, McKee and Abers, 2001).

4.5.4 Floods resulting from earthquakes

Floods have frequented major rivers. Mostly reported have been the rivers associated with damage caused at nearby major towns and villages. Towns along northern coast of PNG, especially Lae, Madang and Wewak have particularly experienced damage caused by floods that have affected livelihood and property. North and south coasts of central New Britain have continuously reported damage to roads, bridges and property.

In Lae, Bumbu and Umi bridges which provided lifeline to Morobe and Madang, and the Highlands of PNG have been damaged at various times. Costs of damages and repair had been substantial.

Floods by the dammed Bairaman River on central/southern coast of New Britain after the 1985 central New Britain Earthquake washed away villages on the south coast after the dams were breached. The earthquake caused landslides, which caused flooding of the north-flowing Ivule River and other rivers on the north coast. These floods washed away many bridges on the Kimbe-Bialla Highway. The damming of the Bairaman River was investigated by King (1986) while King, Loveday and Schuster (1987) reported on the failure of the earthquake-induced landslides dams.

There have been many earthquakes of lesser magnitude intensities responsible for minor landslides and flooding including the 8 September 2002 Wewak Earthquake (Anton and McKee, 2005b) and the Solomon Islands earthquake of 1 April 2007 on Gizo and New Georgia (USGS, 2007).

Chapter 5 Earthquake Distribution Model

Two categories of seismic hazard evaluation are defined, namely deterministic and probabilistic. The deterministic methods assume one or more earthquakes (magnitude, mechanism and location) that give maximum ground motion at the site in question, and that all other earthquakes will give lesser hazard. The earthquakes are chosen considering past seismicity, and the existence of large active faults. The probabilistic methods are based on the statistical distributions, based on past earthquakes and which is an estimation of the occurrence of earthquakes in the future. Here earthquakes in the past are considered in seismogenic zones that may be area sources (usually volumes between two depth limits) or known active faults, thus grouping them in respective tectonic origins. These methods determine the hazard as probabilities of ground motion at varying levels.

This work is based on the probabilistic method, and in particular the four-stage Cornell method. Three factors affect the earthquake waves and resulting ground motion intensity, namely the earthquake source, the travel path and the site effects. In the region so complex as PNG, with varying seismic zone sources and earthquake source mechanisms, seismic amplitude attenuation and the effect of varying local shallow structure and topography on seismic waves, it is not yet possible to consider all factors in a high resolution study.

The earthquake hazard of the region is determined utilising seismicity from zones within 200 to 500 km of any location (usually site of township or significant national project), and the ground motion recurrence determined as a measure of earthquake hazard. Earthquake data utilised is compared with other available data to provide added constraint, for better performance as recommended for the hazard analysis method employed.

Direct comparisons are made here between the seismicity and available maps of regional geology, geographic, topographic and geophysics for better definition of source zones. It is also known that the seismicity is related to active regional tectonics. For example, the shallow seismicity is in a broad sense a result of relative interaction of crustal plates. Well established are the triple plate junctions of the India/Australia (or some other blocks), South Bismarck and North Bismarck near Wewak, and the India/Australia (or some other blocks), South Bismarck and Solomon Plates to the southeast in the vicinity of Lae. Along and beneath the line of the Ramu-Markham-Sepik Valleys is the zone of intermediate depth earthquakes, resulting from within the continuing westward sinking of the Solomon Plate in the region. The other prominent triple plate junction is that between the Pacific, South Bismarck and Solomon Plates in the vicinity of the northern Solomon Sea. Deeper seismicity here is a result of northward subduction of the Solomon Plate.

The Solomon Plate is envisaged to subduct more actively to the west and east beneath the New Britain and Bougainville Trenches. This is possibly indicative of its total annihilation in time. This falling away of the plate is equally reciprocated by the advance of the South Bismarck Plate from the northwest, and to an extent the Pacific Plate to the east. Subduction to the south beneath the Woodlark Plate may have ceased while that to the opposite direction is facilitating ocean basin development in the southeast, in the Woodlark Basin. Ocean floor spreading along the central Bismarck Sea may be a result of, and related to, activity of the Solomon Plate.

5.1 Seismic data and analysis method

By utilizing available data and the use of acceptable methods now existing, the earthquake hazard of PNG was determined. The results of this work will form the basis of the replacement of the existing and outdated hazard maps. The work was based on the four-stage Cornell method.

5.1.1 Methodology

The work began with the development of a seismotectonic model that is representative of seismic source zones identified utilizing available earthquake data, which was comprehensively checked against regional geology, geophysics and geodetic data. Included in the zoning are zones of Quaternary faulting and zones of crustal deformation. Previous studies by numerous workers in the region were considered for additional constraint, especially on source zone boundaries.

The model provides for the identification of active faults, and their relationship to the occurrences of large earthquakes in recent times, although these are not incorporated in the first version. As a result of varying tectonic trends evidenced by numerous lithospheric plates and differing plate boundaries, the analysis of data and discussions of results for each specific source zones (including at varying depth layers) were treated individually. Earthquakes resulting from sinking lithospheric slabs are known to occur at depth, reaching maximum depths of up to 600 km north of New Britain and NE of Bougainville.

The quantification of seismicity at individual zones at varying depths followed, with the determination of the rate of earthquake activity as a function of magnitude. Key parameters defined here were the relative numbers of small to large earthquakes (the b-value), and the maximum credible earthquake magnitude in each zone. During this stage earthquake clustering and sequences, including foreshocks and aftershocks were considered and removed, so that only relevant earthquakes (main events associated with the sequences) were used.

The next stage involved the specification of the ground motion from earthquakes as a function of distance, magnitude and other parameters. During this stage attenuation functions were derived from empirical data, for available data. Due to lack of data it was necessary that the attenuation functions are derived utilising data from other places that are geologically and tectonically similar, until local data are available. These functions were checked against little local data that is available.

Finally the spectral ground motion recurrences were computed by integrating the probabilities of motion from all earthquakes in space (longitude, latitude and depth), magnitude (from negligible to maximum credible), and frequency of motion. This complex integration was done by the use of the software EV-FRISK program (McGuire, 1993). During this stage the spectral ground motion recurrences at individual points were computed, each taking minutes to tens of minutes processing time per point depending on the complexity of the seismotectonic and attenuation models. This stage was repeated at many sites throughout the region. To produce the hazard map many more sites at smaller grids will be included in the analysis, and all the while providing improvement on the resolution attained.

As efforts were made to document the effects of major earthquakes in PNG, earthquake databases were established. The hypocentre and intensity database were set up in 1967 by Denham and Byrne (1969) on the PNG government mainframe computer, and was upgraded by McCue (1981a). As well as being utilised to research PNG seismicity and tectonics, these databases provide catalogues for earthquake hazard and related studies, especially tsunami hazard. It has been established that most PNG tsunamis were caused by earthquakes, either co-seismically or slumping caused by near shore and offshore earthquake shaking. Earthquakes of PNG and region are mostly associated with tectonic plate boundaries. Earthquakes are also associated with stress build-up, especially within the Australian Plate front, beneath the southern PNG highlands. Continent-arc convergence in the region is evident by mountain-building processes dominating the central New Guinea ranges. Denham (1969) was one of the first to interpret and document the distribution of PNG region earthquakes. Everingham (1977) catalogued the large earthquakes of the New Guinea and Solomon Islands in the period 1768 to 1972, and was updated by Ripper and Letz (1991) who included detail accounts of the distribution of large earthquakes for the period 1900 to 1989. Ripper and Moihoi (1996a, 1996b, 1996c) discussed significant earthquake effects and intensities up to 1996. Similar work has not taken place in more than a decade, and so an update is attempted through this work (Chapter 3).

The purpose of this study is to determine the earthquake hazard utilizing the available earthquake catalogue, and to determine attenuation relationships at locations in PNG. Improved methods are envisaged to assist in the earthquake hazard analysis process. As well, problems regarding seismic station network replacement and maintenance are being mentioned for possible future address.

Earthquake hazard studies have been attempted in the last few decades but limited data have restricted proper analytical work. It is the aim of this project to use data that is now available to produce comprehensive hazard parameters never previously achieved. This will include producing modern hazard maps that represent the actual situation at hand. It is the aim of the project to use these maps as the basis to replace the existing and currently used maps of the building code, developed in the 1970s (Beca *et al.*, 1976; Jury *et al.*, 1982).

5.1.2 Defining and quantifying a source zone

A source region is currently defined as an area zone (actually a volume between two depth limits) or an active fault, that for the purposes of a ground motion recurrence calculation may be assumed to have uniform seismicity.

Zones are based on the known earthquake distribution, and should reflect the tectonic movements in the region.

A single tectonic structure may require multiple source regions to model non-uniform seismicity. For example, if the relative motion along a plate boundary is varying due to plate rotation, then the change in earthquake activity must be represented by a series of source regions along the boundary with varying seismicity.

In the future it may be possible to represent source regions with varying activity.

The minimum size of a source region may be limited by the maximum credible earthquake. For example, an active fault region must be at least as long as the rupture length for the maximum credible earthquake.

5.1.3 An example of source zone quantification

A typical source zone, the New Britain Arc, is presented as an example of quantification of a source zone. The earthquakes within the zone were extracted from the catalogue (using the MapInfo GIS system). The catalogue had previously been declustered (independent mainshocks distinguished from dependent foreshocks and aftershocks), and the declustered listing was used for earthquake magnitude recurrence estimates.

A magnitude time plot was produced (Figure 22), and the catalogue completeness is estimated (considering seismograph coverage, and linearity of the earthquake magnitude recurrence plot) and represented by the blue line.

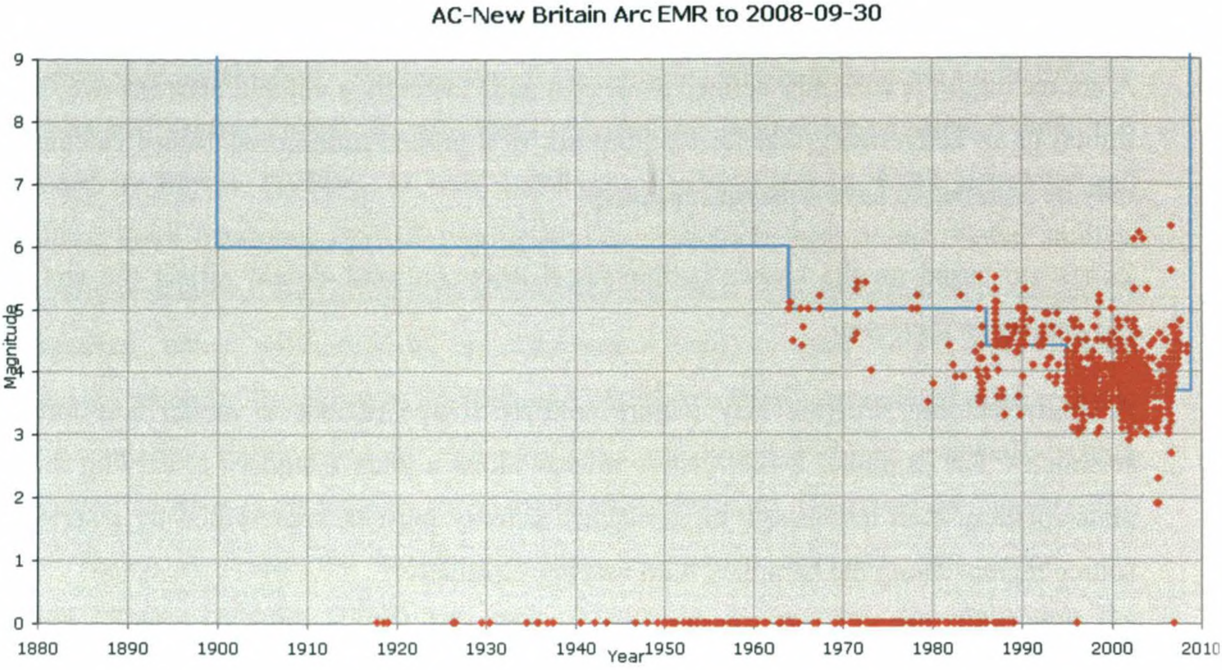

Figure 22: Magnitude-time plot for earthquakes in the New Britain Arc zone
The plot of magnitude against time for the known declustered earthquakes, with dependent foreshocks and aftershocks removed

The blue line indicates the threshold of magnitude coverage during time, and shows the better seismograph coverage during the later years, including the installation of local seismographs in the 1960s (most of which were removed by the early 1990s), and improvements to the global seismograph network in the mid 1980s and again in the mid 1990s. The lack of a local seismograph network limits complete coverage to above minimum magnitude 3.5.

From a risk perspective, this relatively high minimum magnitude of completeness is much less significant than the limitation of precision for earthquake locations that have been computed using global network data. In such a complex tectonic region, relying mainly on distant seismographs, there are random and systematic uncertainties of up to tens of kilometres in epicentre location, and considerably worse precision in depth estimates. A local seismograph network using a local seismic wave velocity model can reduce these uncertainties to less than 5 km, thus allowing delineation of active faults, which can then be included in the earthquake distribution model.

The earthquake magnitude recurrence plot for the New Britain Arc is shown in Figure 23. This is a plot of Nix, the number of earthquakes per year equal to or larger than magnitude x, against magnitude x. Nix values indicating the number of earthquakes in entire source region per year.

An alternative measure of earthquake activity is Axe, which is the number of earthquakes per year per 100 x 100 km., The Nix values depend on source region size so can't be compared (large zones have more earthquakes than small zones), but Axe values can be compared between zones.

The gradient of this plot gives the b-value (a measure of the proportion of small earthquakes to large) for the zone, which in this case is a very high value of 1.386.

In order to provide reasonable estimates of the gradient, at least 50 earthquakes are needed for each zone. Given the high level of activity in PNG, most of the defined zones have hundreds of earthquakes so the gradient is usually well defined. The New Britain Arc included 515 independent earthquakes (excluding dependent foreshocks and aftershocks which are assumed to give weaker motion than the independent mainshock) that are larger than the magnitude for complete coverage at the time they occurred. They range from the lowest magnitude of complete coverage of 3.5 up to the largest earthquake that has occurred during the period of magnitude 6.3. It is assumed that the maximum credible earthquake for the zone was 8.2.

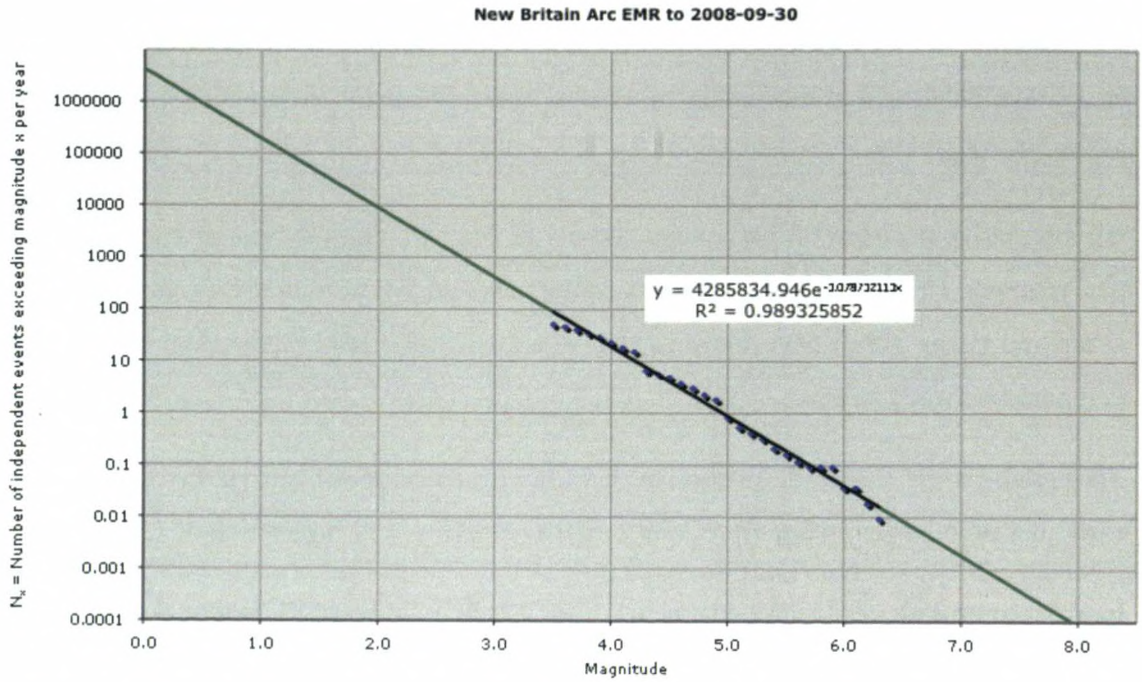

Figure 23: Magnitude recurrence plot for the New Britain Arc zone.

Table 2: Earthquake magnitude recurrence for the New Britain Arc zone.
This zone of model PNG1 used the earthquake catalogue to 2008-09-30. The zone covers 65,730 km^2. The gradient is represented by beta = 3.19, corresponding to b = 1.39.

	Events/year		Events/year /100x100km	Ret Period /100x100km (yr)	Ret Period for zone (years)
No =	4285833	Ao =	652036	0.0000015	0.0000002
N1 =	197167	A1 =	29996.6	0.0000333	0.000005
N2 =	9070.58	A2 =	1379.98	0.000725	0.000110
N3 =	417.287	A3 =	63.4851	0.0158	0.00240
N4 =	19.1971	A4 =	2.9206	0.342	0.052
N5 =	0.883151	A5 =	0.13436	7.44	1.13
N6 =	0.0406289	A6 =	0.00618118	162	24.6
N7 =	0.00186911	A7 =	0.000284362	3517	535

This process was repeated for every source zone for the seismotectonic model PNG1. At this stage the model PNG1 has a total of 120 zones in six depth ranges.

5.2 Earthquake Distribution Model, PNG1

Figure 13, page 65, showed earthquake distribution in PNG based on earthquakes in the period 1900-2008. Figure 14, page 66, showed magnitude 7 and 8 earthquakes in PNG and neighbouring regions in the same period, based on the ISC, USGS/NEIC and PMGO earthquake catalogues. The seismotectonic model PNG1 was developed based on these, and other available data.

Sections 5.3 to 5.8 show the divisions of the PNG region into seismic source zones at different depth zones of the PNG1 model for separate data analysis, but combined for the hazard analysis. The basis of the sub-division is differing tectonic environments rather than geographical or provincial boundaries, nor even national boundaries (Figure 24), although very much derived from checking against these different data sets. Seismicity, as well as geology, topography, gravity, geomagnetic data and other geophysical maps are utilised in determining the seismic zones, especially shallow depth shown in Figure 24. For other depth ranges Figure 27, Figure 29, Figure 31, Figure 33and Figure 35 were derived mainly by use of seismicity, because subduction zones were primarily delineated using earthquakes.

Situated in the region of active tectonism on the plate margin and evidenced by intense earthquake occurrence, the consequent high seismic hazard and related hazards such as landslides, floods, tsunamis and volcanic hazards, is expectedly significant. Closer look involving proper analysis of existing data has assisted quantified the earthquake hazard, at different zones at varying depth ranges.

It is seen from the work that earthquake distribution and patterns in the PNG region are well established. Most earthquakes occur along tectonic plate boundaries and along zones of plate deformation where stress had built up. As well, earthquakes associated with volcanic activity occur well away from the plate margins along volcanic arcs. It is known, though, that volcanic earthquakes and volcanic activity both occur as a result of tectonic forces in the earth.

5.2.1 Maps at depth layers

The seismotectonic model PNG1 was developed for the whole PNG region, based on the distribution of past earthquakes as well as from other data including regional geological and geophysical data. The model involves the division of the region into source zones. In the model the area or volume source zones and the active faults are each assumed to have uniform rates of seismicity. Based on available data, the zones are more detailed than those used in past studies.

As the earthquakes in the region occur at shallow, intermediate and at depths greater than 600 km, the model includes the division of the region into source zones at different depth ranges. The seismicity at different zones within different depth ranges are then analysed separately, but are combined to determine the hazard at specific sites. Model PNG1 consists of 6 layers with each having respective maps developed and these are shown in the following sections 5.3 to 5.8. In this region of varying tectonic trends evidenced by numerous lithospheric plates and differing plate boundaries, the discussions of possible findings for each depth layers and specific zones are treated as such. The b-values maps are shown in figures in the relevant sections, with the colour code red indicating low (0.7) and violet indicating high (1.4) values. High stress-release zones are being indicated by low b-values while high b-values indicate otherwise.

The earthquake hazard map in the region is then developed utilising the seismotectonic model and data analysis carried out, and the earthquake hazard determined. The earthquake hazard is recognized as significant, and proper determination of hazard parameters is required to update previous work as data now becomes available.

At this stage the model does not provide for the identification of active faults, and their relationships to occurrence of large earthquakes in recent times. However, the data for specific PNG locations are analysed, and the results are hereby presented systematically. The data is viewed in 2-dimension, though more correctly in depth layers, and therefore results for each layers discussed separately.

The model is intended to match and parallel regional geology and tectonics, including varying trends of plate boundaries. In particular where at locations the plate boundary is pure subduction and elsewhere not typically pure subduction, but includes a large amount of left lateral strikeslip faulting and extensional or a combination of thrust and strikeslip. In the entire region, left lateral shearing is dominating.

As well there are regions of seafloor spreading, connected by zones of transform faulting, and zones of continental rifting. Typically these zones would count as shallow depths as these are meant to involve only the crust, but with regions of greater depths or thicker crust. Often earthquake activity at depths exceeding crustal thicknesses will be associated with sinking lithospheric slabs, or segments of these. Like those defined by shallow seismicity, these zones are well defined but difficult to be checked against any other data unlike shallow depth seismicity.

It must be noted that many earthquake locations and depths are in error by tens of kilometres. At this stage all locations are used though, with the understanding that the individual events are confirmed to have occurred anyway.

5.3 Shallow Events, Depth range 0 to <35 km

Model PNG1 has forty-five seismic source zones which are identified for the shallowest of the depth ranges, crustal earthquakes for depths from the surface to 35 km, labelled by names representing localised geological or geographical features at respective locations. Earthquakes for this layer are shown in Figure 24, while the zone names are shown in Figure 25 and details listed in Table 3.

Future derivatives of the model will consider shallow earthquakes in three layers, A for upper crustal events, B for mid-upper crust events, C for lower crustal events.

Corresponding source zone earthquake recurrences were determined, especially at sites of settlement and sites of important national projects. Further iterations following the inclusion many more sites provided better resolution for the eventual hazard map that is expected to be the eventual result.

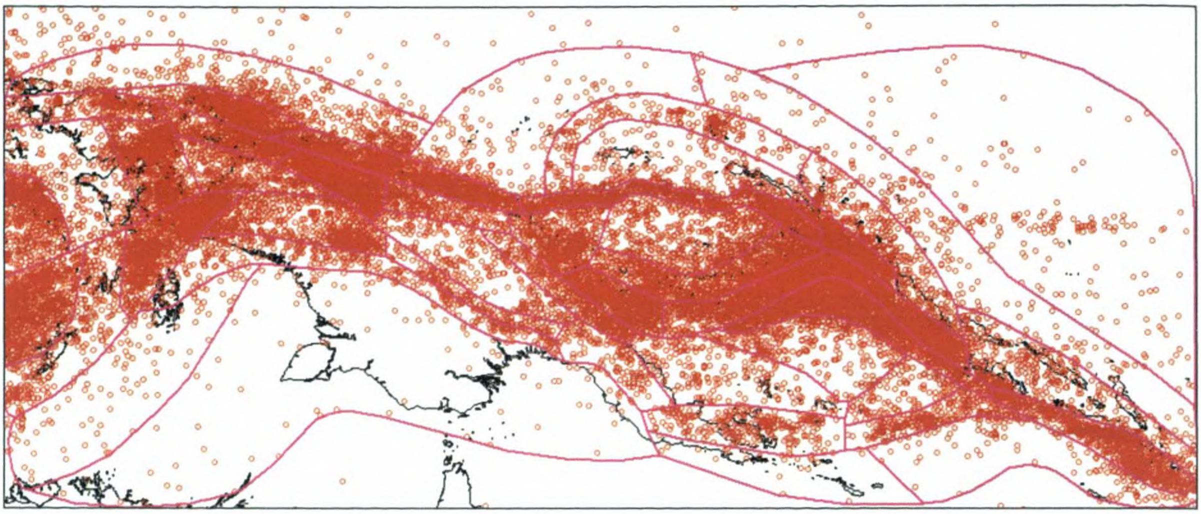

Figure 24: Area source zone earthquakes for depth range, 0 to 35 km.

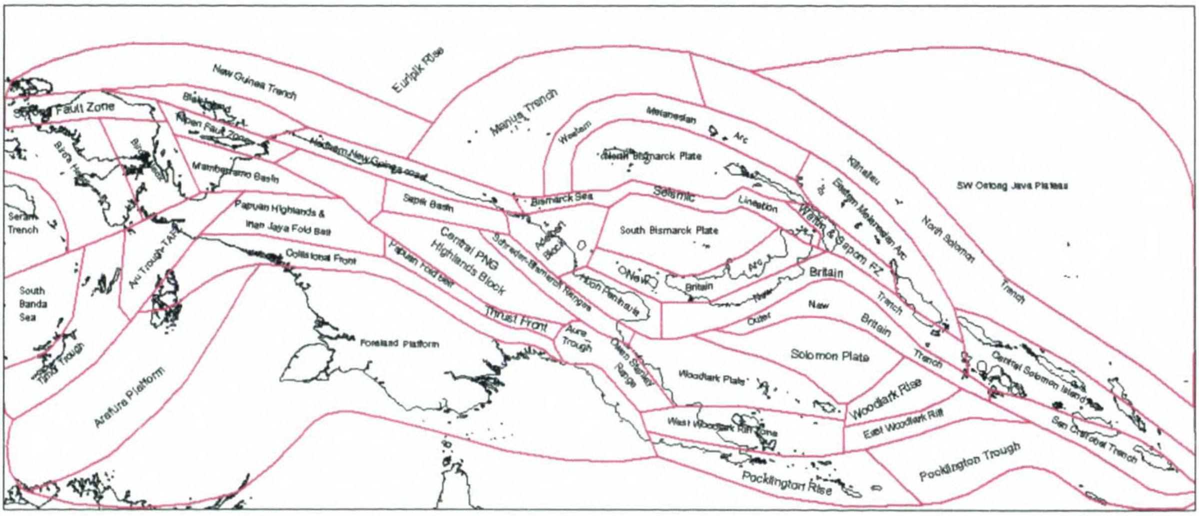

Figure 25: Area source zone names for shallow earthquakes, 0 to 35 km.

As is known, seismicity in this layer is mostly due to interaction of lithospheric plates along respective boundaries, and zones of crustal deformation region-wide. However, while some earthquakes within plates may be intra-plate some others may be mislocations (both in depth and hypocentre) as is typically what is expected in a region of poor seismic station coverage. Mislocated events are understood to be possibly widespread in all zones throughout the region.

The zones in this layer are also classed as either AB or AC, indicating those that have earthquakes occurring in intra-plate zones (in the range 2 to 20 km) and those in subduction zones (in the range 2 to 35 km) respectively. The zones that should have earthquakes occurring at the shallower depth include zones within the foreland platforms south and to the east of the PNG region, and within zones defining lithospheric blocks including the North and South Bismarck and Solomon Plates.

Table 3: Area source zones in PNG1 for shallow and crustal layers.

AB or AC	Source zone	R^2	b-value	Mmax	N5	M 6 Ret Period /100*100 km (yr)
AC	Adelbert Range Block	0.9882	1.0833	7.5	0.772919	62
AB	Arafura Platform	0.9505	0.9492	7.5	0.0525713	6577
AC	Aru Trough-TAFZ	0.9812	1.1379	8.0	3.88377	21
AC	Aure Trough-Owen Stanley Range	0.9524	1.0833	7.8	0.174225	290
AC	Biak Island	0.9548	1.2731	7.8	1.12066	65
AC	Bird's Head	0.9771	1.410	7.8	0.158826	1650
AC	Bird's Neck	0.9608	1.1398	7.8	1.74787	44
AB	Bismarck Sea Seismic Lineation	0.9841	1.0656	8.5	4.60495	12
AC	Central PNG Highlands Block	0.9224	0.9492	7.8	0.323052	218
AC	Central Solomon Island Arc	0.9829	1.3005	7.8	0.565942	361
AC	Collisional Front	0.9649	1.40	7.8	0.550	436
AC	Eastern Melanesian Arc	0.9873	1.40	7.5	0.230	877
AC	East Woodlark Rift	0.9740	1.40	7.8	1.0	96
AB	Foreland Platform	0.9804	1.2519	7.5	0.0660208	17639
AC	Huon Peninsula	0.9784	1.1578	8.0	1.46299	32
AC	Kilinailau-North Solomon Trench	0.9852	1.3735	7.8	0.10854	5498
AC	Mamberramo Basin	0.96297	1.030	8.0	0.637151	74
AC	Mamberramo Range	0.9785	1.3729	7.8	3.45637	22
AC	Manus Trench	0.95663	1.1365	7.8	0.258209	1074
AC	New Britain Arc	0.9890	1.38629	8.2	0.932132	172
AC	New Britain Trench	0.98577	1.0843	8.5	6.4523	16
AC	New Guinea Trench	0.97764	1.3967	8.0	0.955626	442
AB	North Bismarck Plate	0.9807	1.2025	7.5	0.264636	678
AC	Northern New Guinea Coast	0.96842	1.2791	8.0	6.29929	16
AC	Outer New Britain Trench	0.9933	1.0796	8.5	4.19941	18
AC	Papuan Fold Belt-Thrust Front	0.96945	1.0698	7.8	0.716341	45
AC	Papuan Highlands & IJ Fold Belt	0.98945	1.4192	7.8	1.85989	95

AC	Pocklington Rise	0.96848	0.80	7.5	0.053	1081
AC	Pocklington Trough	0.97445	0.9926	7.5	0.228676	580
AC	San Cristobal Trench	0.99335	1.1611	8.0	4.38185	18
AC	Schrader-Bismarck Ranges	0.943746	1.3363	7.8	0.179084	393
AC	Sepik Basin	0.96569	1.2127	7.8	0.717098	70
AC	Seram Trench	0.97963	1.40	7.8	1.50	79
AB	Solomon Plate	0.9797	0.9647	7.5	0.426446	176
AC	Sorong Fault Zone	0.97203	1.40	7.8	0.679999	149
AC	South Banda Sea	0.97759	1.40	7.5	1.50	101
AB	South Bismarck Plate	0.9800	1.4174	7.5	0.327386	716
AB	SW Ontong Java Plateau	0.9643	1.40	7.5	0.035534	48727
AC	Timor Trough	0.94175	1.2055	7.8	0.583929	234
AC	Weitin & Sapom FZ	0.98384	1.3648	8.2	1.10977	50
AC	Western Melanesian Arc	0.94631	1.1616	7.8	0.45901	262
AC	West Woodlark Rift	0.94895	1.2396	7.8	1.01419	122
AB	Woodlark Plate	0.9808	0.9279	7.5	0.233938	346
AC	Woodlark Rise	0.97007	1.2806	7.8	0.0779833	912
AC	Yapen Fault Zone	0.9332	1.0399	8.0	0.884358	36

Note that the coefficient of determination, R^2, for most zones is above 0.95, indicating a very good fit of the data, and reflecting the high rate of earthquake activity in PNG.

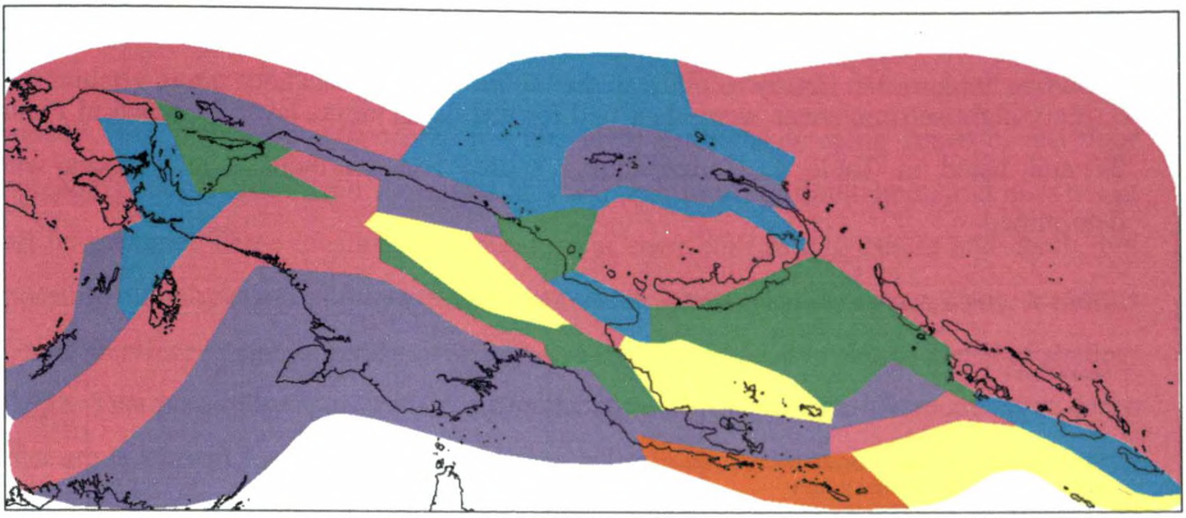

Figure 26: The b-value distribution for depths less than 35 km.

Map showing the distribution of b-value in the shallow layer throughout the region, from 0.8 (orange), 0.9 (yellow), 1.0 (green), 1.1 (blue), 1.2 (indigo) and 1.3 or higher (violet). The map is showing low stress patterns dominating, indicating high activity throughout.

5.4 Depth range 35 to <70 km

Twenty-eight seismic zones were identified for this depth range, layer 2, shown in Figure 27 and listed in Table 4. Corresponding source zone earthquake recurrences were determined.

Table 4: Area source zones in PNG1 for depths 35 to 70 km.

Source zone	R^2	b-value	Mmax	N5	M 6 Ret Period /100*100 km (yr)
Adelbert-Sarawaget-Finisterre Ranges	0.9832	1.2381	8.2	4.59175	24
Arafura Platform	0.9492	0.740	7.9	0.130889	896
Aru Trough-TAFZ	0.9689	1.40	7.9	1.49194	222
Bird's Head East	0.9716	1.40	7.9	0.849998	2547
Bird's Head West	0.8464	1.2323	7.8	0.0772179	2547
Bismarck Sea Seismic Lineation	0.9846	1.3743	7.8	0.942635	165
Bougainville Trench	0.98418	1.3937	8.5	10.0319	11
Cenderawasih Bay	0.92844	0.9711	8.0	1.10186	95
Central New Guinea Collisional Zone	0.95741	1.2142	7.9	1.10393	293
Central Solomon Island Arc	0.98493	1.0681	8.3	3.92643	17
East Melanesian Arc	0.98674	1.1793	7.8	0.53328	361
Mamberramo Basin	0.97187	1.40	7.9	2.79999	23
New Britain Trench	0.98958	1.40	8.5	8.49998	19
North Bismarck Plate	0.94051	1.40	7.8	0.224	2699
North NG-Bewani-Torricelli Ranges	0.9885	1.40	7.9	1.65	101
North Solomon Island Arc	0.97855	1.40	8.0	0.715693	345
Northern Solomon Plate	0.95547	1.0579	7.8	0.11296	322
OJP Front	0.8232	1.4	7.8	0.030107	26289
Outer New Britain Trench	0.9548	1.4	8.0	1.1886	117
San Cristobal Trench	0.9546	0.9382	8.5	0.116498	427
Sepik Basin	0.9695	1.2352	7.9	0.666809	153
Seram Trench	0.9802	1.4	8.0	3.1	114
South Bismarck Plate	0.9566	1.4	7.8	0.610377	659
Weitin-Sapom FZ	0.9879	0.9667	8.2	3.6681	3
West Papuan Highlands	0.94123	1.2720	7.9	0.493263	210
West Woodlark Rift	0.9882	1.3890	7.9	0.533455	433
Woodlark Plate	0.9113	1.40	7.8	0.17	1067
Woodlark Spreading Centre	0.9666	1.40	7.8	0.186792	1050

The seismicity in this layer is mostly associated with activity along plate boundaries, particularly along subduction zones, but not along zones of crustal deformation associated mostly with plate convergence. Within this layer earthquakes along zones of sea-floor spreading should strictly not show. But they are seen to occur throughout, and may not at all be genuine. These locations are therefore in error both in hypocentre and depth, but possibly more by depth as they are occurring within known shallow zones. These locations could therefore be appropriately used in the analysis in respective source zones of shallow depth. That possibility is not considered in the current work though. There are some zones that are too broad for what they should appropriately be, for instance the North Bismarck Plate, Central New Guinea Collisional Zone, the zones of the Foreland Platform and Ontong Java Plateau. It is not also certain the seismicity of the South Bismarck and Solomon Plates, earthquake locations and depths and whether the data could be well suited for use in shallow source zones.

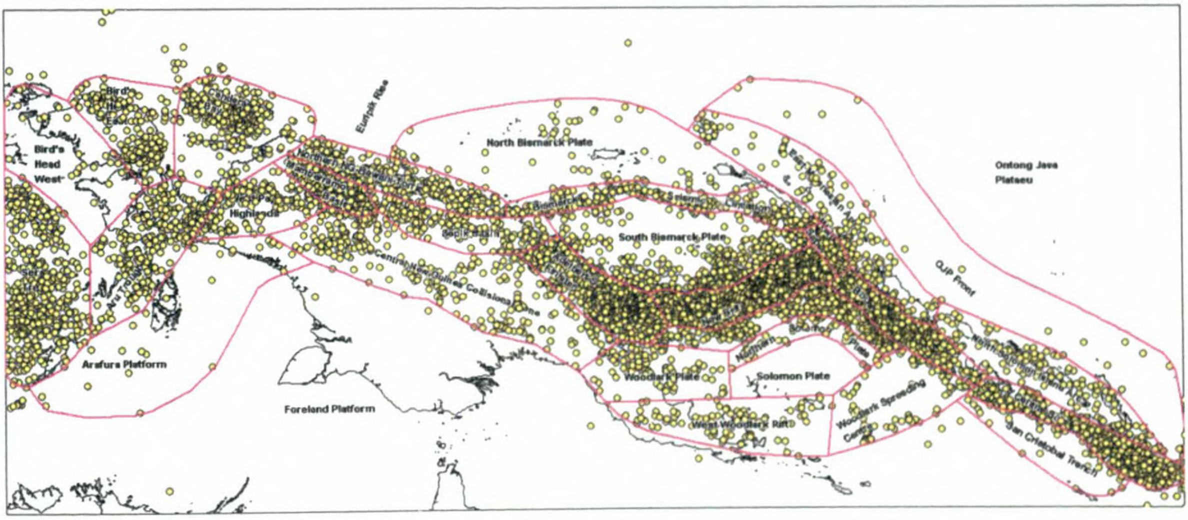

Figure 27: Area source zones in PNG1 for depths 35 to 70 km.

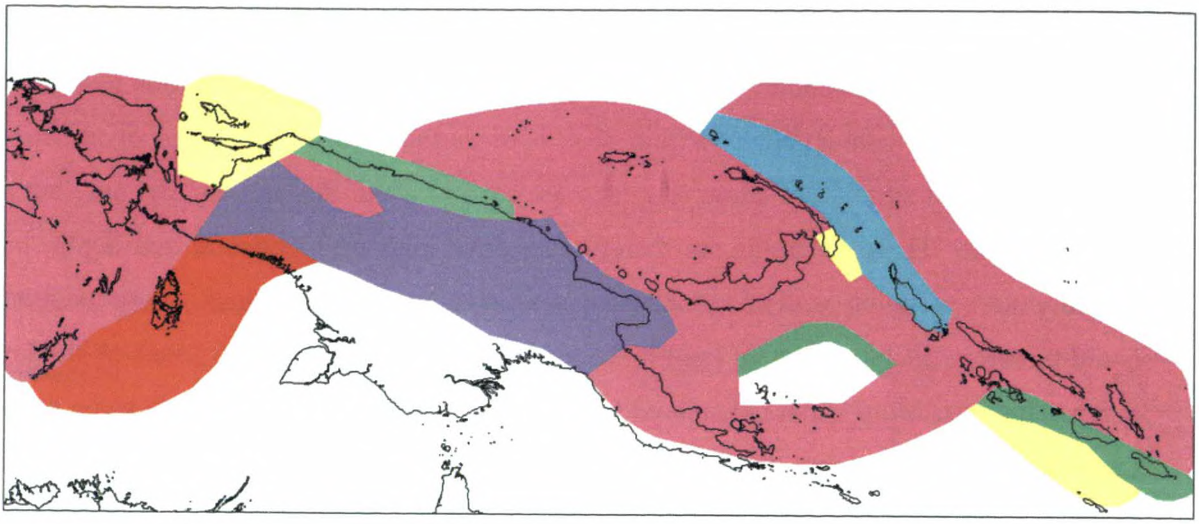

Figure 28: The b-value distribution for depth range 35 to 70 km.
Coded 0.7 (red), 0.9 (yellow), 1.0 (green), 1.1 (blue), 1.2 (indigo) and 1.3 or more (violet).

5.5 Depth range 70 to <150 km

Twenty seismic source zones were identified for this next depth range, shown in Figure 29 and listed in

Table 5, and the b values in Figure 28. For each source zones, corresponding earthquake recurrences were determined.

Again many of the source zones may have been taken too broad than what they could rather be, for instance the Euripik Rise-North Bismarck Plate. Seismicity here and that within the South Bismarck and Solomon Plates are possibly with error in both location and depth. Some locations could well be intra-plate events although mostly unlikely, particularly within zones at these depths.

The main seismic zones are clearly seen to trend the main subduction zones from the southeast in the Solomon Islands to New Britain, and then southwest to eastern New Guinea, and westward to Papua along central/northern New Guinea (Figure 29). Ruptures of huge lengths are possible along these main seismic zones, in both lateral and vertical directions. This implies possible large events originating from intermediate depth.

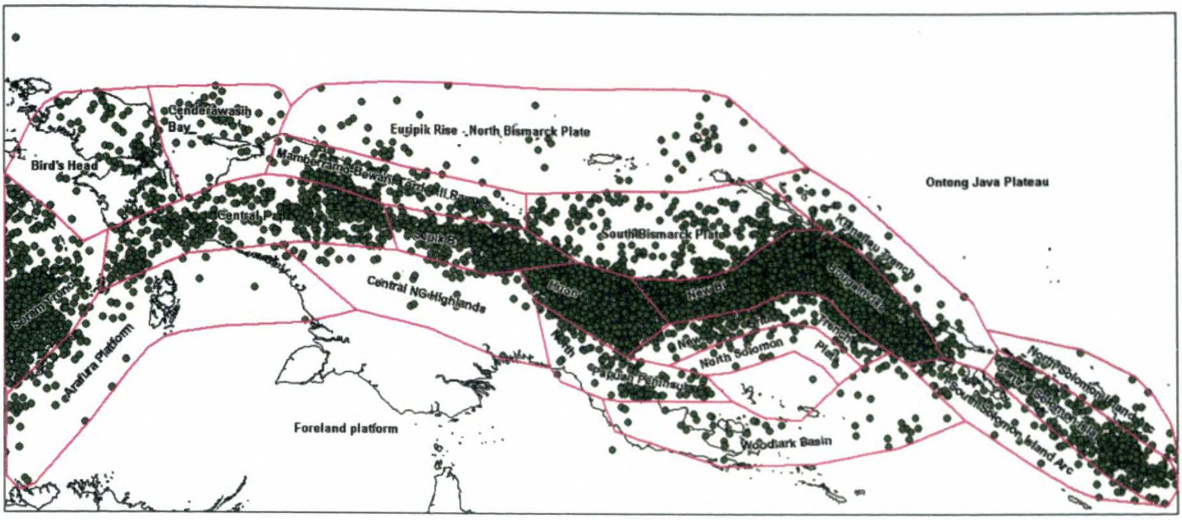

Figure 29: Area source zones in PNG1 for depths 70 to 150 km.

Table 5: Area source zones in PNG1 for depths 70 to 150 km.

Source zone	R^2	b-value	Mmax	N5	M 6 Ret Period /100*100 km (yr)
Arafura Platform	0.96915	1.1364	7.5	0.0782839	4653
Bird's Head	0.9550	1.40	7.5	0.085799	6359
Cenderawasih Bay	0.8368	1.40	7.0	0.062677	4683
Central New Guinea Highlands	0.90834	0.8717	7.5	0.116208	1014
Central Papua	0.9790	1.2536	7.5	0.837921	353
Central Solomon Island Arc	0.98127	1.4000	7.5	2.19	100
Euripik Rise-North Bismarck Plate	0.88628	0.8009	7.5	0.237229	1131
Huon Peninsula	0.96482	1.40	7.5	2.8	67
Kilinailau Trench	0.96553	1.2145	7.5	0.127784	1475
Mamberramo-Bewani-Torricelli Ranges	0.94343	1.40	7.5	0.88424	283
New Britain-Bougainville Arc	0.98923	1.40	8.0	7.01301	55
New Britain Trench	0.97147	1.40	8.0	0.1541	1186
North Papuan Peninsula	0.93225	1.1434	7.5	0.357698	303
North Solomon Island Arc	0.9303	1.1999	7.5	0.0610813	1863
North Solomon Plate	0.9131	1.1117	7.8	0.00637323	10305
Sepik Basin	0.98304	1.3110	7.8	1.63657	90
Seram Trench	0.981384	1.40	7.5	3.55342	90
South Bismarck Plate	0.9834	1.40	7.5	0.2	2419
South Solomon Island Arc	0.926362	0.8755	7.5	0.153036	432
Woodlark Basin	0.9463	1.3896	7.5	0.0592355	7982

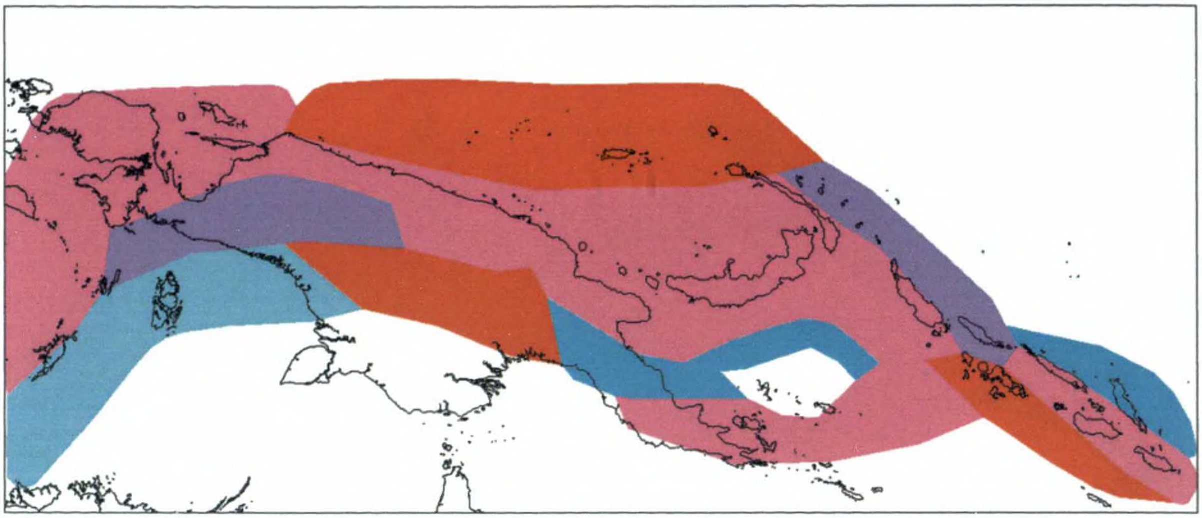

Figure 30: The b-value distribution for depth range 70 to 150 km.
Coded 0.7 (red), 0.9 (yellow), 1.0 (green), 1.1 (blue), 1.2 (indigo) and 1.3 or more (violet).

5.6 Depth range 150 to <300 km

Fifteen seismic source zones were identified for this next depth range, layer 4, shown in Figure 31 and listed in Table 6. Corresponding zone earthquake recurrences were determined. While the main seismic zones are defined, much more seismicity is yet noted to scatter randomly in zones not expected. Again, locations and depths are possibly in error by tens of kilometres. Earthquakes outside the main zones in this layer could easily be included in nearby and adjoining zones, where the events probably occurred, rather than where they were probably mislocated. Large events are possible from ruptures of huge lengths, especially at subducting zone interfaces.

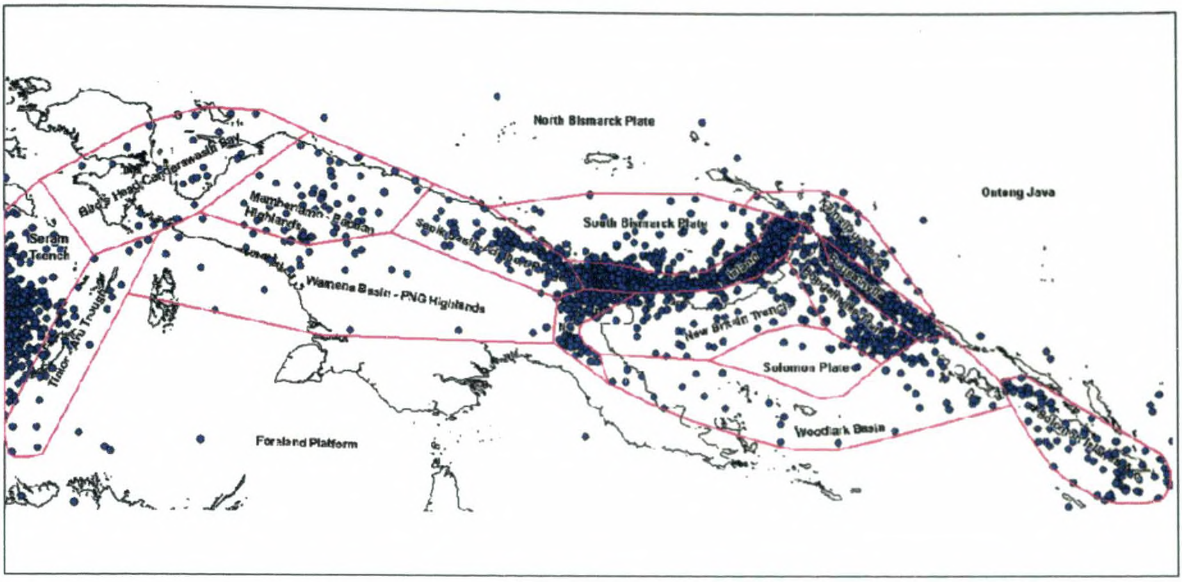

Figure 31: Area source zones in PNG1 for depths 150 to 300 km.

Table 6: Area source zones in PNG1 for depths 150 to 300 km

Source zone	**R^2**	**b-value**	**Mmax**	**N5**	**M 6 Return Period /100*100 km (yr)**
Bird's Head-Cenderawasih Bay	0.9343	0.9304	7.0	0.0293039	5814
Bougainville Island Arc	0.9698	1.4000	7.5	0.874039	2167
Bougainville Trench	0.97068	1.4000	7.8	0.073000	92
Eastern New Guinea	0.98364	1.2869	7.8	0.345643	168
Kilinailau Trench	0.96917	1.3169	7.5	0.200704	626
Mamberramo-Papuan Highlands	0.93766	1.3925	7.5	0.038156	9602
New Britain Island Arc	0.9737	1.3828	8.0	4.510260	31
New Britain Trench	0.97927	1.3139	8.2	0.056587	4806
Sepik Basin-Adelbert Range	0.957111	1.1923	7.5	0.199964	732
Seram Trench	0.971455	1.4000	7.8	0.777199	342
Solomon Island Arc	0.96415	1.3584	7.8	0.094030	2432
South Bismarck Plate	0.96008	1.1257	7.5	0.068660	3023
Timor-Aru Trough	0.937972	0.8107	7.5	0.039431	1816
Wamena Basin-PNG Highlands	0.900668	1.4000	7.5	0.015108	52331
Woodlark Basin	0.9272	1.4000	7.0	0.015610	34146

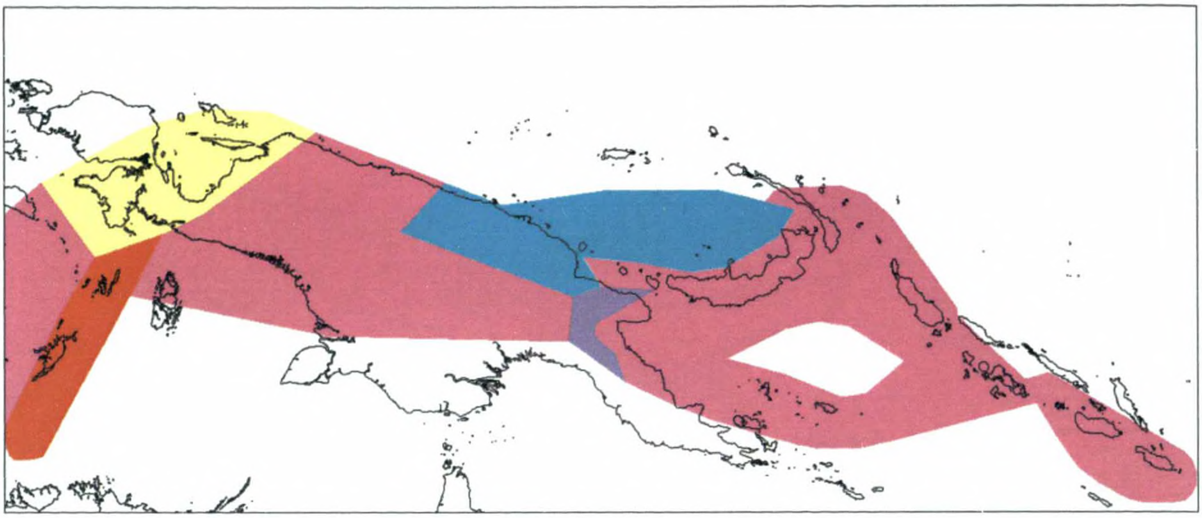

Figure 32: The b-value distribution for depth range 150 to 300 km.

Coded 0.7 (red), 0.9 (yellow), 1.0 (green), 1.1 (blue), 1.2 (indigo) and 1.3 or more (violet).

5.7 Depth range 300 to <500 km

Seven main seismic source zones can be identified with this depth range, layer 5, shown in Figure 33 and listed in Table 7. The zones are most possibly associated with the segments of the Solomon Plate lithospheric slab, beneath New Guinea Highlands, north New Britain and Bougainville, and the Solomon Islands. The zone in the west is possibly indicative of the activity associated with subduction at the Seram Trench.

The earthquake hazard determined may not be significant, and negligible, and would not have any effect on the hazard determined for zones within shallower layers. Further, earthquake locations and depths are expected to be in error by tens of kilometres. It is not certain if intra-plate earthquakes are possible at great depths, apart from those events expected where sinking segments of lithospheric slabs are encountering the upper mantle. Large events are possible from within this depth range laterally or vertically.

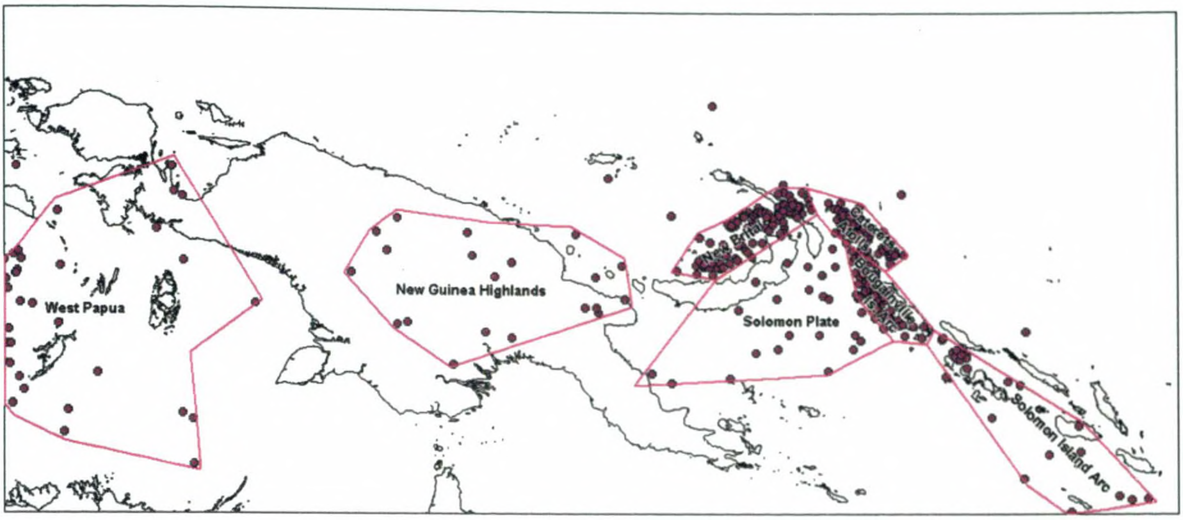

Figure 33: Area source zones in PNG1 for depths 300 to 500 km.

Table 7: Area source zones in PNG1 for depths 300 to 500 km.

Source zone	**R^2**	**b-value**	**Mmax**	N5	**M 6 Return Period /100*100 km (yr)**
Bougainville Island Arc	0.97299	1.3280	8.0	0.481082	161
Cataret Atolls	0.9799	1.2847	7.5	0.298315	214
New Britain	0.96064	1.3298	8.0	0.20267	635
New Guinea Highlands	0.9106	1.40	7.5	0.0039	188133
Solomon Island Arc	0.942996	1.40	8.0	0.05641	6060
Solomon Plate	0.82821	1.2837	7.8	0.011571	37768
West Papua	0.97061	1.3876	7.5	0.0034553	358834

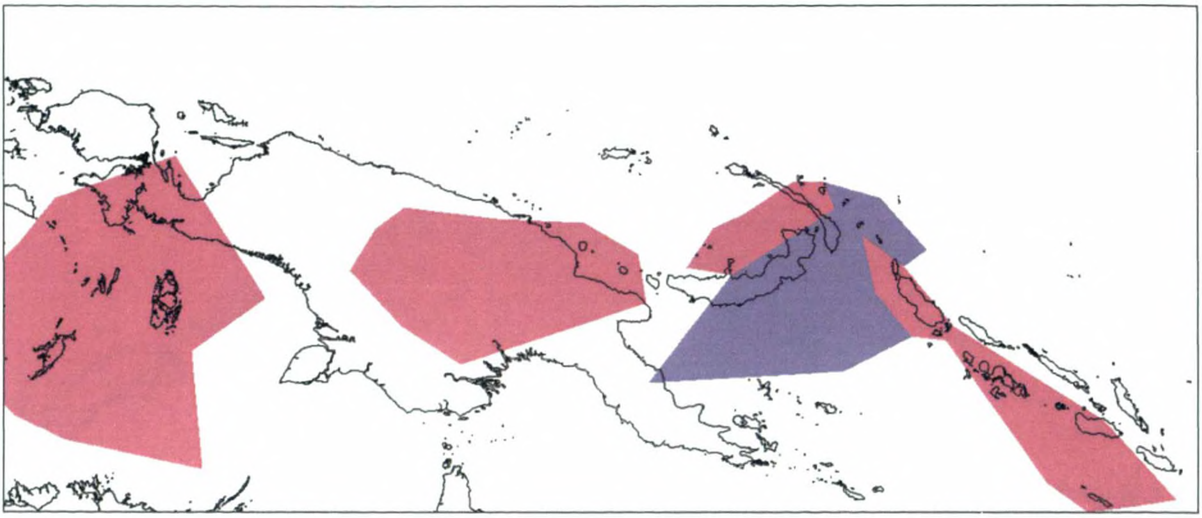

Figure 34: The b-value distribution for depth range 300 to 500 km.

Colour codes are same as those of the upper layers; indigo indicates value 1.3 and violet 1.4.

5.8 Depths greater than 500 km

Five seismic source zones are identified within this last and deepest of the layers, layer 6, shown in Figure 35 and listed in Table 8. The zones possibly indicate associated lithospheric slab segments of the subducting Solomon Plate beneath New Britain, Bougainville and the Solomon Islands, and the subduction at the Seram Trench in the west, possibly of the Banda Plate. It is not certain what the sources of seismicity beneath the New Guinea Highlands and Solomon are due to. At depth the seismicity may be associated to forces exerted on the sinking Solomon Plate, or segments of, as it falls away and assimilates into the mantle at respective locations.

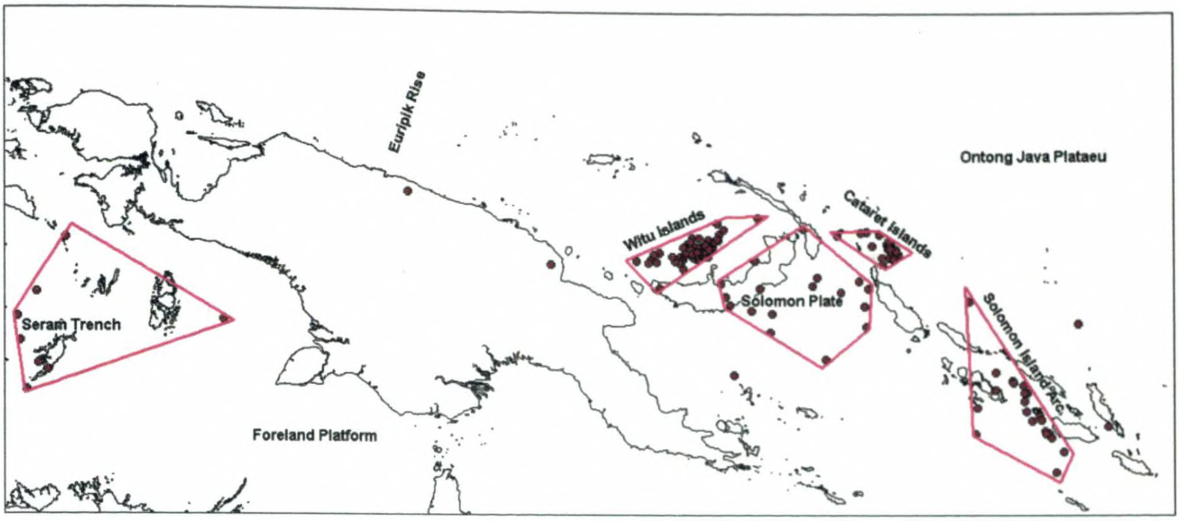

Figure 35: Area source zones in PNG1 for depths greater than 500 km

Some earthquakes may have been located with large errors, either in the epicentre or depth, and are not within the defined source zones. It is known that poor seismic network coverage in the region has resulted in huge errors in hypocentral and magnitude determinations. It is also noted that the current earthquake catalogue does not list any event larger than magnitude 6.0 at depth greater than 500 km. It is however known from other regions of subduction that large sized magnitude earthquakes are possible, and zones listed here are possible sites of larger events. Rupture propagation is possible in any direction, but most likely upwards, as this depth is basically the deepest known depth range.

Table 8: Area source zones in PNG1 for depths greater than 500 km.

Source zone	**R^2**	**b-value**	**Mmax**	**N5**	**M 6 Return Period /100*100 km (yr)**
Cataret Atolls	0.9526	0.9096	7.5	0.0863857	141
Seram Trench	0.9197	0.7000	7.5	0.0177087	4995
Solomon Islands	0.9026	0.9403	7.5	0.0833928	4532
Solomon Sea	0.901904	0.8039	7.5	0.0177833	586
Witu Islands	0.950634	1.2310	7.5	0.209953	301

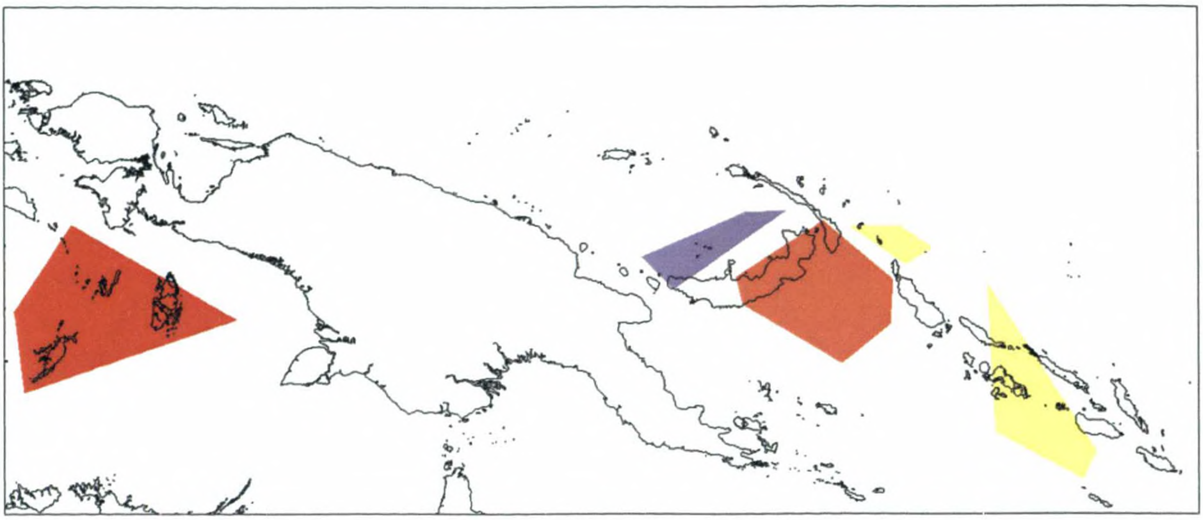

Figure 36: The b-value distribution for depths greater than 500 km.

Red denotes value 0.7, orange denotes 0.8, yellow denotes 0.9 and indigo denotes 1.2.

Chapter 6 Ground Motion Models

Earthquake shaking is enhanced and wave amplitude attenuation at local sites complicated by the complicated tectonic structural fabric involved. Numerous tectonic blocks co-exist with zones of lithospheric slab contortions and detachments, as well as zones of crustal extensions and folds-and-thrusts accommodating compressions resulting in crustal deformation. Additionally, valleys overlain by sediment accumulation readily alleviate amplification of seismic wave energy, posing threat to infrastructure and population. As noted from the few operated accelerographs in the past, hilly topography has resulted in accelerations that are abnormally high, as high as ten times that of nearby firm foundations.

As a result detail localised studies and dense seismic station networking, and in particular strong motion recordings are required to appropriately determine attenuation functions for individual local sites – in the region geological heterogeneity having known to dominate. Consequently, no one attenuation relationship is envisaged to work appropriately for the whole region (Ripper, 1992).

Seismic acceleration attenuation relationships for the entire PNG region were derived from the analysis of a few accelerograms available and synthesized with the distribution of seismicity, regional geology and tectonics of the region to produce new maps of seismic zoning. The resultant maps closely matched the distribution of shallow seismicity and regional geology. In determining the attenuation relationships for sites, it is important to take in to account such factors as wave path, topography and geological conditions.

6.1 Earthquake path

Earthquake wave energy transmitted from source to recording sites under go refraction, reflection, or both at interfaces it encounters along the transmission path. In general energy easily becomes dissipated in unconsolidated surface regions, thus reducing the intensity of earthquake shaking at location further along the transmission path.

The tectonic structural fabric of the PNG region very is complex; varied and particular for specific localities and therefore no simple horizontally layered structure exists as might be expected in a mid-oceanic or mid-continental environment. Present are structures as much vertical as horizontal, with sloping structures such as subducting lithospheric plates as well.

Wadati-Benioff zones defined by subducting lithosphere exists the entire New Britain and Bougainville regions, from the New Britain Trench in the Solomon Sea to regions of the eastern Bismarck Sea, southern New Ireland and vertically beneath Bougainville respectively. Lithosphere here is being evidenced by earthquakes to depths of more than 600 km at various localities.

The subducting Solomon Plate lithosphere is underlying different transform plate boundaries at three different places. On southern New Ireland, the northwest trending Weitin Fault has been suggested to mark the boundary of the South Bismarck and Pacific Plates. Deeper earthquakes in the region of central New Ireland are indicating the subducting Solomon Plate lithosphere.

The Ramu-Markham lineament is the collision suture of the India-Australia and South Bismarck Plates, indicated by shallow depth earthquakes. Here the India-Australia Plate front is extending downward from the surface, beneath Huon Peninsula. As well as subducting northward beneath New Britain, the Solomon Plate is also subducting beneath the volcanic islands north of the Huon Peninsula. The crest of the lithospheric arch formed plunges to the northwest beneath the Ramu-Markham lineament and the Huon Peninsula where it is being indicated at intermediate depths. Milson (1981) suggested that the Huon Peninsula is a shallow thrust having slid about 50 km southward from its original position in line with New Britain on the volcanic arc.

The Solomon Plate lithospheric slab also dips southward beneath the Papuan Peninsula, along the less active Trobriand Trough. The Owen Stanley Range Fault system further south may be a suture zone, accommodating continental rifting that is ongoing further southeast along the Peninsula (Ferris *et al.*, 2006).

As an illustration of the effect of transmission path, Ripper (1992) gave example of earthquakes that have occurred near Madang at different depths. It is suggested that sloping lithospheric slabs channelled up energy from the deep earthquake more effectively. A magnitude 7.0 earthquake, which occurred at a depth of 42 km, recorded an acceleration of 0.079g at Yonki, while a magnitude 6.6 earthquake at the same place but at a depth of 189 km recorded an acceleration of 0.14g.

6.2 Site topography and foundation conditions

The effect of topography on accelerograph recordings for sites in close proximity (a few kilometres) on different foundations and in different topography have revealed differences in the ratios of maximum accelerations, sometimes exceeding 10:1. This has been a direct result of hills and embankments unsupported laterally, and unconsolidated or thick soil covers have given rise to amplified ground accelerations.

Four classical examples exist of sites in close proximity with differing recordings, a direct result of topography and foundation conditions. Ripper (1992) identified differences 4.5 times in horizontal accelerations at two close sites in Musa, Papuan Peninsula. The sites are on alluvium on top of a hill and on bedrock respectively. Gaull (1974) determined that both the effects of site foundation and topographical differences have to account for the acceleration difference.

Close sites at Yonki have had differences of about 5 to 10 times (Ripper, 1992). These have been a direct result of accelerographs being sited on alluvium near the edge of the river valley compared to site at river level on bedrock; or sites lower than 45 m below on conglomerate compared to sites on bedrock.

Comparing recording sites in Rabaul, Ripper (1992) documented differences of 9 times for sites on bedrock foundations. The hilly topography for one site on a hill 160 m above the other was concluded to be effect.

Also on the Gazelle Peninsula at Warangoi sites in close proximity, on the edge of a 7 m high conglomerate rock bank compared to a site on a thin soil cover over volcanic ash, respectively resulted accelerations differing about two times (Ripper, 1992).

6.3 Attenuation relationships for PNG

No single acceleration attenuation relationship, or ground motion model, uniquely describes all recorded earthquake accelerations, in PNG or at any other place. The ground motion depends on many factors other than just magnitude and distance, including source parameters (mechanism, stress drop), travel path (absorption, scattering), and site effects (at least 8 factors including impedance amplification, enhanced absorption, resonance, scattering, basin effects, topography effects). However, Ripper (1992) made suggestions of several relationships that suit some condition situations of PNG. These include a relationship by Denham *et al.* (1973), which was based on Yonki and Panguna data and relates to hilly topography and a thick overburden; with an alternative relationship for slant distances shorter than about 50 km. Available also are the firm ground relationships of Esteva and Villaverde (1973), and Fukushima and Tanaka (1990) developed in Japan for use on situations of hard to medium soil types.

For PNG hilly topography in coastal areas as well as inland sites where the topography is hilly as well as mountainous must be differentiated from the sites of bedrock with no soil cover. Differences also account for sites on hilly terrain near the coast.

Further, close earthquakes are the most potentially damaging, especially earthquakes of large magnitudes occurring within several kilometres. Ripper (1992) documented accelerations at Yonki and Kandrian that were recorded at close epicentral distances. Yonki has a special significance because of its close proximity to the South Bismarck, Solomon, India-Australia Plate triple junction. McCue (1981a) documented the fault plane analyses of an almost vertical nodal plane for the magnitude 5.9 Kandrian earthquake of 01 November 1976, which caused an acceleration of 0.29g, and suggested that Kandrian was probably much closer to the fault plane than the slant distance to the focus suggested.

As well, recent surface faulting or uplift, indicative of a fault plane breaking through or coming close to the surface, would be indicative of high local accelerations from the causative earthquakes. Only seven earthquakes have been reported to have caused permanent surface effects or to have occurred on a surface fault system, as discussed earlier.

There have been two significant developments in ground motion modelling in recent years. A special edition of Seismological Research Letters in 1997 (volume 68, no 1) included descriptions of a wide range of attenuation functions, applicable in a range of tectonic environments. Unfortunately, the coverage of subduction regions was limited, and the published functions proved inappropriate for distances beyond about 200 kilometres, which in fact resulted in over-estimate of motion. These functions were replaced by subduction attenuation functions published by Atkinson and Boore (2003).

The second major development began in 2005 with the Next Generation Attenuation (NGA) project. At first the focus was on earthquakes in western USA, and the results were published in 2008. The NGA functions used considerably better data than was used to produce the 1997 functions. The results proved better at extremes (near and far earthquakes, small and large earthquakes, short and long period motion). The functions defined spectra at more periods, so plots were smoother, and interpolation more reliable. Different research teams developed more consistent functions compared to those than in 1997.

One aspect of the NGA project is that greater emphasis has been placed on earthquake source effects and site effects, apart from simple travel path attenuation of motion with distance. Because of this, the NGA functions are being described as ground motion models, rather than attenuation functions.

It is anticipated that NGA functions will be produced for stable continental regions (central and eastern USA) in the next few years. Although NGA functions for subduction regions will be developed in the future, there is relatively little data available and so this will be more difficult.

For the purposes of this preliminary study, a typical NGA has been used for crustal earthquakes (apart from shallow events related to subduction). This function is by Chiou and Youngs (2008), and is a development of the function by Sadigh *et al.* (1997). The functions used for subduction events are those published by Atkinson and Boore (2003), for interplate and intraslab earthquakes (where relevant).

For future studies it is hoped that local PNG ground motion models will eventually be determined. In the meantime, it is likely that other functions may be used, or multiple functions used and the results averaged. It is quite easy to compute ground motion recurrence using PNG1 with alternative ground motion models. Each full computation run takes about two to three hours with the current simplified ground motion models, so experimentation with other functions will be very time consuming.

Chapter 7 Ground Motion Recurrence Results

As seen, source zone map for model PNG1 near surface seismic zones (to depth of 35 km) was developed with added constraints from regional geology, geophysics and geodesy; as well as topography and from the work of many others. Five additional layers are used to specify the distribution of deeper earthquakes. The seismic hazard determined for these zones at deeper layers may not be significant and won't affect the overall hazard, particularly the significant hazard contribution from those zones in the shallower layers at respective locations of interest.

Having quantified the seismicity however, the process must now involve the specification of the ground motion from earthquakes as a function of distance, magnitude and other parameters - to determine the seismic hazard.

The final stage in the method is to compute spectral ground motion recurrence by integrating the probabilities of motion from all earthquakes in space (longitude, latitude and depth), magnitude (from negligible to maximum credible), and frequency of motion. This stage involves complex integration thus requiring the use of commercial software FRISK program. This computed the spectral ground motion recurrence at a point. The processing time per point depend on the complexity of the seismotectonic and attenuation models.

The more sites there are included in the data analysis, the better the resolution it is to produced the hazard map. The first run of model PNG1 was its' application to the cities and towns of Port Moresby, Lae, Kokopo, Madang, Buka, Wewak, Kimbe and Honiara. The source zones in respective layers used for the determination of seismic hazard at individual sites are extracted from Table 3 to Table 8.

For each sites considered here, the determinations were based on magnitude 5.0 earthquakes and larger, and incorporate all source zones that are within 300 km of the sites. Determined were the PGA as a function of return period, uniform probability response spectra for selected return periods, and the magnitude-distance deaggregation for motion determined in return periods. Seismic hazard contributions at respective sites are also determined.

7.1 Port Moresby

Seismic zones of the six layers of the PNG1 seismotectonic model of 500 km within Port Moresby were combined in the analysis to determine the hazard. The parameters of the source zones were extracted from Table 3 to Table 8.

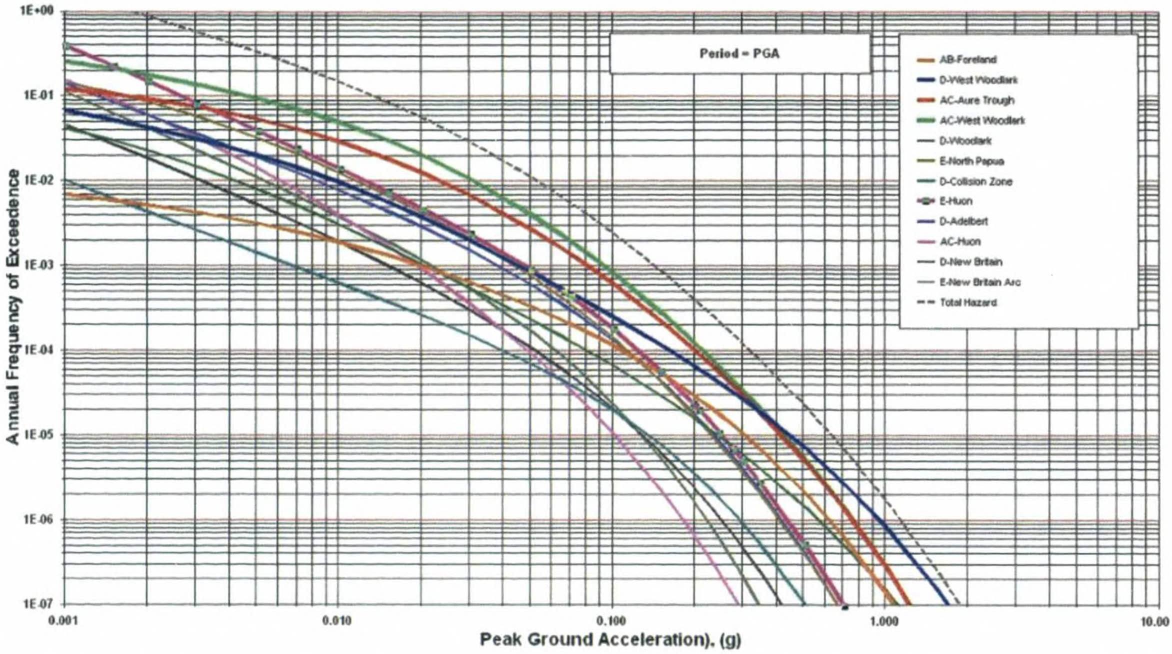

Figure 37: Source zone contributions for Port Moresby ground motion.
This plot gives contributions for peak ground acceleration.

Port Moresby lies south of the fringes of the main seismic zones of PNG and so the contributions of the hazard are those originating mostly from shallower layers, and to the north, east and west. However, the Capital City is often shaken, especially on the top floors of high rises, by earthquakes occurring deep beneath northeastern New Guinea and southwestern New Britain. These are distances more than 300 km away. To the south is the stable and inactive Australian craton, where the hazard is non-existence. Australia is known for its' shallow intra-plate earthquakes though, and this must be given some consideration to zones on the craton, especially those bordering the foreland platform.

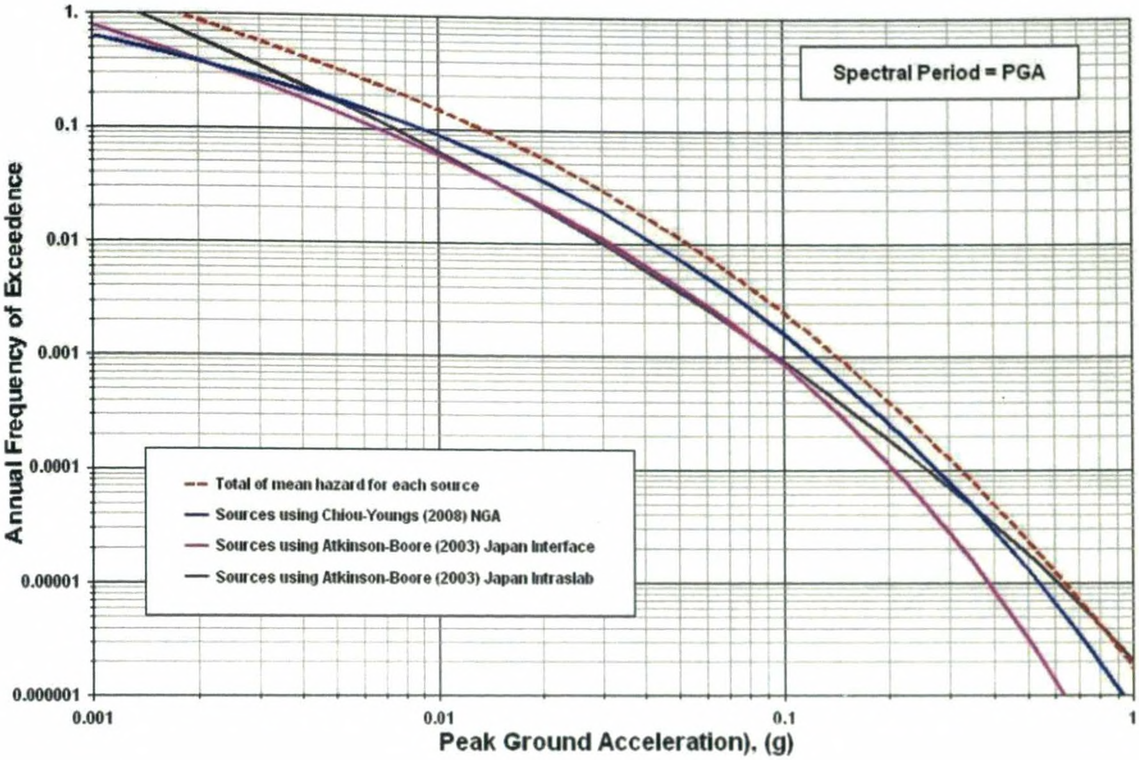

Figure 38: PGA recurrence for Port Moresby.

This is for bedrock motion, considering magnitudes 5.0 and higher.

Figure 38 shows that the high-frequency peak ground acceleration at Port Moresby is dominated by hazard contributions from shallow or crustal seismic zones using the attenuation of Chiou-Youngs (2008), but higher accelerations may be originating from the intra-slab zones, using the attenuation function of Atkinson-Boore (2003).

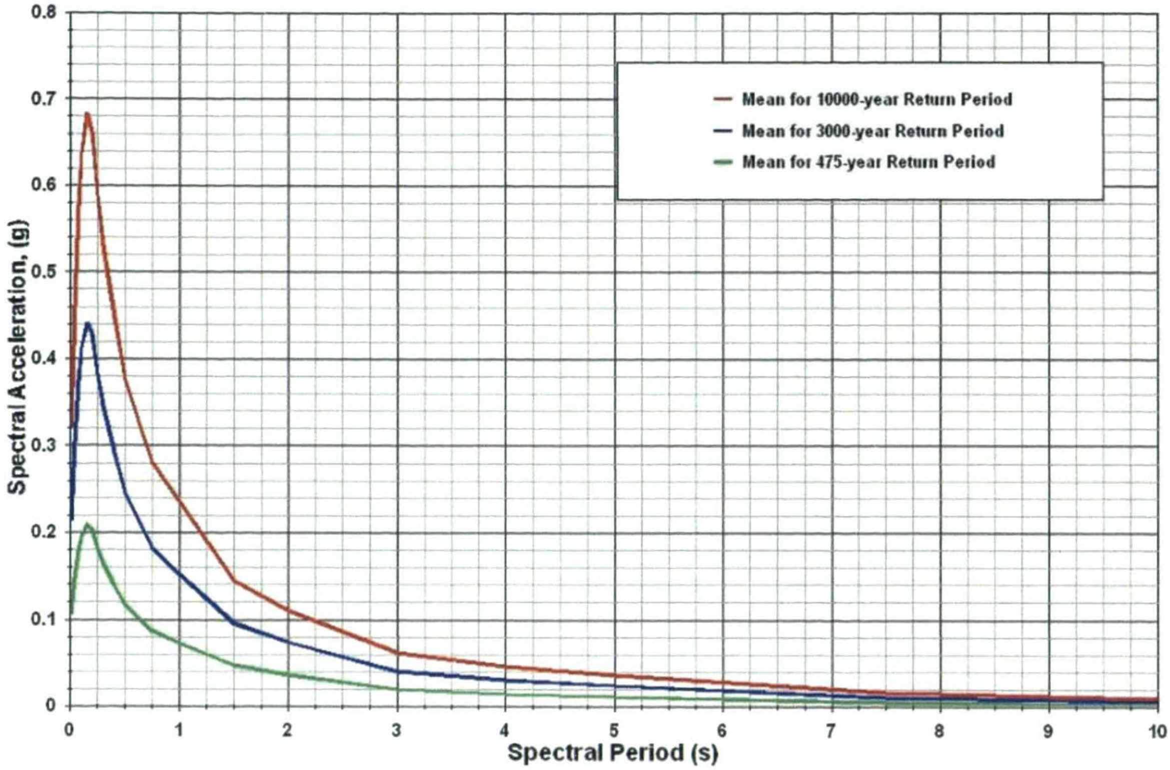

Figure 39: Response Spectra for Port Moresby.

Figure 39 shows the uniform probability response spectra at Port Moresby for return periods of 475 years, 3000 years and 10,000 years, for bedrock, and using magnitudes from 5.0. The peak ground acceleration is numerically equal to the response spectral acceleration at near zero period, or all the left-most points on each of the plots. The spectra for other return periods can be found by re-calculation, or approximately by interpolation.

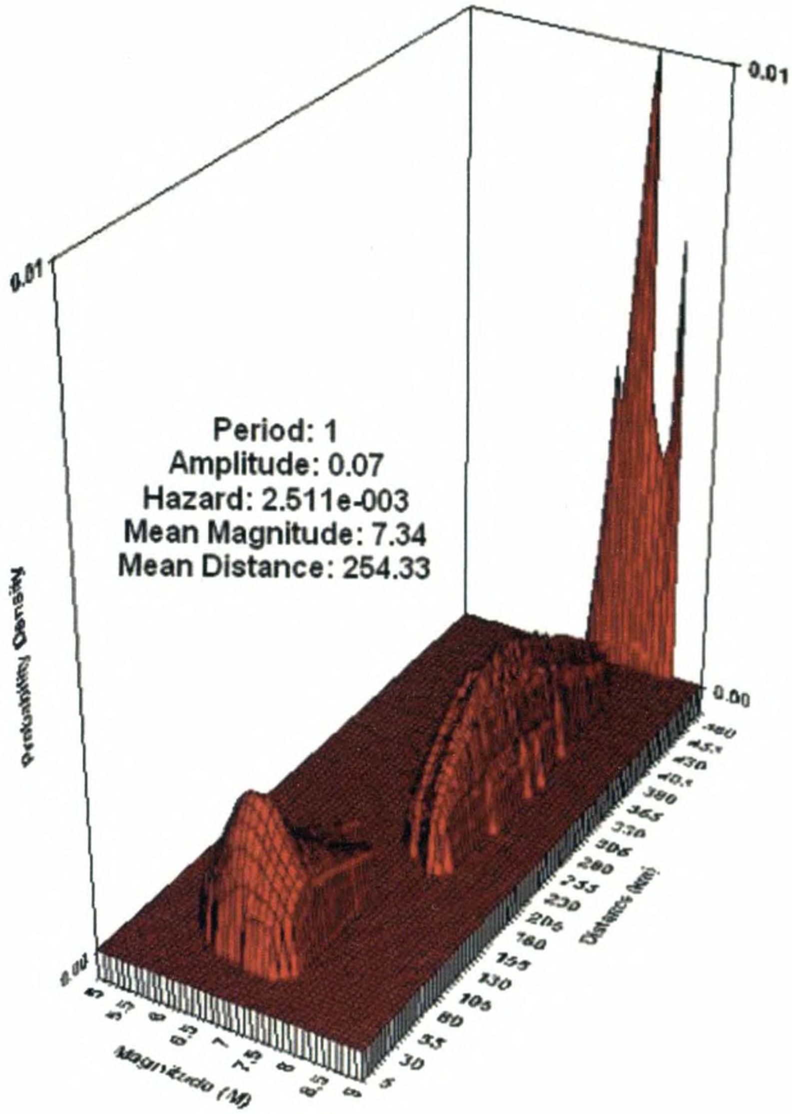

Figure 40: Magnitude-distance deaggregation for motion at Port Moresby.

Figure 40 shows the deaggregation plot for 1.0 second period motion at a return period of 975 years for Port Moresby (corresponding to a relatively low amplitude of 0.07 g spectral acceleration). It shows three main source of hazard, including moderate magnitude nearby events, larger events at distances of 20 to 500 km, and some contribution from great earthquakes at distances of 500 km and beyond (cumulatively plotted at 500 km).

Magnitude 6 earthquakes near Port Moresby occur infrequently, while the maximum credible magnitude of 7.5 has been estimated, with a near-zero recurrence rate.

7.2 Lae

Seismic zones within 500 km of Lae of the 6 layers of the PNG1 seismotectonic model were combined to determine the hazard at Lae. The parameters of the source zones were extracted from Table 3 to Table 8.

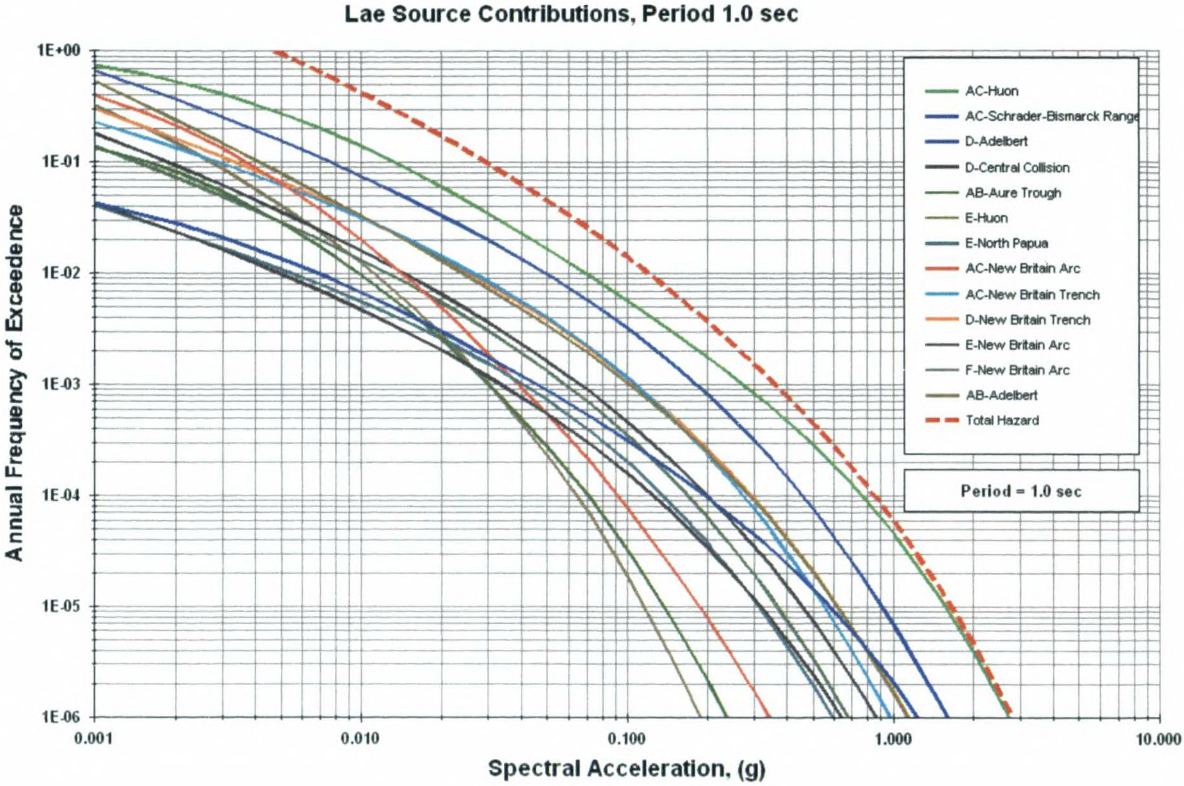

Figure 41: Source zone contributions for Lae ground motion.
This plot gives contributions for peak ground acceleration.

Figure 41 shows that the source contributions in Lae are dominated by the Huon seismotectonic zone, within which the city is located, and the neighbouring Schrader and Adelbert zones.

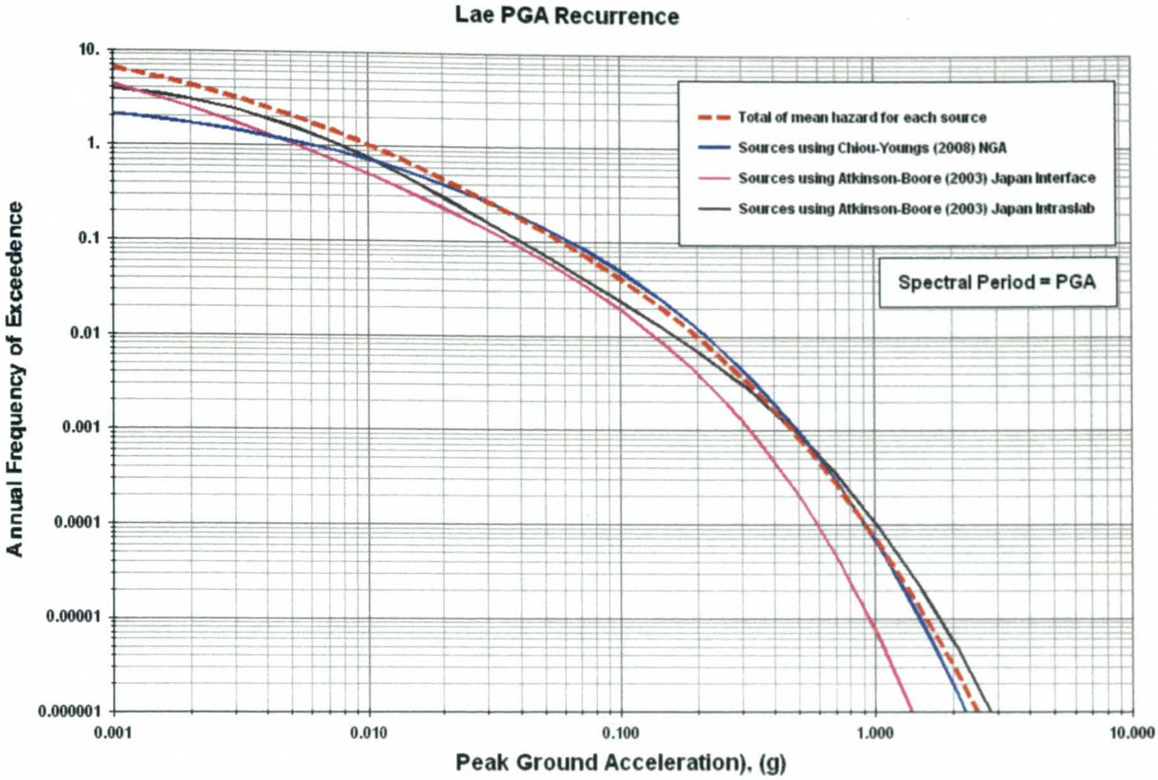

Figure 42: PGA recurrence for Lae.

Results for bedrock motion and peak ground acceleration, considering magnitudes 5.0 and higher.

Figure 42 shows that the high-frequency peak ground acceleration at Lae is totally dominated by contributions from nearby local earthquakes, determined using the Atkinson-Boore (2003) attenuation function.

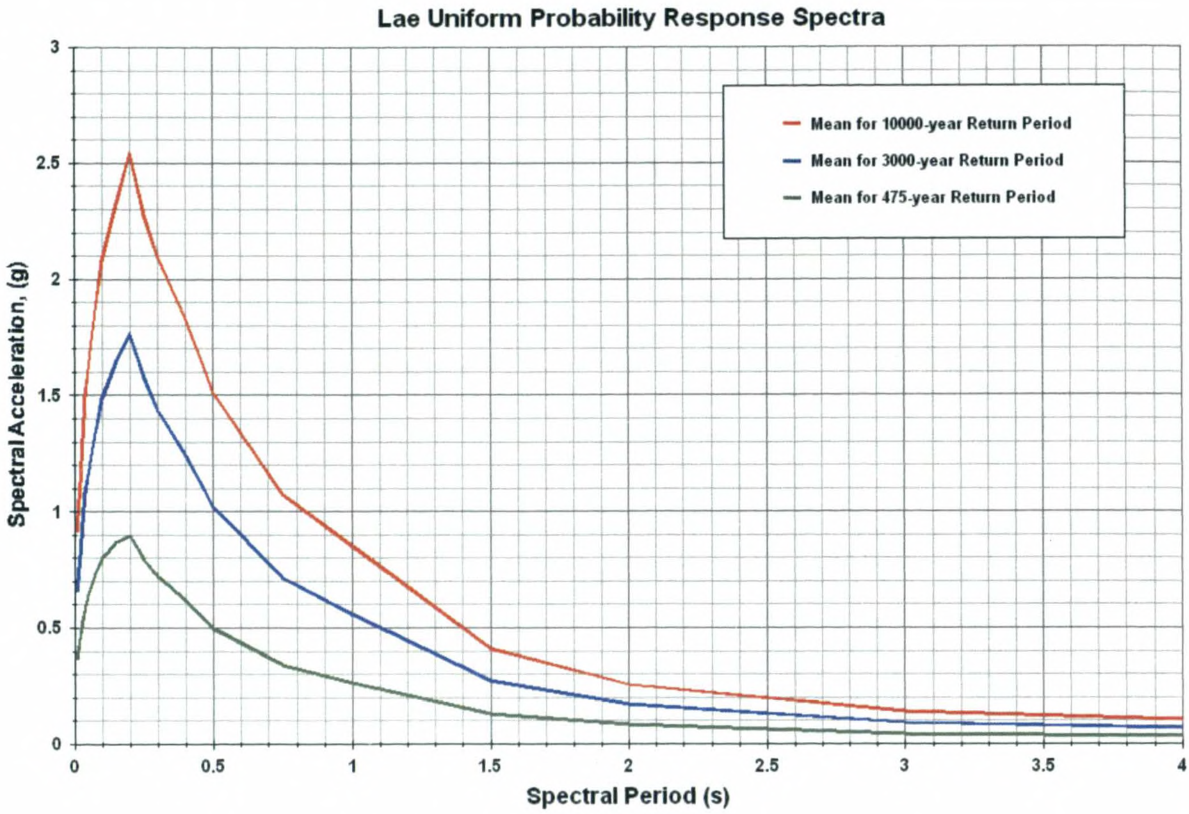

Figure 43: Response spectra for Lae.
These uniform probability response spectra are for bedrock, using magnitudes from 5.0.

The peak ground acceleration is numerically equal to the response spectral acceleration at near zero period, for all the left most points on each of the plots.

The uniform probability response spectra for return periods of 475 years, 3000 years and 1000 years are shown in Figure 43. Spectra for other return periods can be found by re-calculation.

For Lae, the deaggregation plot of 1.0 second for a return period of 975 years (Figure 44) shows that most of the contributing earthquakes are originating locally, but the situation extends gradually and tapers off to a distance of about 200 km.

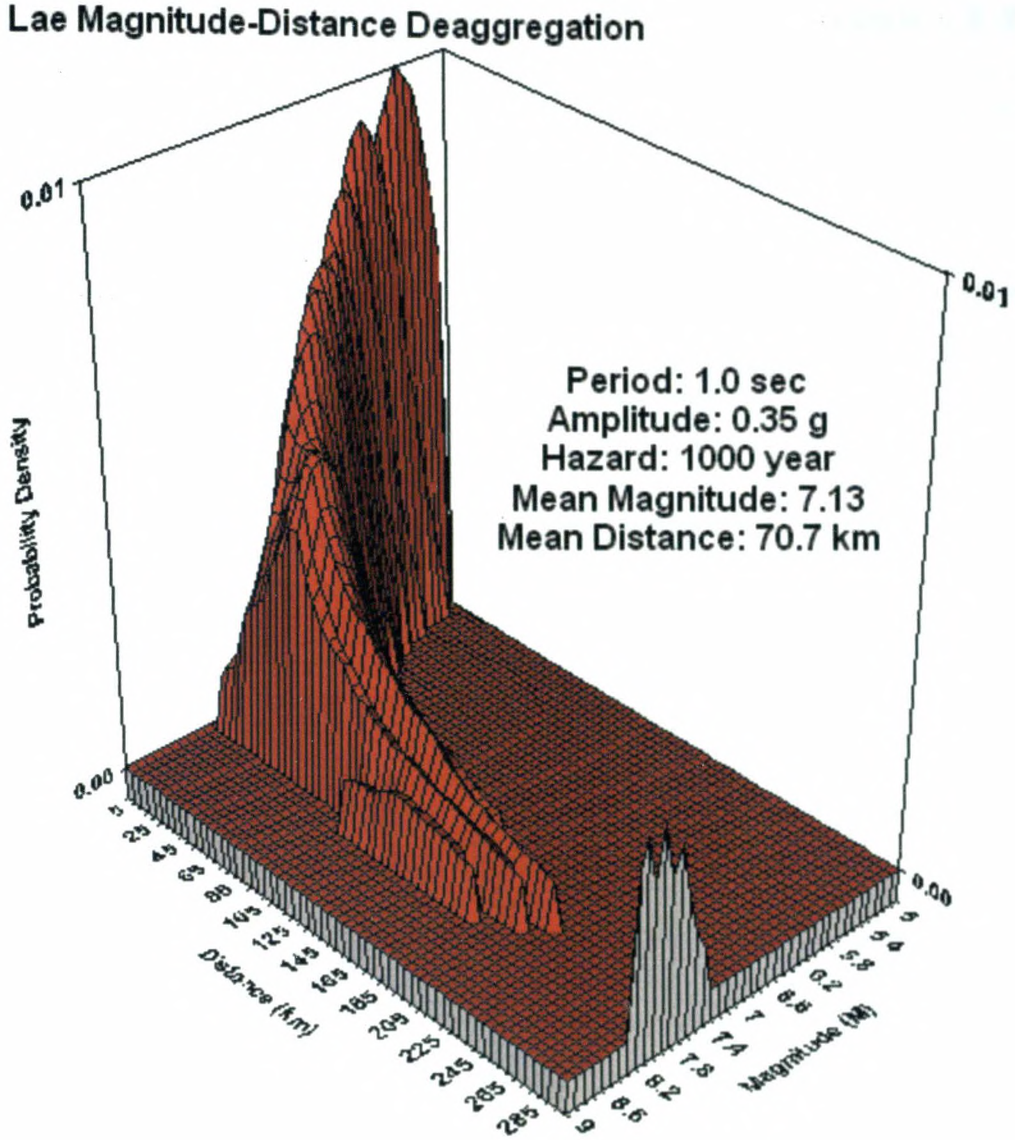

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Figure 44: Magnitude-distance deaggregation for motion at Lae.

Results for bedrock motion of period 1.0 seconds, considering magnitudes 5.0 and higher.

7.3 Kokopo

Seismic zones within 500 km of Kokopo of the 6 layers of the PNG1 seismotectonic model were combined to determine the hazard at Kokopo. The parameters of the source zones were extracted from Table 3 to Table 8.

Kokopo is situated on the northern fringes of the New Britain Trench, eastern Gazelle Peninsula on New Britain. The seismic source zones contributing to the hazard are generally active, and in fact include some of the most active in worldwide standards. The earthquakes are in zones that continue to exist in zones at successive deeper layers.

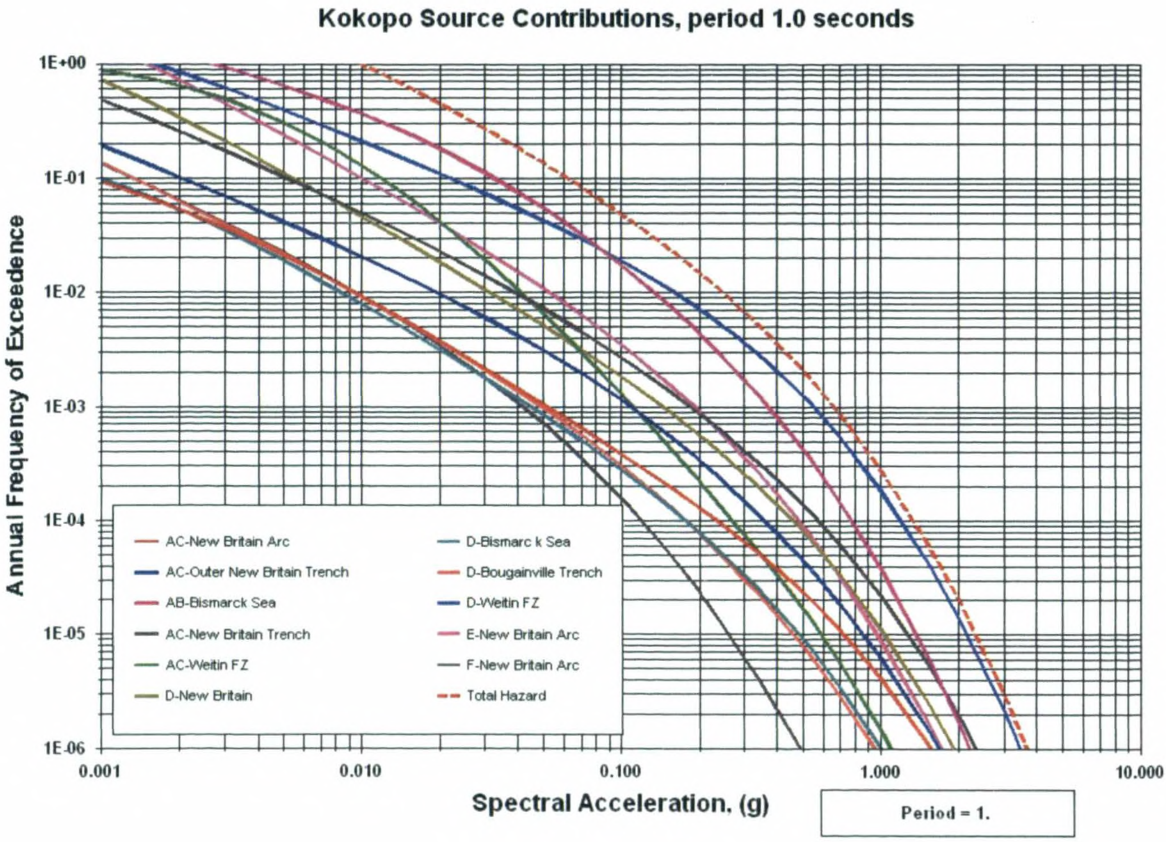

Figure 45: Source zone contributions for Kokopo ground motion.

This plot gives contributions for motion with spectral acceleration at a period of 1.0 second.

Figure 45 shows that the zones contributing most to the hazard are those closest to Kokopo and the most active are the zones of the New Britain Arc and New Britain Trench. These zones consequently contribute highest to the total hazard, or otherwise are spread amongst many other zones.

The town is located on firm soil and is surrounded by low to moderate hilly topography. Strong motion recordings have been few and not continuous or incomplete. Ripper (1992) documented a highest recorded acceleration of 0.05g from a magnitude 5.6 earthquake 117 km distant. The Mw 8.0 earthquake of 16 November 2000 was not recorded locally and therefore the acceleration was not determined.

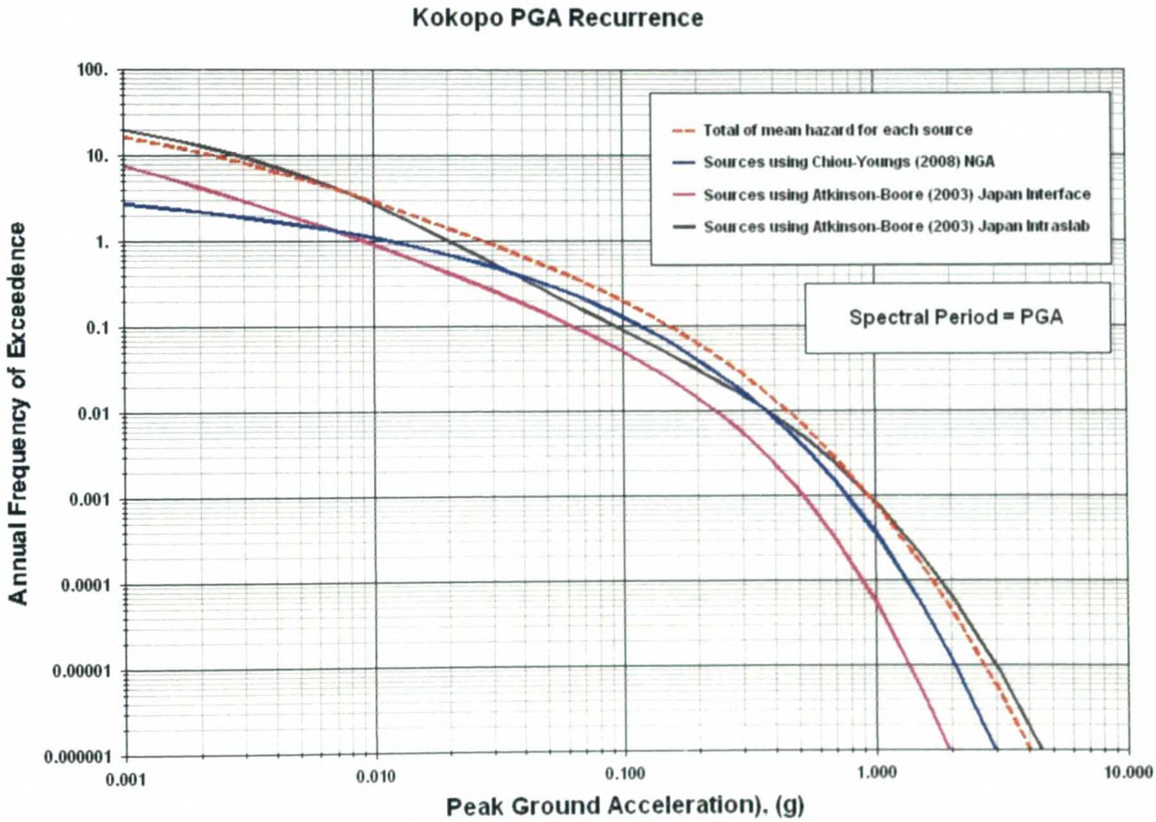

Figure 46: PGA recurrence for Kokopo.

Results for bedrock motion, considering magnitudes 5.0 and higher.

Figure 46 shows the strength of seismic zones of the subduction zone in the total hazard using the attenuation function by Atkinson and Boore (2003), especially in the lower and upper PGA. There was a reasonable contribution from zones non-subducting lithosphere using the attenuation function by Chiou and Youngs (2008), especially at the mid-range PGAs.

Note that for the total motion at the site, the Atkinson-Boore attenuation functions for subduction events are each weighted by 0.5, while the plot shows the ground motion recurrence for full weighting for each.

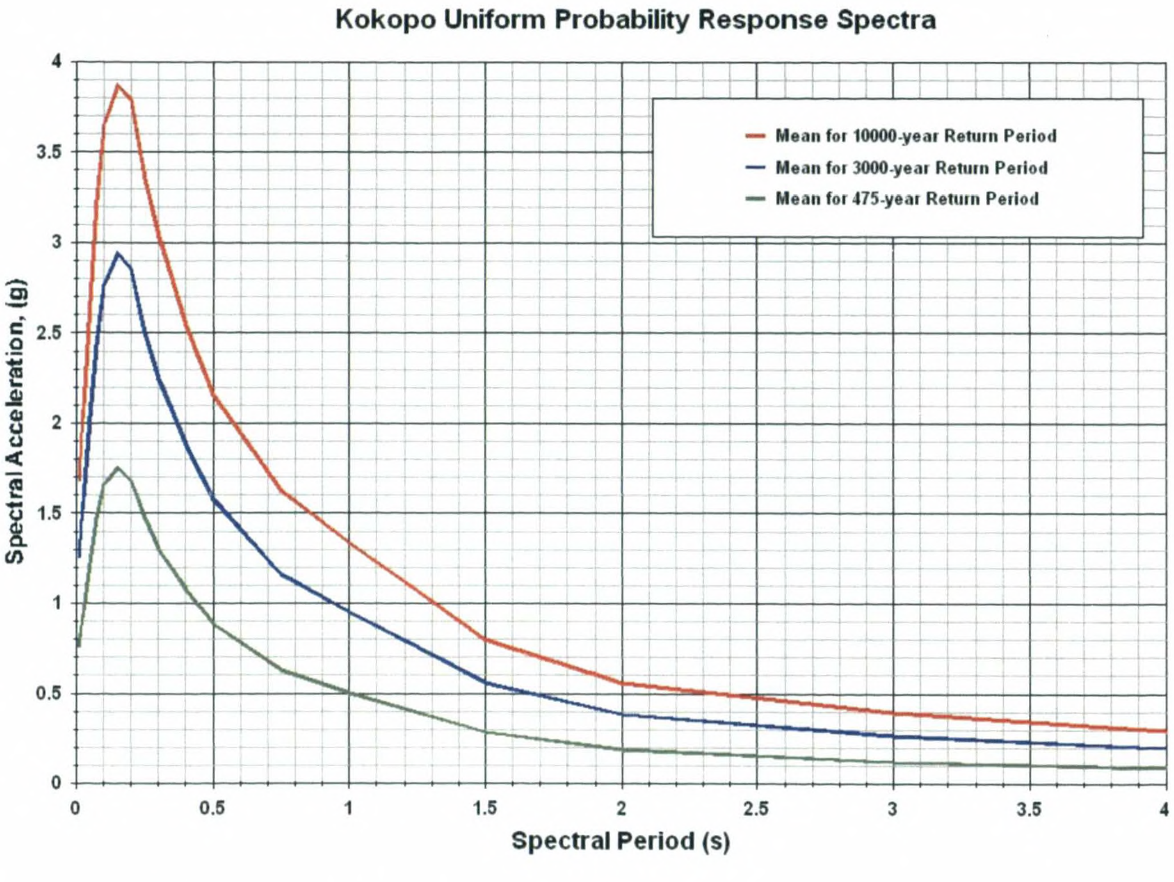

Figure 47: Response spectra for Kokopo.

These uniform probability response spectra are for bedrock, using magnitudes from 5.0.

Figure 47 shows response curves for 475, 3000, 10,000 year return periods. Spectra for other return periods can be derived from re-calculation, or approximately by interpolation.

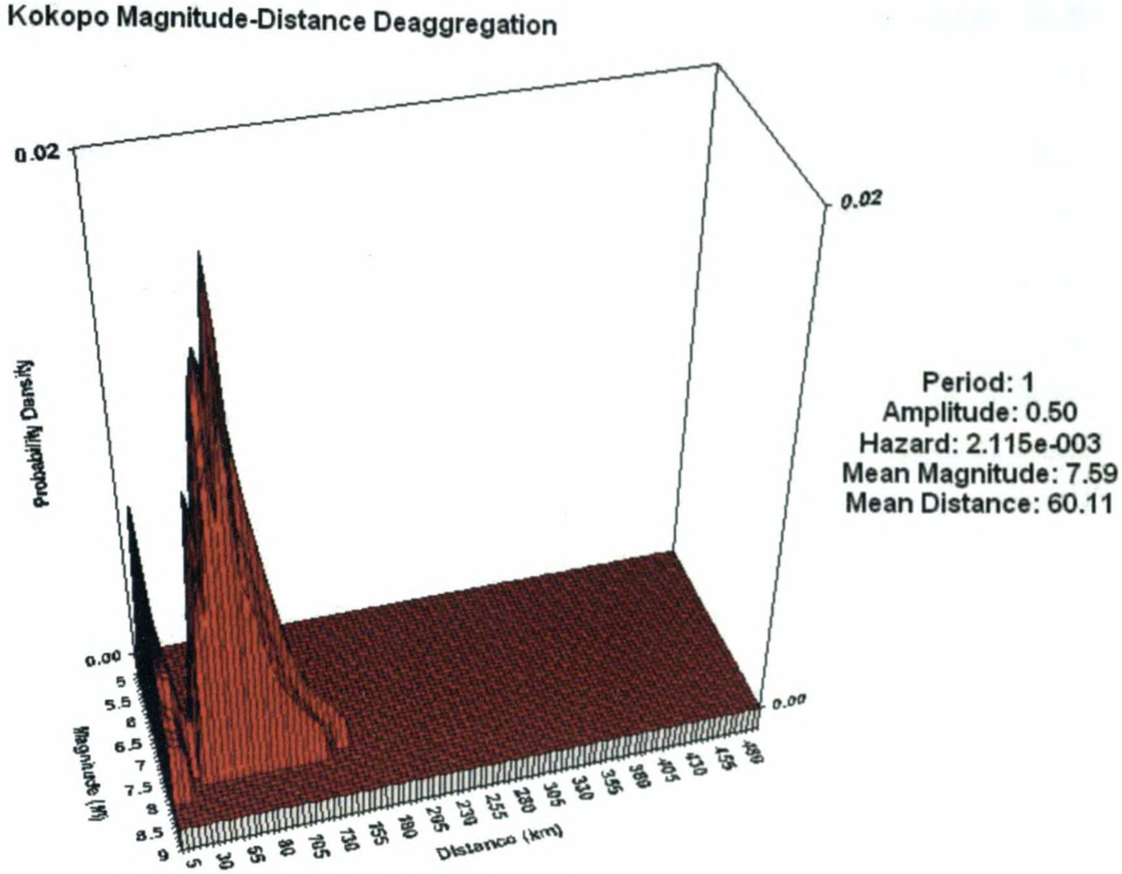

Figure 48: Magnitude-distance deaggregation for motion at Kokopo.
Results for bedrock motion of period 1.0 seconds, considering magnitudes 5.0 and higher.

Figure 48 shows the deaggregation for all source zones within 500 km, with associated hazard parameters. Two parts are shown to contribute earthquakes, from very local distance (0-25 km) and that from distance up to 150 km. Located within active, no seismic zones is observed to contribute hazard at Kokopo from farther distances, even in adjoining subduction zones are observed.

7.4 Madang

Seismic zones in the six layers of the PNG1 seismotectonic model were combined in the analysis to determine the seismic hazard of Madang. The parameters of the source zones were extracted from Table 3 to Table 8.

The town of Madang is located on the north coast of New Guinea, PNG mainland, to the south of and on the fringes of New Guinea Trench. Here the southern edge of the South Bismarck Plate is clearly noted at shallower depth then the deeper north-dipping Solomon Plate at depth. The town is situated generally on a coralline foundation. Ripper documented a 0.10g acceleration recorded from a magnitude 5.6 earthquake at a slant distance of 66 km, and a maximum acceleration of 0.094g from a magnitude 7.1 earthquake at a distance of 250 km.

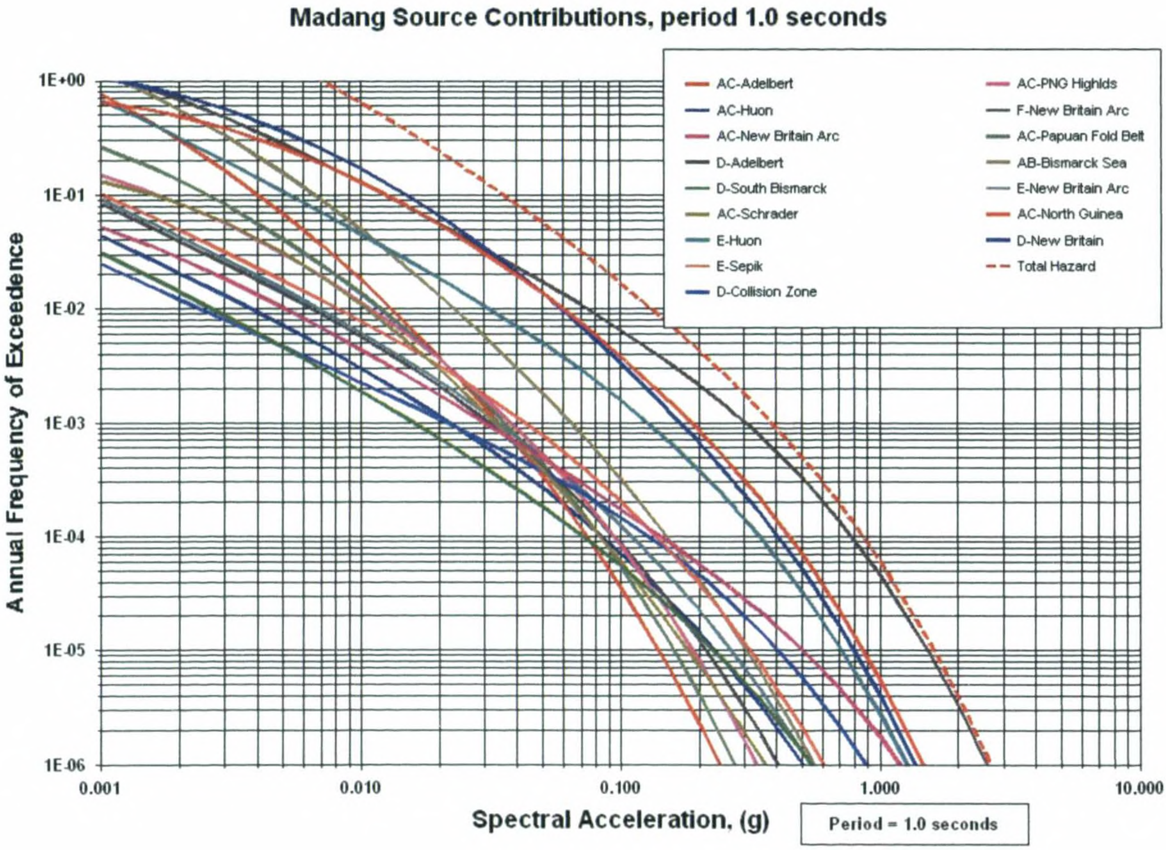

Figure 49: Source zone contributions for Madang ground motion

The seismic zones contributing significantly to the hazard are Adelbert and Huon, though also spread among other seismic zones as shown in Figure 49. Here it appears source zones at deeper layers are contributing reasonably as well.

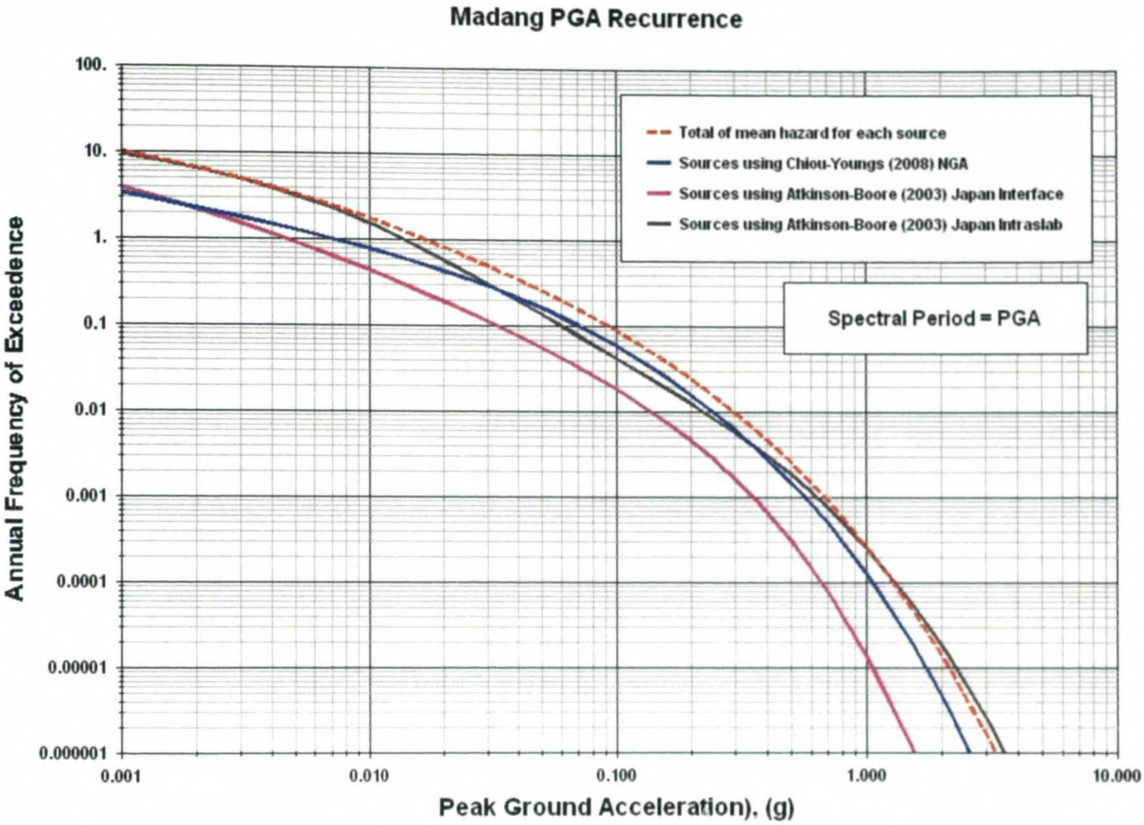

Figure 50: PGA recurrence for Madang.
Results for bedrock motion, considering magnitudes 5.0 and higher.

Figure 50 shows that the intra-slab seismic zones contributed most to the total seismic hazard at Madang, utilising the attenuation relationship of Atkinson and Boore (2003), particularly for the lower and upper PGAs.

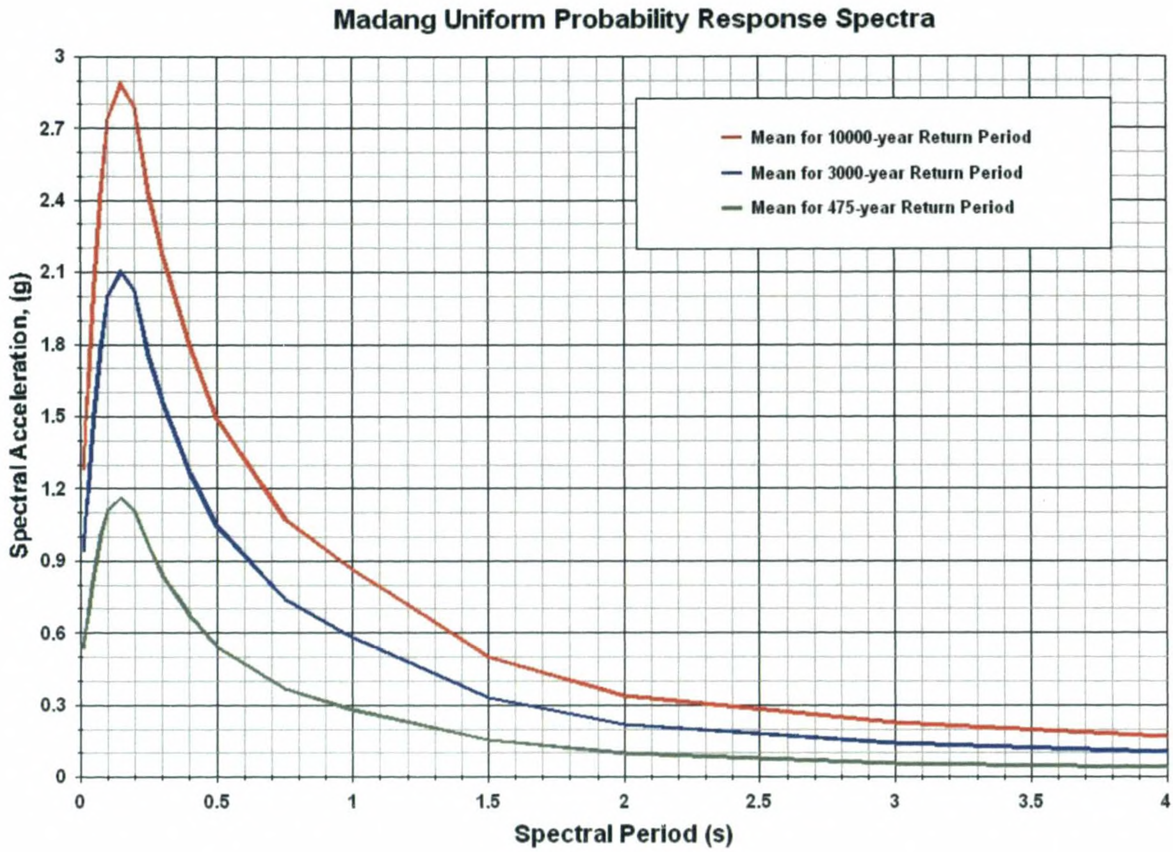

Figure 51: Response spectra for Madang.

These uniform probability response spectra are for bedrock, using magnitudes from 5.0.

Figure 51 show curves for uniform probability response spectra at various return periods. Spectra for other return periods can be derived from re-calculation, or approximately by interpolation.

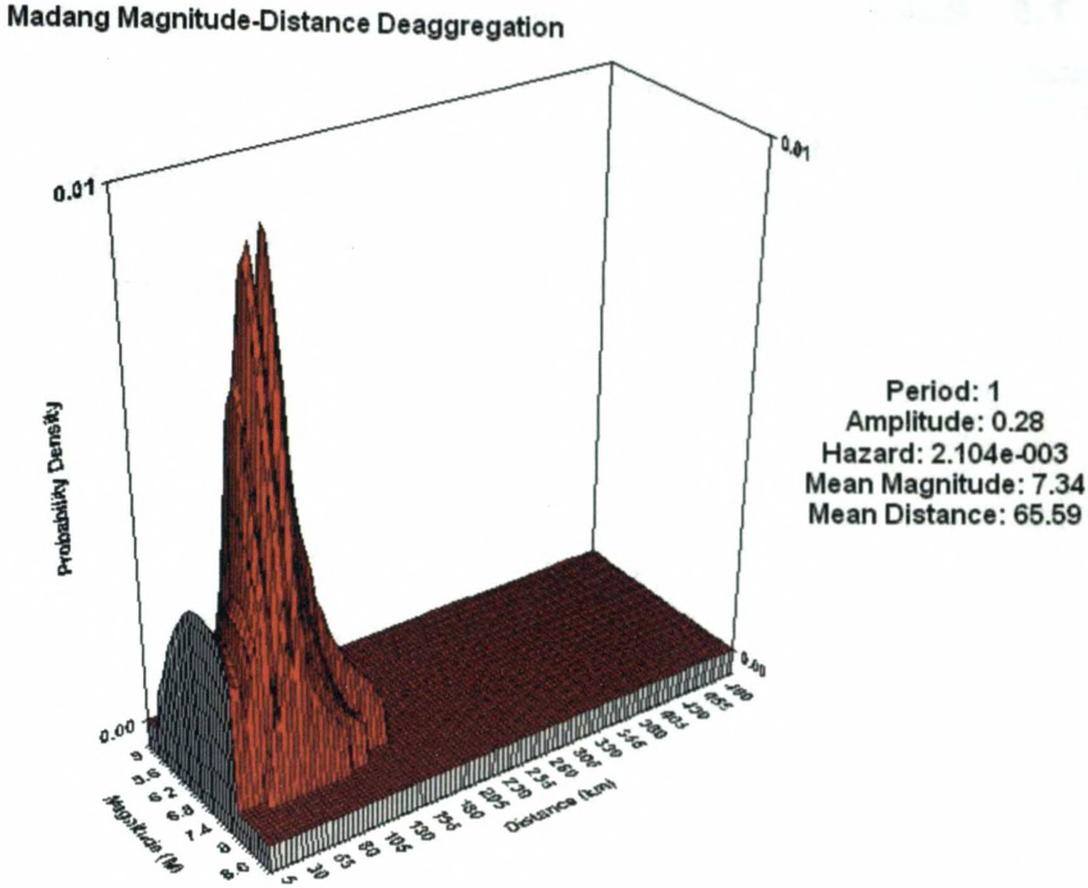

Figure 52: Magnitude-distance deaggregation for motion at Madang.
Results for bedrock motion of period 1.0 seconds, considering magnitudes 5.0 and higher.

Figure 52 shows the deaggregation for all source zones within 500 km of Madang, but effects of earthquakes up to only 155 km are observed. Madang being seismically active, effects from earthquakes beyond this distance are not observed. Associated hazard parameters are also determined, as shown with the deaggregation figure.

7.5 Buka

Seismic zones within 500 km of Buka in the six layers of the PNG1 seismotectonic model were combined to determine the seismic hazard. The parameters of the source zones were extracted from Table 3 to Table 8.

Buka Town is situated on the northeastern side of the New Britain Trench, on the island arc system that lies in front of, and is now part of, the docked OJP at the trench. Like Kokopo, Buka is in the vicinity of some of the most active seismic zones in world standards.

The stable and dominating OJP is situated to the east, which means most activity is associated with subduction in the general region west and beneath Buka Town. This is as a result of the massive, thick and buoyant nature of the OJP, which then influences the subducting Solomon Plate to sinking nearly vertically beneath and mostly west of Bougainville and Buka Town. The seismic zones here include those at depth, outline seismicity trending vertically to depths and not necessarily a normal Wadati-Benioff zone typically expected.

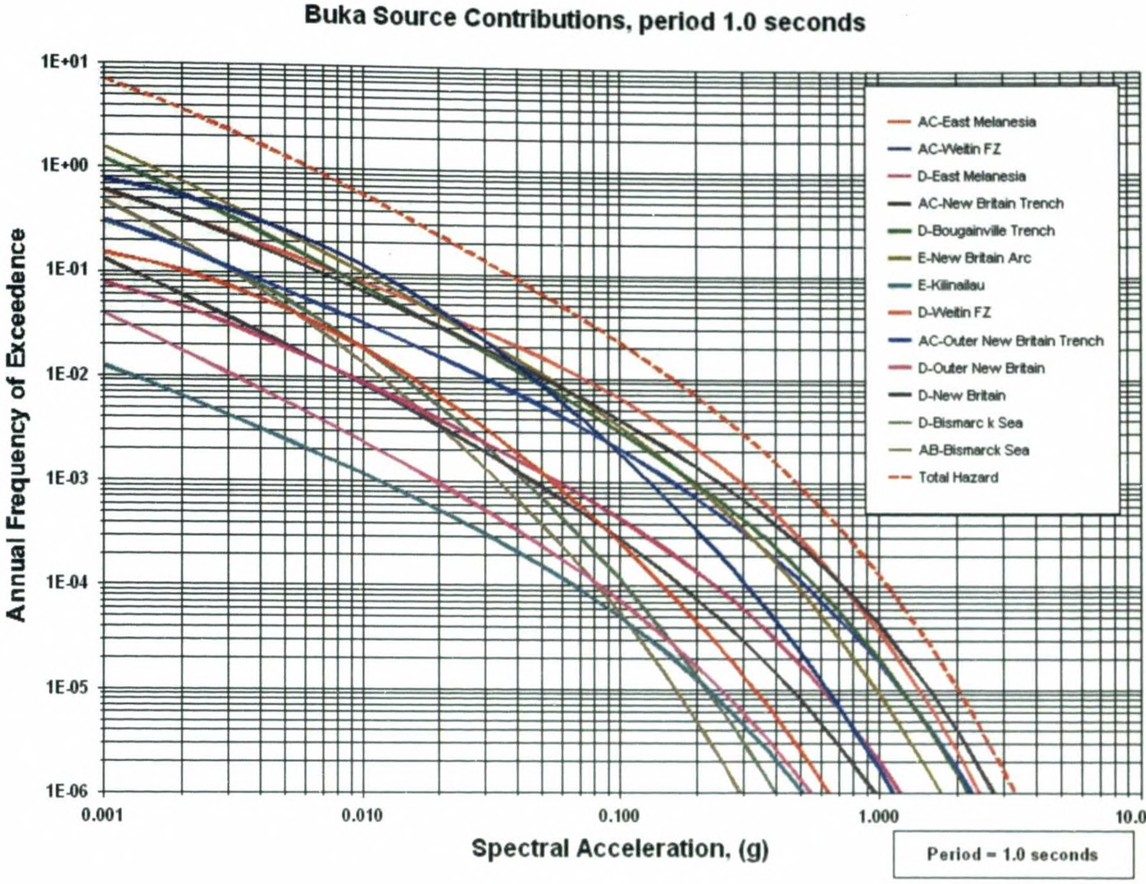

Figure 53: Source zone contributions for Buka ground motion.
This plot gives contributions for motion with spectral acceleration at a period of 1.0 seconds, considering earthquakes of magnitude 5.0 and higher.

The seismic hazard contributions within 500 km of Buka are shown in Figure 53. Weitin, New Britain and Bougainville seismic zones contribute most to the hazard, although it can be concluded that the contributions were fairly spread.

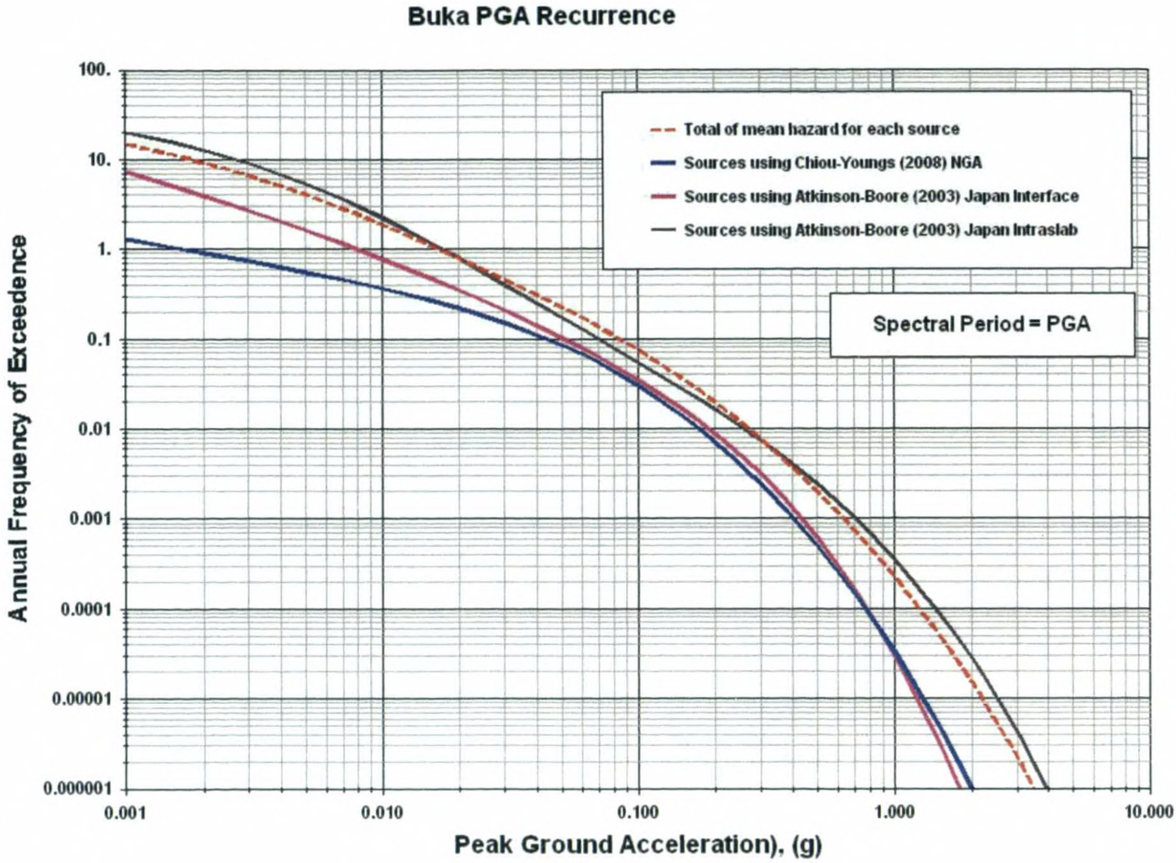

Figure 54: PGA recurrence for Buka.
Results for bedrock motion, considering magnitudes 5.0 and higher.

Figure 54 shows that the intra-slab source zones dominating the contributions of earthquakes having effect at Buka, these associated with the subducting Solomon Plate beneath Bougainville and New Britain to depths. The plot shows the motion for full weighting, whereas the total motion gives 0.5 weighting for the two subduction functions by Atkinson and Boore (2003).

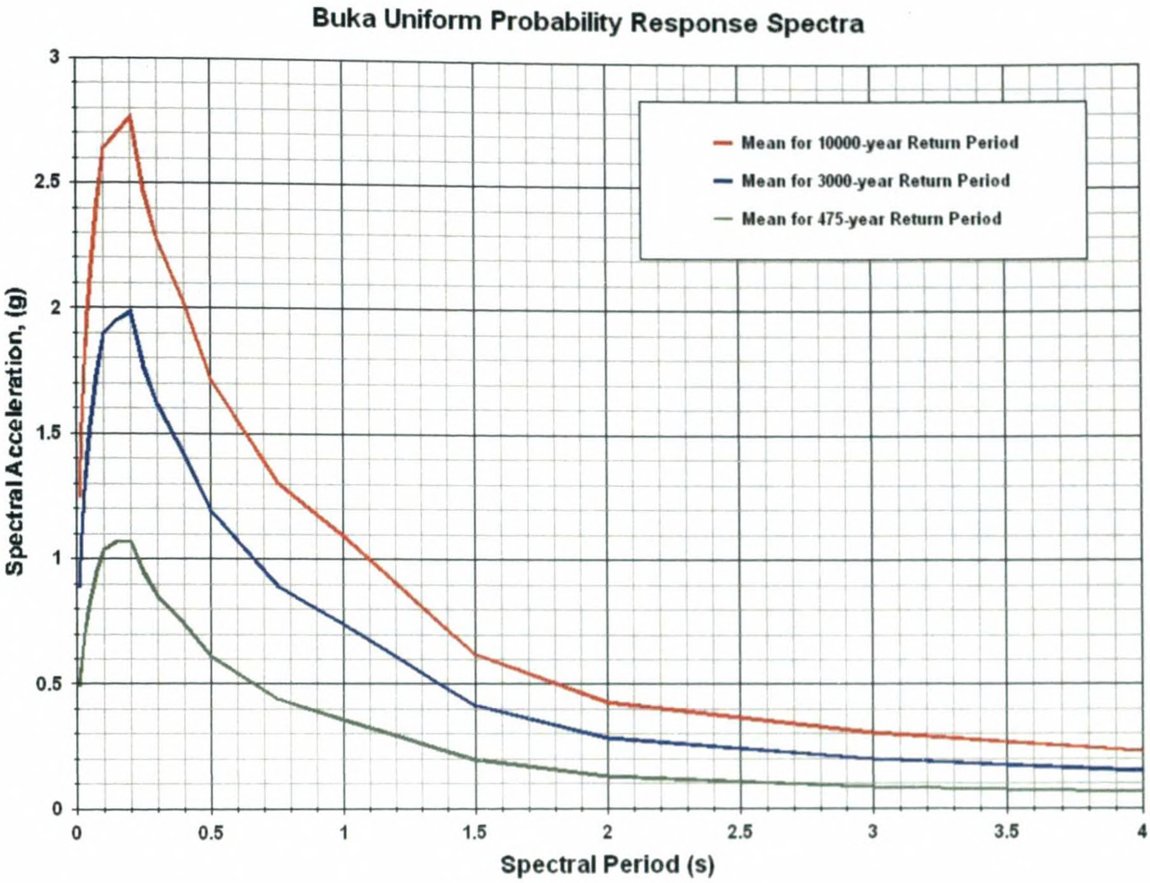

Figure 55: Response spectra for Buka.
These uniform probability response spectra are for bedrock, using magnitudes from 5.0.

Figure 55 shows the uniform probability response spectra for Buka for 475, 3000, 10,000 year return periods. Spectra for other return periods can be derived from re-calculation, or approximately by interpolation.

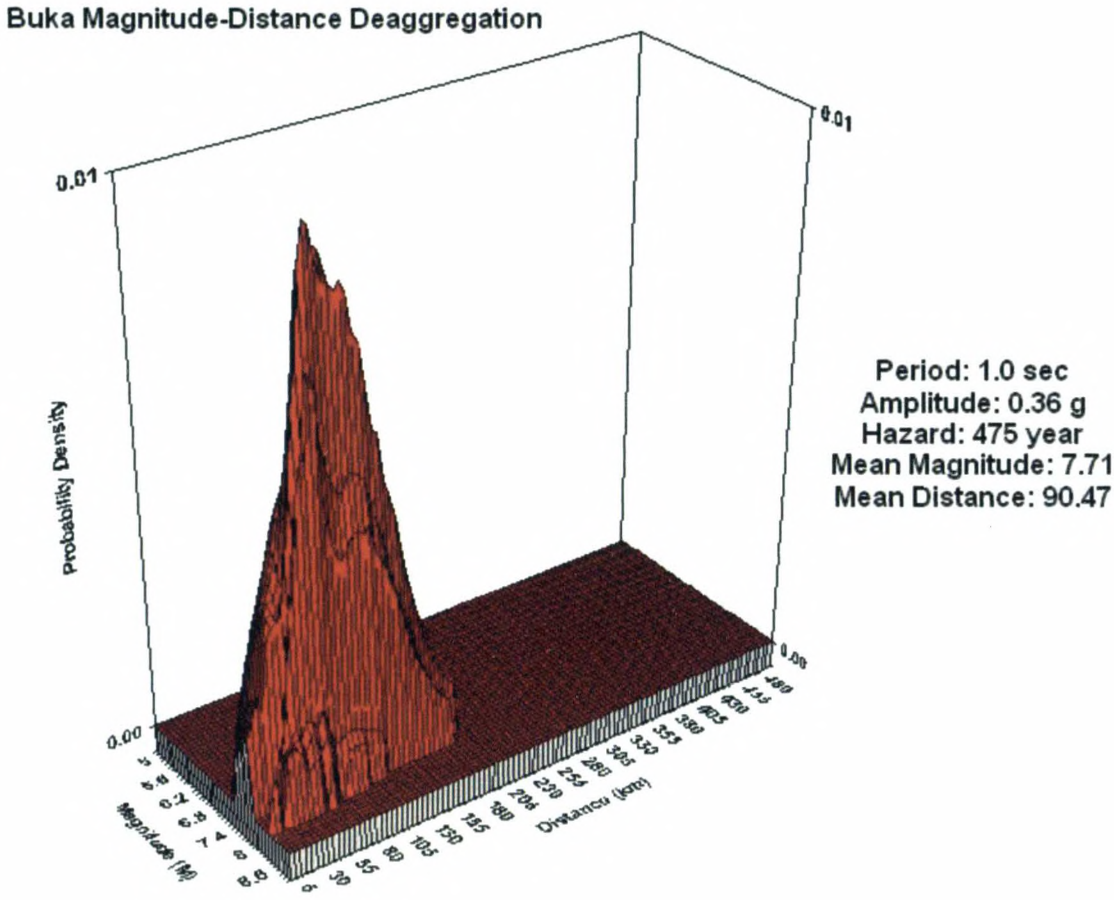

Figure 56: Magnitude-distance deaggregation for motion at Buka.
Results for bedrock motion of period 1.0 seconds, considering magnitudes 5.0 and higher.

The deaggregation shown in Figure 56 indicates effects of earthquakes originating locally to a distance of up to 200 km from Buka. Effects from farther distances, including those from the western New Britain and southeastern Bougainville Trench or San Cristobal Trench, are relatively insignificant, as Buka is situated on the seismically active region.

7.6 Wewak

Seismic zones in the six layers of the PNG1 seismotectonic model were combined to determine the earthquake hazard at Wewak. The parameters of the source zones were extracted from Table 3 to Table 8.

As is Madang, Wewak is situated on the southern fringes of the New Guinea Trench on northern New Guinea. Large earthquakes have been frequent and future events are highly likely.

Wewak Town is sited on coralline foundation surrounded by moderate hilly topography. Ripper documented only two accelerations having been recorded, the largest of these being 0.18g from a nearby magnitude 6.6 earthquake. Strong motion recording has been very limited in this region.

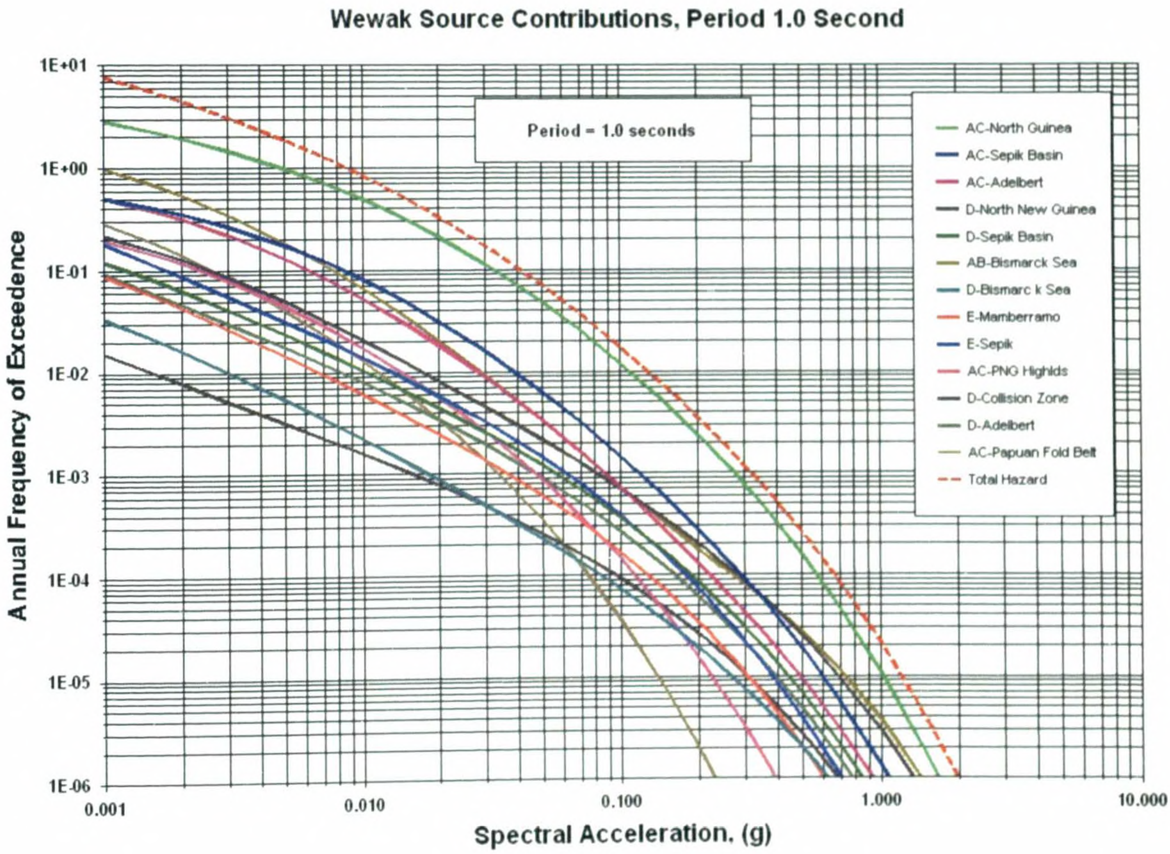

Figure 57: Source zone contributions for Wewak ground motion.

This plot gives contributions for motion with spectral acceleration at a period of 1.0 seconds, considering earthquakes of magnitude 5.0 and higher.

The plot showing source contributions in Figure 57 indicates a dominant source contribution by the North New Guinea zone, within which Wewak is situated. Other zone contributions are relatively low.

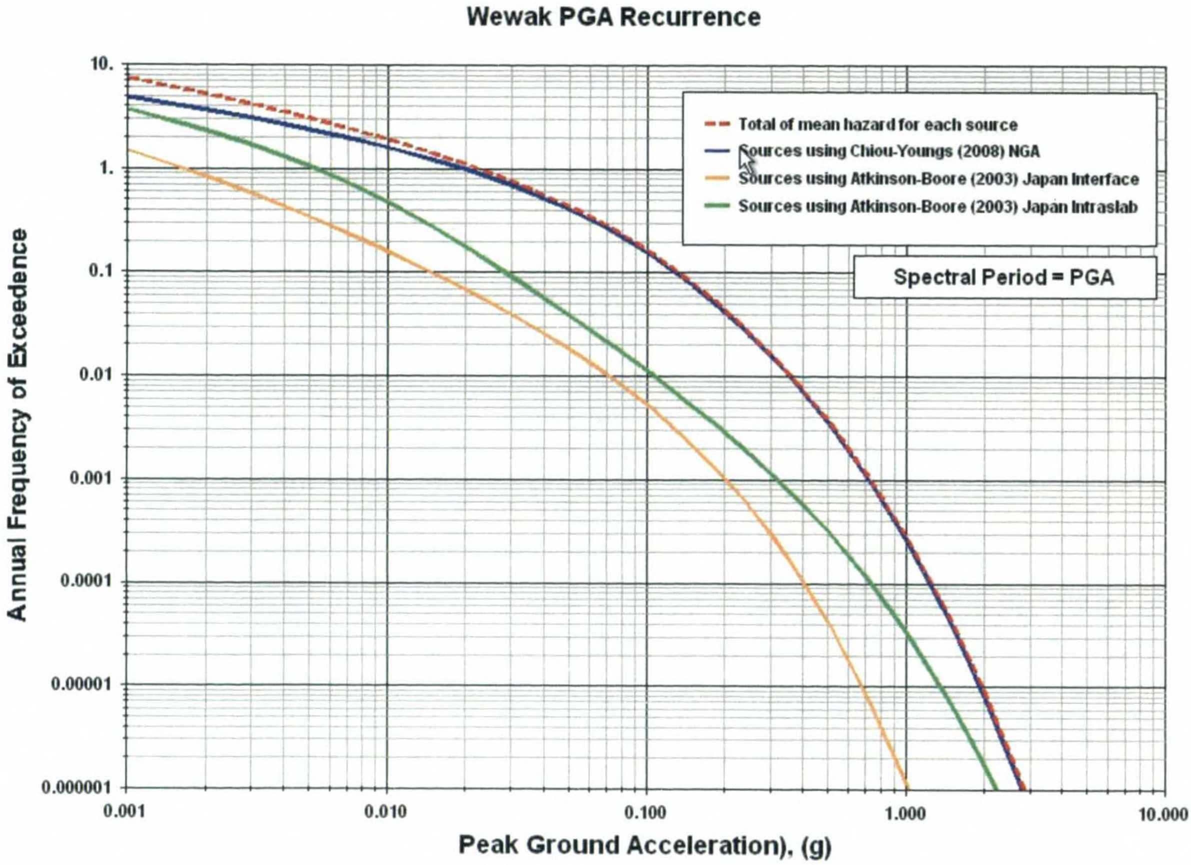

Figure 58: PGA recurrence for Wewak.
Results for bedrock motion, considering magnitudes 5.0 and higher.

Figure 58 shows that shallow or crustal source zones dominate the hazard, determined using the attenuation relationship of Chiou and Youngs (2008).

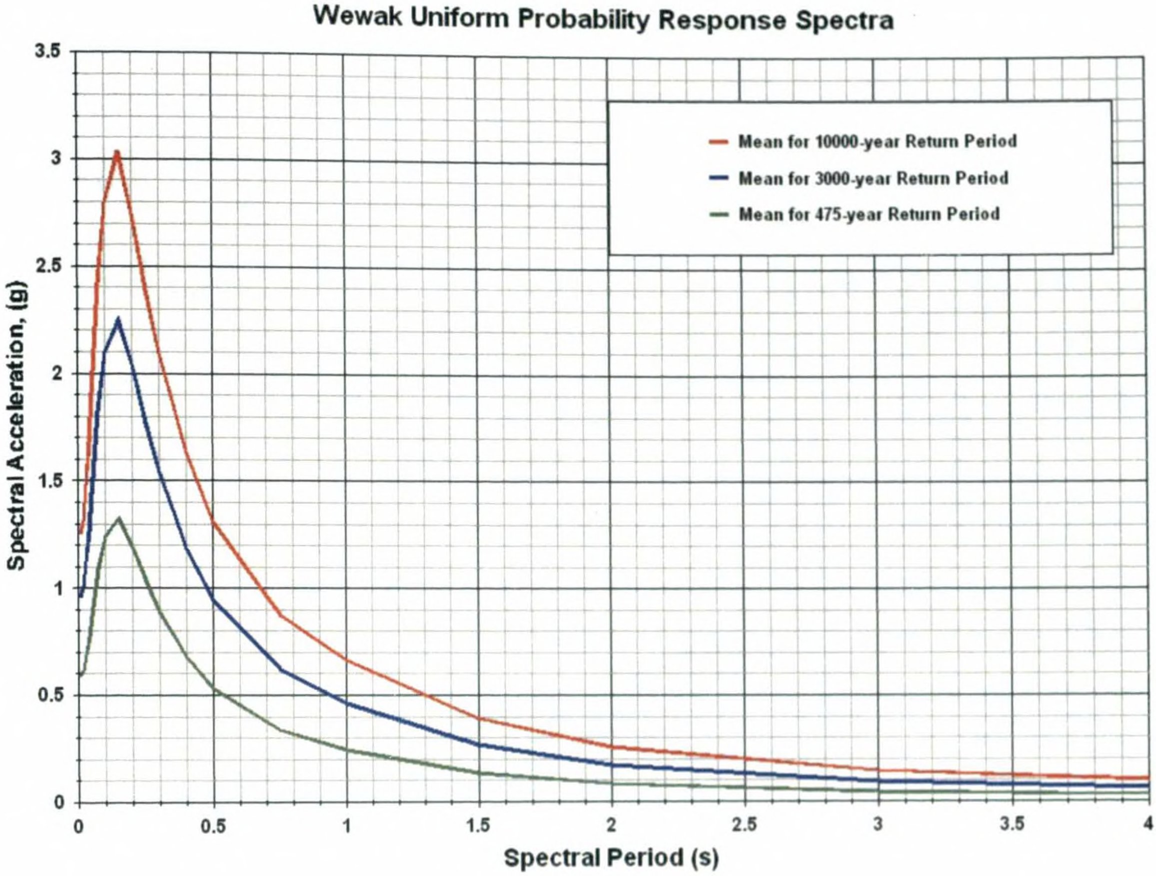

Figure 59: Response spectra for Wewak.

These uniform probability response spectra are for bedrock, using magnitudes from 5.0.

Response spectra curves for 475, 3000 and 10000 year return periods are shown in Figure 59. Spectra for other return periods can be derived from re-calculation, or approximately by interpolation.

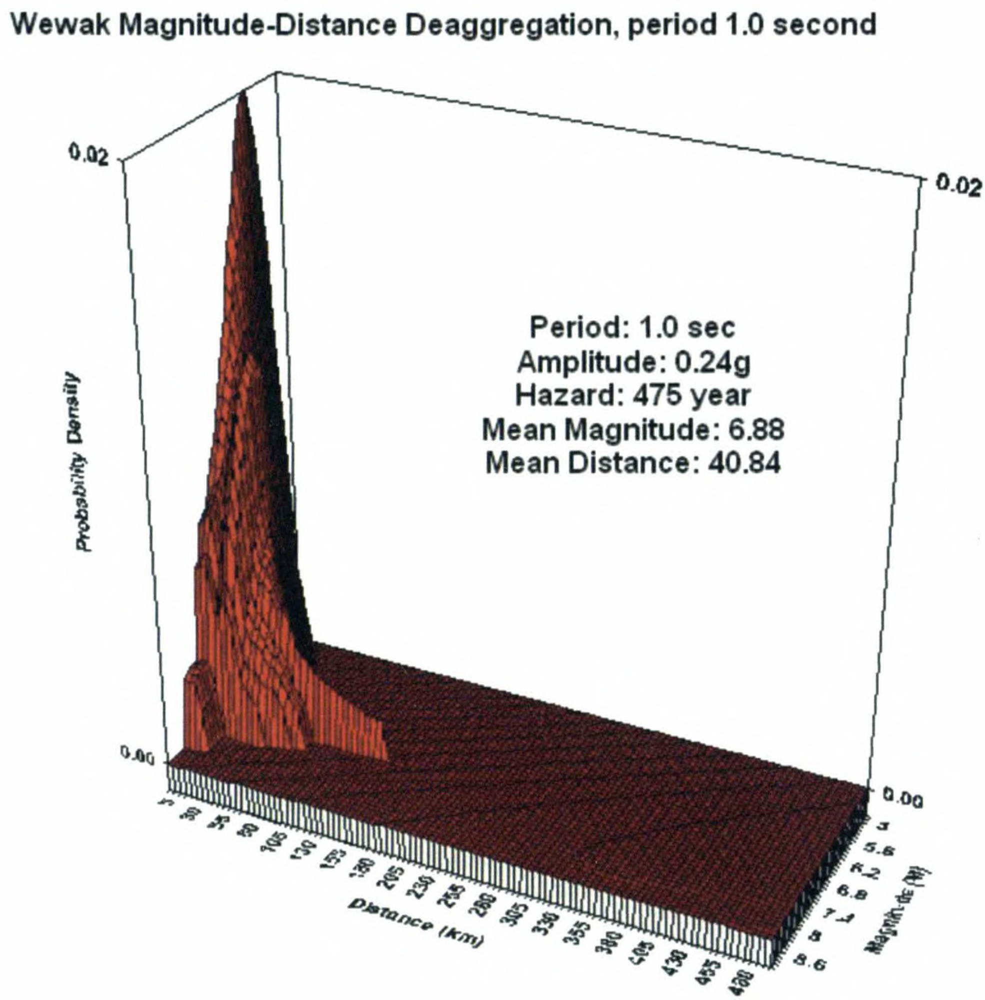

Figure 60: Magnitude-distance deaggregation for motion at Wewak.
Results for bedrock motion of period 1.0 seconds, considering magnitudes 5.0 and higher.

The plot of the deaggregation data in Figure 60 indicates that earthquakes in the distance 0 to less than 150 km totally dominate the hazard in Wewak. The associated hazard parameters are as indicated.

7.7 Kimbe

Seismic zones from the six layers of the PNG1 seismotectonic model were combined and appropriate attenuation functions applied to determine the hazard at Kimbe. The parameters of the source zones were extracted from Table 3 to Table 8.

Kimbe, like Kokopo, is situated north of the fringes of the New Britain Trench, and is amongst the most active. The subduction slab is a perfect Wadati-Benioff zone trending northwest beneath New Britain. Seismic zones contributing are amongst the intense to world standards.

Kimbe is sited on alluvium coastal plain and volcanic ash foundations, and surrounded by hilly topography that includes actual volcanic cones and calderas. Site conditions change to that of coralline foundation in the south at Kandrian where an acceleration of 0.29g from a magnitude 5.9 earthquake at a slant distance of 56 km (epicentral distance 17 km) was recorded. Much of activity is originating in the frontal arc including the New Britain Trench south of New Britain.

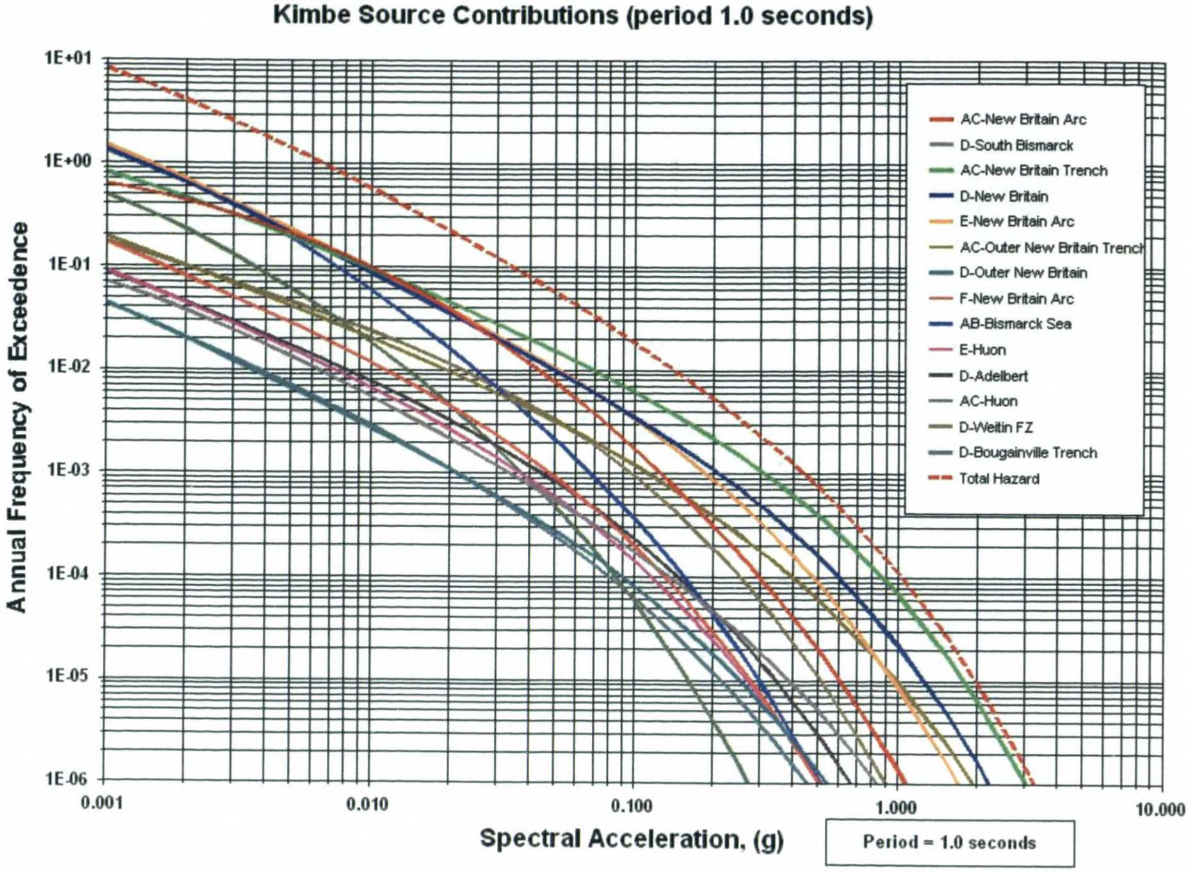

Figure 61: Source zone contributions for Kimbe ground motion.
This plot gives contributions for motion with spectral acceleration at a period of 1.0 seconds, considering earthquakes of magnitude 5.0 and higher.

The source contributions plot in Figure 61 indicates a fairly uniform contribution from all zones within 500 km of Kimbe, with most of the stronger motion originating from within the New Britain Arc and New Britain Trench.

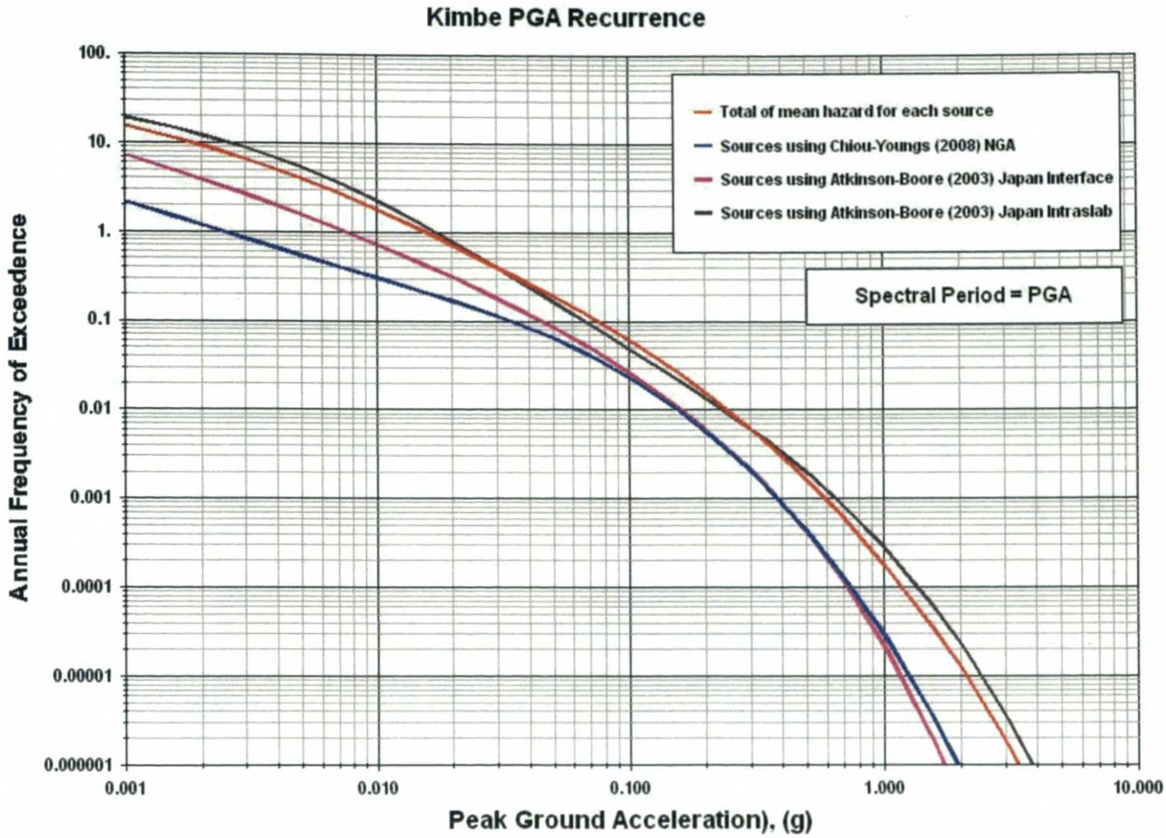

Figure 62: PGA recurrence for Kimbe.

Results for bedrock motion, considering magnitudes 5.0 and higher.

Figure 62 indicates that intra-slab source zones dominate in the source zone determination, using the attenuation function of Atkinson and Boore (2003). The total hazard uses weighting of 0.5 for each of the two Atkinson and Boore subduction functions.

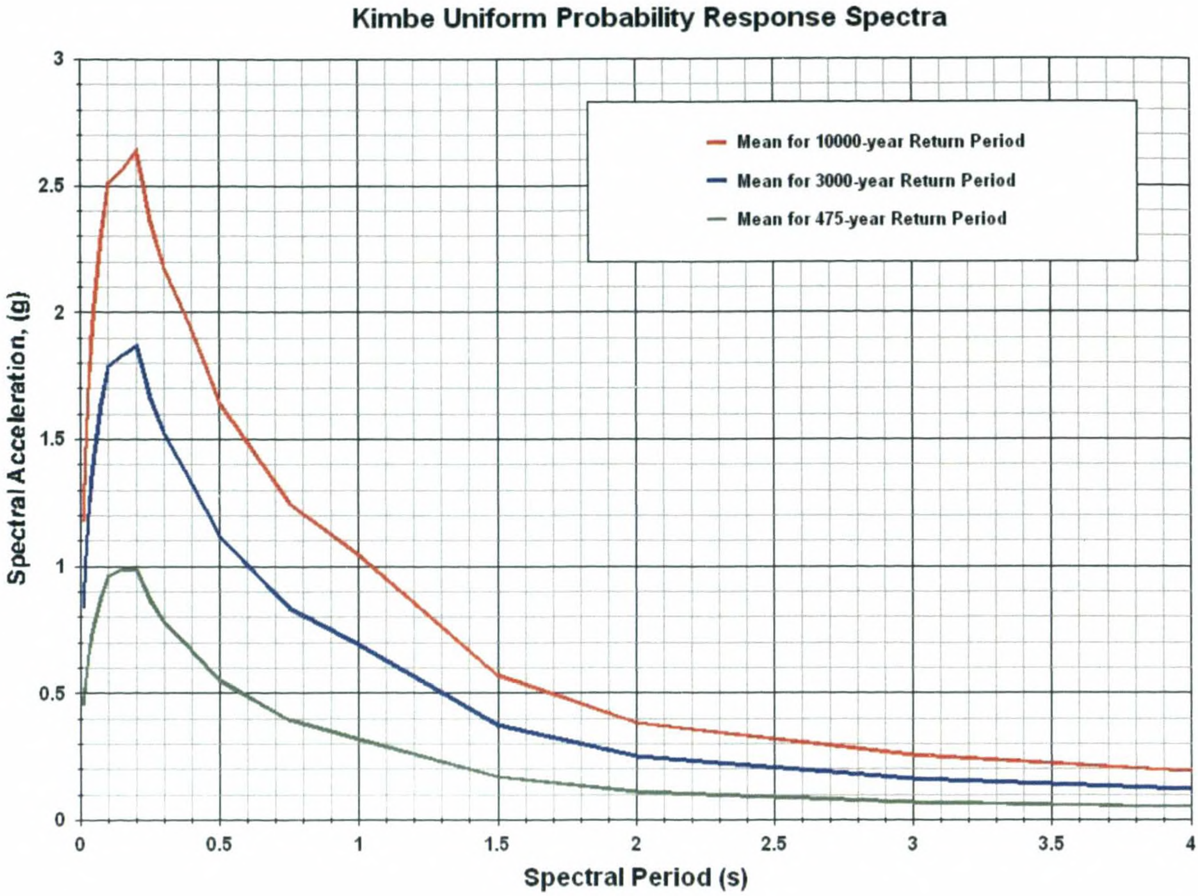

Figure 63: Response spectra for Kimbe

These uniform probability response spectra are for bedrock, using magnitudes from 5.0.

Figure 63 shows the uniform probability response spectra curves for 475, 3000, 10000 year return periods. Spectra for other return periods can be derived from re-calculation, or approximately by interpolation.

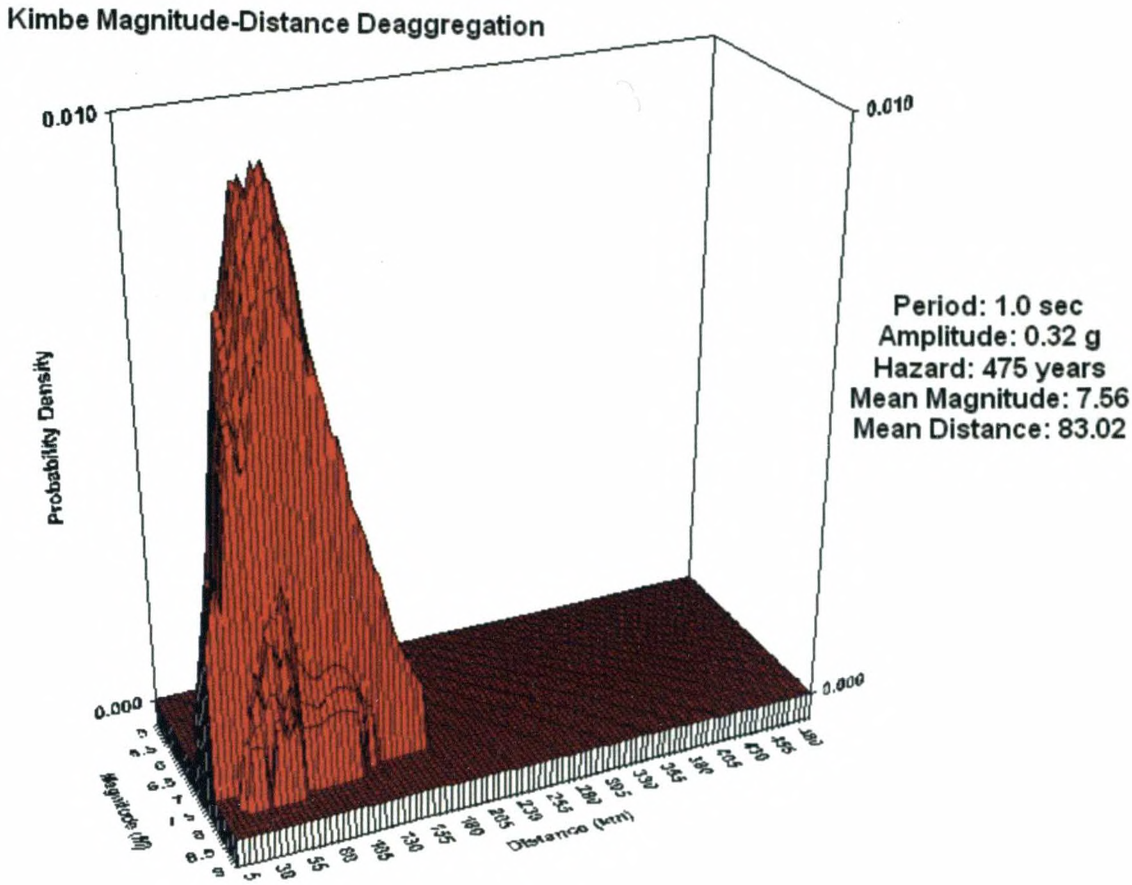

Figure 64: Magnitude-distance deaggregation for motion at Kimbe.
Results for bedrock motion of period 1.0 seconds, considering magnitudes 5.0 and higher.

Figure 64 shows the deaggregation for source zones within 500 km of Kimbe. The plot indicates though, that the vast majority of the hazard is from within about 160 km. This is typically of seismically active sites.

7.8 Honiara

Seismic zones in the six layers of the PNG1 seismotectonic model were combined with appropriate attenuation functions to determine the seismic hazard at Honiara. The parameters of the source zones were extracted from Table 1 to Table 8.

Honiara is situated on northern side of Guadalcanal Island of the Solomon Island Arc, away from the trend of the San Cristobal Trench but inline with the volcanic arc. The site conditions include firm alluvium and volcanic ash with shorelines of coralline foundation and surrounded by moderate hilly topography.

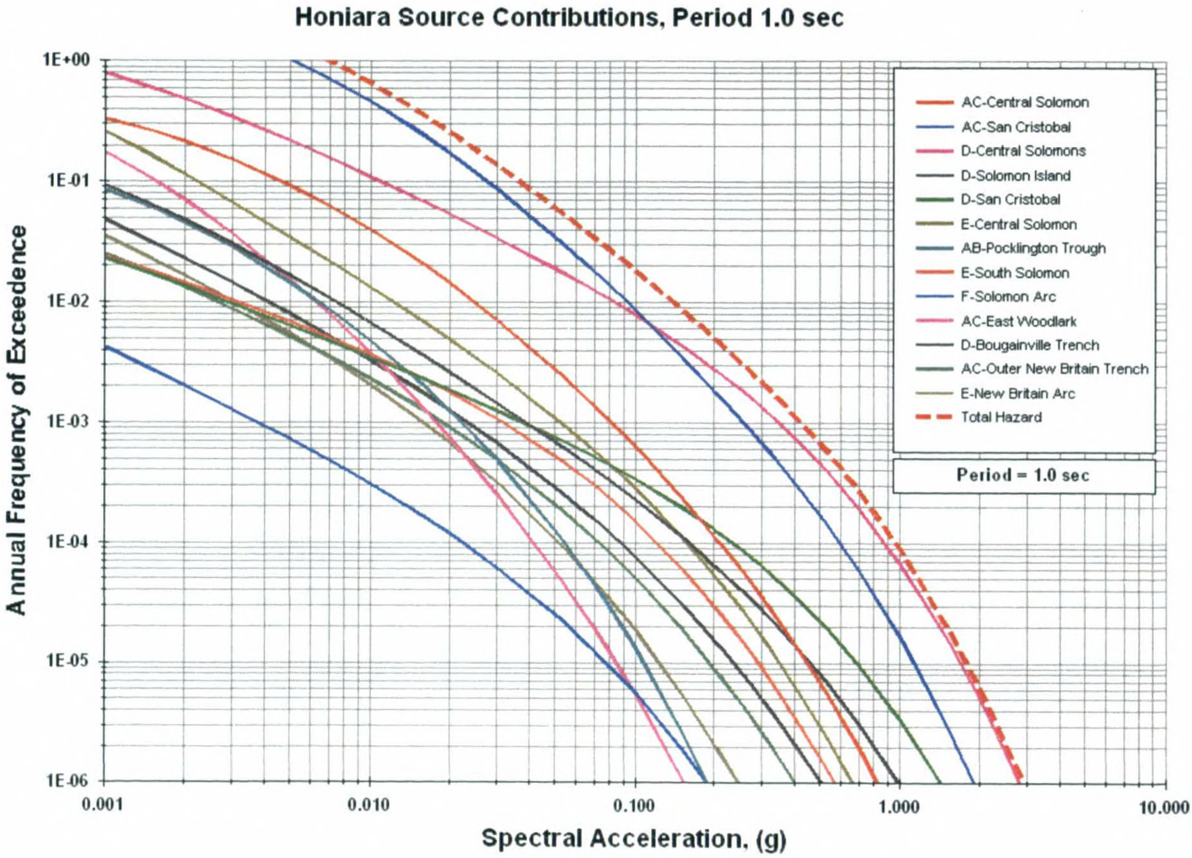

Figure 65: Source zone contributions for Honiara ground motion.

This plot gives contributions for motion with spectral acceleration at a period of 1.0 seconds, considering earthquakes of magnitude 5.0 and higher.

Figure 65 indicates a major contribution of the hazard originating from the San Cristobal in layer 1 and Central Solomons of layer 2. The contribution from elsewhere was much less significant.

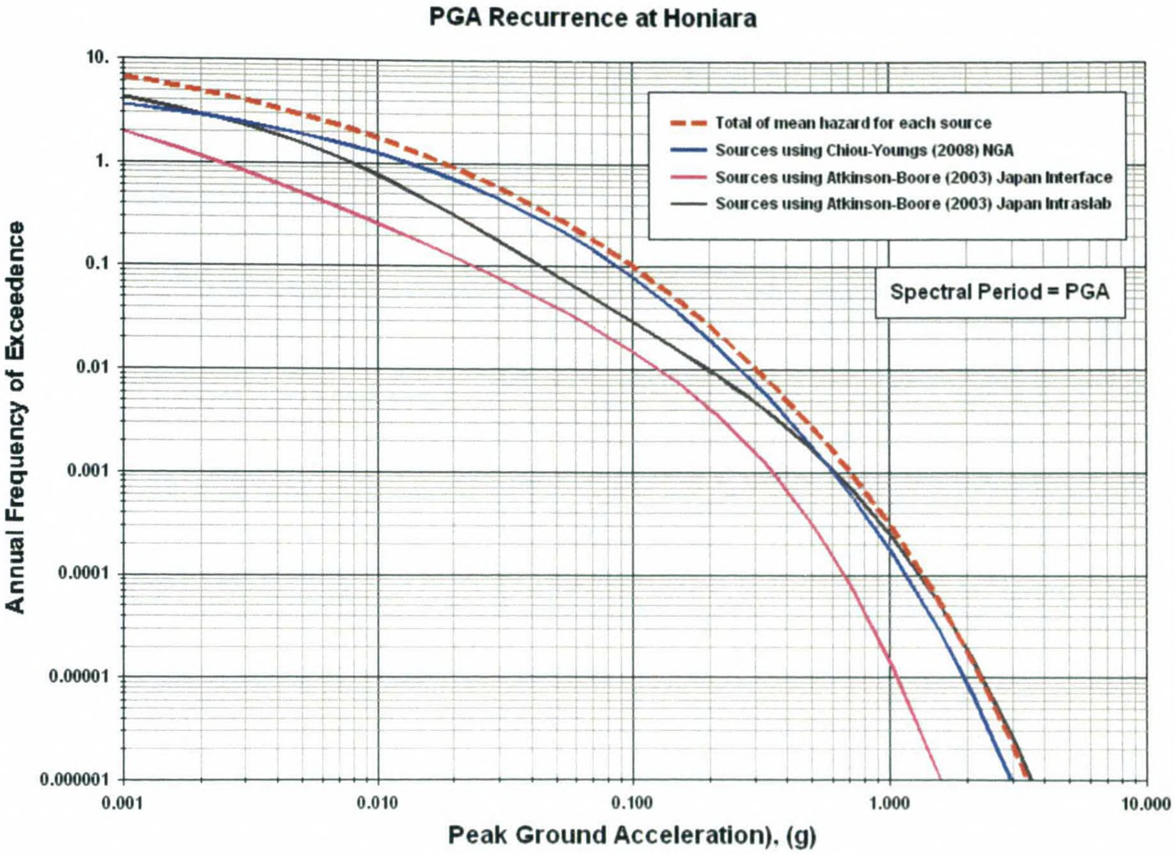

Figure 66: PGA recurrence for Honiara.
Results for bedrock motion, considering magnitudes 5.0 and higher.

Figure 66 shows that the hazard was dominated by shallow nearby source zones, with contributions from the subduction zone events giving a slightly higher proportion of the hazard for stronger motion. This plot gives PGA, and a higher proportion of the hazard will be from subduction events for longer period motion.

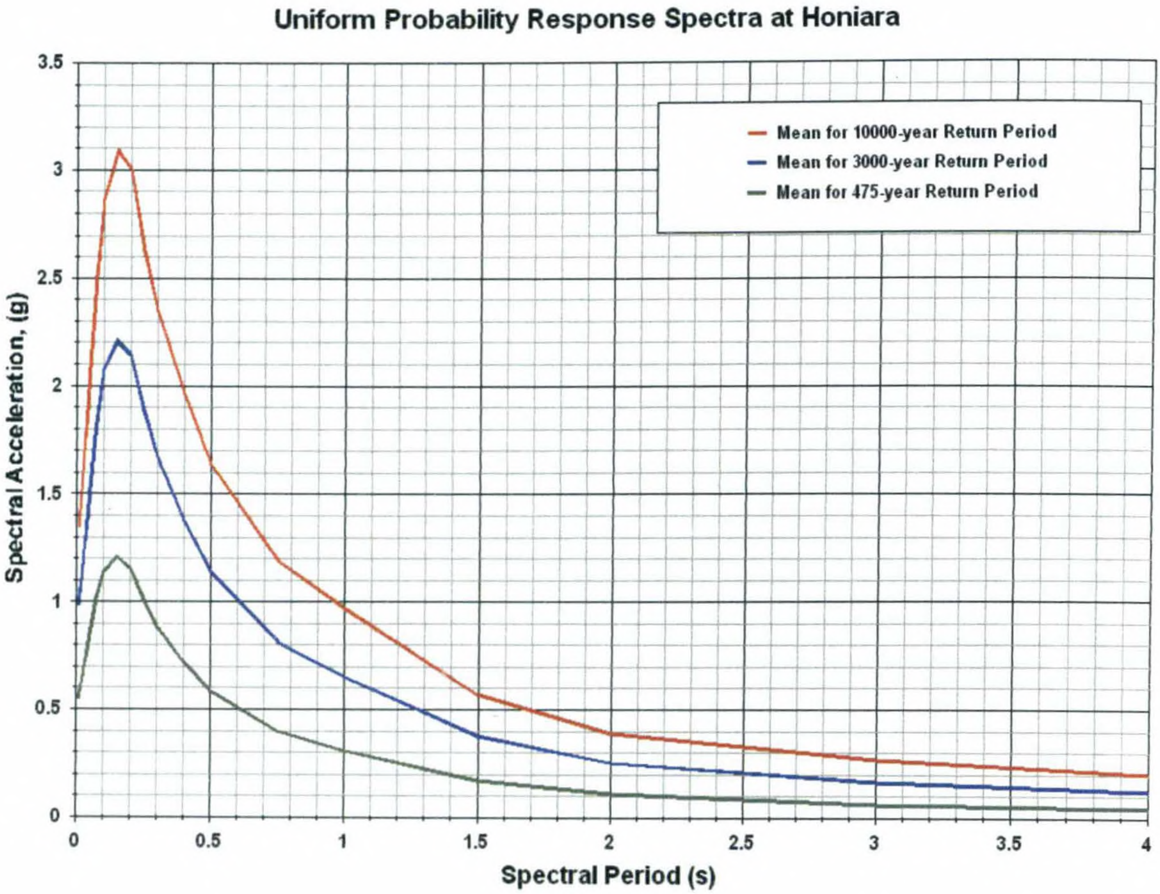

Figure 67: Response spectra for Honiara.

These uniform probability response spectra are for bedrock, using magnitudes from 5.0.

Figure 67 shows the uniform probability response spectra curves for 475, 3000, 10000 year return periods. Spectra for other return periods can be derived by re-calculation, or approximately by interpolation.

7.9 Earthquake hazard map

7.9.1 Response spectra

Spectral ground motion recurrence was finally computed by integrating the probabilities of motion from all earthquakes in space (longitude, latitude and depth), magnitude (from negligible to maximum credible), and frequency of motion. The complex integration required the use of the software EZ-FRISK program (McGuire, 1993), which resulted in the computation of the spectral ground motion recurrence at a point. The process took up to two hours processing time per point depending on the complexity of the seismotectonic and attenuation models. To produce a hazard map, the process would be repeated at many points on a grid typically covering the region. A high-resolution hazard map for the region will be computed using the models developed here, preferably in an iterative process.

7.9.2 Strong Motion and attenuation

Ground motions from earthquakes were specified as a function of distance, magnitude and other parameters. Attenuation functions were derived from empirical data. As considerable instrumentation is lacking in most places and very limited in PNG, attenuation functions derived using data from other places that are geologically and tectonically similar are applied until local data are available. The applicability of these relationships was checked against the performance little local data that is available. Local attenuation affects estimates of local earthquakes, especially smaller events, so variations will affect the magnitude estimates of the earthquakes in the catalogue, used in stage one.

Seismic acceleration attenuation relationships for the entire PNG region were adopted from similar tectonic regions, such as those for Japan, as local data is lacking to derive own. These were used in place of local data, and were synthesized with the distribution of seismicity, regional geology and tectonics of the region to produce a new map of seismic zoning. The resultant maps closely match the distribution of shallow seismicity and regional geology.

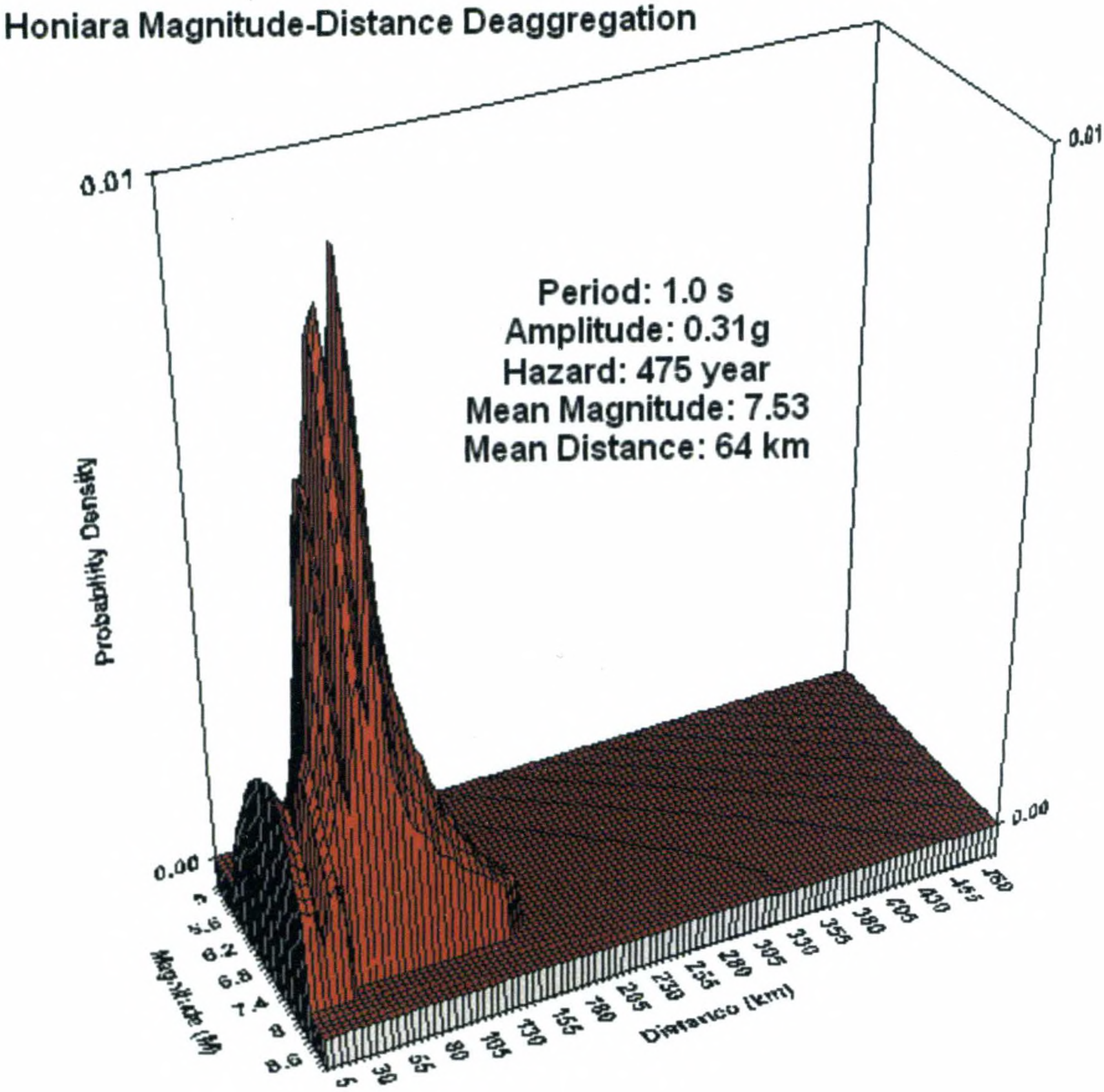

Figure 68: Magnitude-distance deaggregation for motion at Honiara.
Results for bedrock motion of period 1.0 seconds, considering magnitudes 5.0 and higher.

Figure 68 is the magnitude-distance deaggregation plot that indicates typically intense activity shown by other sites of the subduction zone (New Britain-Bougainville-Solomon Islands Trench and Arc system). Earthquake contributing most to the hazard range in distance up to about 160 km, with a small but notable contribution from shallow nearby events within 20 to 30 km.

Chapter 8 Discussion

8.1 Earthquake hazard and risk

One aspect of earthquake hazard is strong ground motion generated by earthquake shaking. This is expressed by ground acceleration, velocity and displacement, but most commonly acceleration. Earthquake hazard or ground motion can be represented by values of seismic intensity.

As the PNG region is a region of significant seismic hazard manifested in intense earthquake activity, it is important to understand the hazard as much as possible so as to properly mitigate the risk that is involved. Three factors are involved, and which greatly affect ground motion intensity. These are seismic source, seismic attenuation and site response. Being so geologically and tectonically complex, the region is subjected to ground shaking from earthquakes where waves are generated in varied ways and are subjected to diverse shallow or near-surface rock-type complexities.

Ground motions of current and past earthquakes are estimated using newer available methods to predict ground motions that may result from earthquakes in the future. Conditions having effects on strong ground motions have been listed (Somerville and Graves, 2003) as near-fault rupture directivity effects, crustal waveguide effects, and basin response effects. These may be based on magnitude-distance relations affecting ground intensities during shaking and soil conditions that make up the medium of seismic wave travel.

8.1.1 Source zones

First to determine are seismic sources zones. In this study seismic source zones are identified using seismicity (particularly shallow seismicity) with added constraints from regional geology and geophysics data, as well topography, bathymetry and geography. This emulates a multi-tier approach proposed by Brown and Gibson (2004) for Australia which can have applications for PNG, envisaging that some source zones are better defined by and with other data rather than seismicity alone. This is the most difficult part of the process, which includes evaluating faults and estimating the magnitude distribution of earthquakes that are expected to be produced, and involves determining average slip rates per fault. For purposes of seismic hazard analysis the practice is to assume uniform earthquake distribution for source zones within and away from major faults. And for the PNG region at this stage, fault zones are not analysed separately.

8.1.2 Seismic intensity attenuation

This is the condition by which earthquake ground motion intensity or amplitude decrease with increasing distance from the epicentre or region of earthquake rupture, due to energy absorption, geometric spreading and dissipation. These factors are determined by the characteristics of transmission medium with which the seismic waves are propagated from point of rupture outwards. Ground motion attenuation describes the level of ground shaking as a function of distance from the earthquake source.

However, the diverse structural fabric, and the co-existence of tectonic boundary styles with complicated geometries have made it all the more difficult to assign suitable attenuation relationships which appear to vary (Ripper, 1992), indicated by the few strong motion data that exist. Recording instruments and better coverage is required.

8.1.3 Site response

This is the effect of local, shallow geologic structure on waves generated by earthquake rupture and its' influence on ground motion. The effects vary from geologic types such as sediments (soft rock) causing waves to slow down (low velocity) and amplifying ground motion intensities, to basement rock which speed up waves (high velocity) and cause amplitudes to decrease (attenuate). Four rock-types are commonly recognised by seismologists, for purposes of keeping methods simple. These are hard rock, weathered rock, old compact sediments, and young unconsolidated sediments.

8.2 The influence of tectonic models on hazard estimates

It is important that accepted tectonic models represent the sources of seismicity in the region, as current ones may not. It has been recognised that the structural fabric consists of an existing array of lithospheric blocks. Subjected to ongoing debate and re-modification of the plate configuration, the model adopted is developed having checked details of against relevant data now available, and compared with the work by many workers. In particular, the use of seismicity, regional geology, geophysics, and geodesy data have confirmed the existence of source zones that define the existence of these blocks. Careful look at the data is revealing more plate blocks that were not recognised previously.

8.2.1 Complex tectonics

Seismicity of PNG is amongst the most intense in the world. As is any earthquake-prone regions, in PNG the earthquakes occur mostly along plate boundaries and within broad regions of plate deformation. The most intense seismic zones have been along subduction zones, but there are zones of sea-floor spreading as well as zones of transform faulting, mostly left-lateral shearing which typically dominates northern PNG. Earthquakes define quite well specific source zones, including those at depth.

The offshore topography of the region clearly show features outlining some of the tectonic elements that exist – including regions of depressions indicating trenches and valleys, outline some of the existing lithospheric segments or blocks. Onshore, known geological features such as Quaternary faulting give some indication of the edges or rather zones indicating blocks which seismicity at all depths over the entire region define clearly many of existing blocks.

The significance of the existence of numerous tectonic blocks may be that the activity defining these blocks becomes responsible for continuous stress release, therefore resulting in lower stress accumulation that are indicated by high b-values determined in the study. Such regions include the subduction zones of New Britain and Bougainville. Further, and as a result of the existence of numerous blocks co-existing in the region, possible rupture lengths are significantly reduced. The maximum rupture length anywhere in the region may be between 500 km to 600 km. This is far less in comparison by more than a half the kind experienced during the December 2004 Northern Sumatra Earthquake.

Klootwijk *et al.* (2003) categorised the region from Tonga in the east to Sulawesi in the west as a mega-shear zone developed by the interaction of the three major plates in the region, namely the westward moving Pacific Plate, the northward moving India-Australia and the almost stationary Eurasian Plate in the west. This is basically the cause of the development of the complex tectonic structural fabric manifested throughout the region that is resulting in mountain building processes and the creation of the complex array of plate blocks that exist herein.

PNG is situated within this region, rather, on the western edge of the Melanesian Subduction Zone system, which is a system extending to a wide-slab length of about 4,400 km eastward from New Guinea Island in the west (Schellart *et al.*, 2007). This length of plate subduction system was initially linear about 10M years ago but during time both the eastern end, and the PNG end retreated (migrated) trench-ward and evolved faster than the middle of the subducting plate (being the Pacific Plate). The consequent of this is evident by the curvature in the trench system, manifested in the 90° bend on the New Britain Trench. As the plate edge curved and retreated trench-ward, plate edge fragmentation occurred and therefore formed numerous blocks that now exist, primarily as a consequence of the regional tectonic setting, being on the slab edge.

The approach and arrival of during time since 25Ma and now docked massive OJP in the east at the Solomon Arc since 6Ma, at about the time of commencement of the retreat of plate edge (Schellart *et al.*, 2007), had only contributed to this already ongoing complicated tectonic structural fabric. The OJP was too thick and buoyant to subduct at the Bougainville-Solomon Trench when it arrived there about 12-6 million years ago, and consequently caused a reversal of the SW-directed subduction to NE-directed subduction (Yan and Kroenke, 1993; Petterson *et al.*, 1999; Mann and Taira, 2004). This feature is now a significant source of most seismicity in the region.

The evolving tectonic plate fragments have developed various tectonic boundary styles consequently, including subduction of the Solomon Plate at both this OJP/Pacific Plate front and the South Bismarck Plate front in the west. The subduction of the Solomon Plate is in turn responsible for the opening of the Woodlark and Manus Basins evidenced by segments of seafloor spreading, which are appropriately linked by transform faults at respective regions.

The reality of lithospheric plate or block interactions may be that at the front of the Pacific and South Bismarck Plates, the Solomon Plate is being annihilated and possibly taken out of existence in the region.

Farther in the west, the Birds Head region has been described as a fragment of Pacific Plate involved in the subduction process now being sheared away from the collisional axis, and that the Seram Trench have had to accommodate for this process (Pubellier and Ego, 2002). Being at the western most edge of the retreating Melanesian Subduction Zone (Schellart *et al.*, 2007), this part of the island arc may have docked ahead on the northward approaching India-Australian Plate (~5 Ma), and subsequently got sheared westward by the approaching Pacific Plate in that direction (~2 Ma), pushing the Bird's Head away from the main strain zone (Pubellier and Ego, 2002).

In the meantime along the centre of the subduction zone, the region between the New Britain-Bougainville Trench and San Cristobal Trench migrated or moved very little, either trench-ward or away from the trench. As was determined by Schellart *et al.* (2007), the subduction zone in the centre was either stationary or doing the opposite, advancing. For this region the central San Cristobal segment is nearly stationary with a neutral overriding plate, while the New Britain and New Hebrides segments on both plate edge ends are retreating, and respectively inducing back-arc spreading (Manus and North Fiji basins).

Uplift on the Solomon Island Arc is caused by northeastward subducting Solomon (and/or Woodlark) Plate and the collision of the India-Australian Plate with the in-placed massive, thick and buoyant OJP on the Pacific Plate front. Further to the east in the Solomon Islands there is evidence of southwest-directed subduction that is suspected to still persist from the Shortland Islands to Guadalcanal (Mann and Taira, 2004). This may be the cause of compressional convergence directed from both directions, and this being the accommodation zone.

The PNG seismicity was examined, especially at depth, in 2-D and 3-D, and was attained from this an understanding focused at strengthening the current perceptions of the existing tectonic structural fabric. It was further attained a better understanding of the tectonics of the region, especially that at depth for the purposes of redefining the regional understanding of lithospheric plate configuration, and the eventual attempt to use this understanding to improve the earthquake hazard determinations.

It was revealed aspects not previously recognized. The occurrence of seismicity in the trend descending with and defining features of the sinking lithospheric slab at depths particularly within subduction zones, expresses well the spatial characteristics of segments of plates.

The seismicity of the region is a result of the convergence, within PNG, of the major India-Australia and Pacific Plates. Observations made by many investigators indicated that the region of collision is complicated with the existence of numerous tectonic blocks. The existences of these minor plates span the length and width of the region from western Solomon Islands through northern mainland PNG to eastern Indonesia in the west, and further. These blocks or fragments of lithosphere appear from existing data to be numerous. Lithospheric segments detached from subducting plates (particularly the Solomon Plate) are now source zones rather then separate existing tectonic blocks. Being squeezed in the collision zone of the major plates of the region is suggesting that current trends may continue as plate fragmentation will continue. Geodetic measurements through GPS observations have indicated high rates of block rotations and the process of mountain building being envisaged as fast as any arc-continental collision zone. With intense seismicity resulting from high rates of plate movements, many more tectonic blocks or plates may have gone unrecognized yet (Wallace *et al.*, 2004; 2005).

Ripper, Letz and Anton (1996) summarized the seismicity of the PNG region in depth ranges, and attributed the occurrences of earthquakes to the complex tectonic structural fabric. Anton *et al.* (2008) noted that the existing plate configuration is complex and that no one model is preferred as being the correct one.

Mountainous topography of New Guinea highlands is created by active tectonics of the more than 1000 km long chain fold-and-thrust belt, an example of continental-arc collision by highly oblique convergence. Deformation of crust as evidenced by intense earthquake activity is both compressional and left-lateral shear, with depths of thrusting ranging within 2-5 km and strike-slip ranging with 7-10 km (Abers and McCaffrey, 1988). There is clear evidence that thrust faulting is both thin-skinned and thick-skinned, involving basement at high angles therefore resulting in crustal thickening (or shortening), and that most left-lateral faults parallel the mountain front.

8.3 Structural fabric

The complex tectonic structural fabric making up the PNG region is resulting in the intense regional seismicity. Numerous tectonic lithospheric blocks are envisaged to exist in the region, which is essentially the collision zone of the major Pacific and India-Australia Plates. The collision is not simple compressional but highly oblique, causing left-lateral shearing across most of northern PNG. Higher rates of plate interactions are proposed as being the result of faster rates of plate edge retreat trench-ward, here being the Pacific Plate. This is causing the plate edge to fragment and resulting in respective fragments to move independently of each other thus generating higher levels of seismicity.

Therefore, while lithospheric blocks may be numerous causing many earthquakes and contributing higher levels of seismic hazard, on the other hand the same blocks are responsible for the reduction in the number of very large events. Long lengths of possible fault ruptures are reduced by the existence of smaller plate blocks resulting in frequent occurrences of smaller to moderately sized events.

Several models of the array of tectonic plate blocks in the PNG region are understood to exist, although no one model of the plate configuration is preferred (Anton, Gibson and McCue, 2008). The boundaries are identified from seismicity, with added constraints from regional geology, volcanism, topography, and taking into account relative plate velocities from moment tensor solutions, geodesy and geophysics including magnetic anomalies in the case of Manus Plate by Martinez and Taylor (1996) and South Bismarck Plate by Weiler and Coe (2000) for Palaeomagnetic rotation rates in the Finisterre Range, as well as much more from literature. Identified are plate blocks including Caroline in the west, North Bismarck Plate (Tregoning, 2002), Manus Plate (Martinez and Taylor, 1996), Adelbert Range Block (Wallace *et al.*, 2004; Anton *et al.*, 2008), South Bismarck, Solomon Sea, Woodlark Plate, Solomon Island Block (Petterson *et al.*, 1999; Mann and Taira, 2004; Anton *et al.*, 2008), possibly a Papuan Peninsula Block (Anton *et al.*, 2008), New Guinea Highlands Block (Wallace *et al.*, 2004; Anton *et al.*, 2008), Maoke (Bird, 2003), Cenderawasih (Bird, 2003; Anton *et al.*, 2008), the Mamberramo-Sepik Basin Block (Anton *et al.*, 2008), North New Guinea (Anton *et al.*, 2008) and Bird's Head (Bird, 2003; Pubellier and Ego, 2004; Anton *et al.*, 2008).

Free-air gravity anomalies for the New Guinea and Solomon Islands regions (Mann and Taira, 2004), were also used while the Papua Province of Indonesia studies by Abers and McCaffrey (1988) and Pubellier and Ego (2002) were considered with available geology at a regional scale, while the study of active subduction of New Guinea Trench by Tregoning and Gorbatov (2004) was used. In the Solomon Islands region, Mann and Taira (2004) showed evidence from earthquake profiles the existence of NE subduction along the south-lying SE trending New Britain-San Cristobal Trenches. As well, profiles show SW subduction along the north-lying SE trending Kilinailau-North Solomon Trenches, but are indicating that this SW-dipping slab is less seismogenic.

The USGS model presented by Bird (2003) does have a south-lying Woodlark Plate running the length of PNG from the Sepik Basin in the northwest to the Woodlark Basin in the East. A division of this for a separate New Guinea Highlands Block (NGHB) is preferred, as recognized by Wallace *et al.* (2004), but to border the Woodlark Plate around the Aure Trough and defining a northern boundary of a separate Papuan Peninsula Block. As well, the NGHB includes the central part of PNG Highlands and ends at about northern New Guinea in the Sepik Basin in the north and includes Maoke of Bird (2003). There is also a preference for a separate Adelbert Block as indicated by Wallace *et al.* (2004) from geodetic data, a Mamberram-Sepik Basin, Cenderawasih Bay and Northern New Guinea Blocks.

Tregoning *et al.* (1998, 1999, 2000), Tregoning and McQueen (2001), Tregoning (2002) and Wallace *et al.* (2004, 2005) have confirmed from geodetic measurements through GPS observations the existence of several plates in the region, complimenting work achieved through seismological investigations, in particular findings from Centroid Moment Tensor solutions (Abers and McCaffrey, 1988), and seismic reflection (Hamilton, 1979), and Palaeomagnetic data (Martinez and Taylor, 1996; Weiler and Coe, 2000). These and many other studies have been for very localized and specific studies.

8.3.1 Convergence of major plates

The major plates, the Pacific Plate in the east and the India-Australia Plate in the southwest, are not in direct contact in the PNG region. The interactions at the respective plate fringes across the entire region are between the fragments of lithosphere break-offs now become trapped and re-arranged. These plate blocks, referred to as buffer or minor plates, are continuously evolving and motions of are subject to the relative motions of the others. Plate boundaries are not static, and inherently change as plates move. Anderson (2007) compares plates with floating bubbles or foams, constantly coalescing and changing shapes and sizes. Islands of bubbles can move coherently even though they are far from rigid. At times they may swap to a neighbouring 'plate'. Definitions of plates usually do not consider the origin of the rocks within any sub-plate or block – only relative movement.

In the west, the Pacific Plate is being pulled forward (westward) by its' own sinking/subduction at the Philippines and Japan Trenches north of PNG, and subduction at the India-Australia Plate front along its Indonesian margin. All tectonic earthquakes and processes in the PNG region are derived from this collision (Ripper and Letz, 1991). A tectonic lithospheric plate configuration of the PNG region was developed from available data and literature by investigators working mostly with seismic, geodetic and palaeomagnetic data (Anton *et al.*, 2008).

The OJP which is a predominantly thick crust occupying the leading edge of the Pacific Plate and being too buoyant to subduct, is the source of most seismicity in the region, coupled with the subduction of the Solomon Plate at both this front and the South Bismarck Plate front. The subduction of the Solomon Plate here is in turn responsible for the opening of the Woodlark and Manus Basins – convergence is thus facilitating extension in the region. In fact, the reality may be that the Solomon Plate is being annihilated, and taken out of existence in the region.

8.3.2 Buffer Plates

The direction of the motions of the major India-Australia and Pacific Plates are northeast and west-northwest respectively. Within the collision zone there exist several minor plates. The Solomon Plate lies to the southeast and is subducting north-northwestwards beneath the New Britain plate front of the South Bismarck Plate. The South Bismarck, which lies in the centre, is in turn advancing southeastward. GPS observations by Tregoning *et al.* (1998, 1999, 2000) and palaeomagnetic rotation rates observations by Weiler and Coe (2000) in the Finisterre Range provide confirmation of movement of the South Bismarck Plate. Available data in present times is revealing the existence of numerous other blocks.

The Solomon Plate is also subducting beneath the northeastern mainland PNG (Pegler *et al.*, 1995), and sinking westward, as far west as 142°E and possibly further west (Ripper *et al.*, 1996). As well, the Solomon Plate is subducting northward and arching in the region of southern/central New Ireland, and also subducting northeast beneath Bougainville front of the Pacific Plate.

With the southeastward advance of the South Bismarck Plate, the Bismarck Sea is being pulled open to form the back-arc basin, i.e. the Manus Basin. Earthquake activity on the spread zone indicate left-lateral strike-slip movements with evidence of off-set transform faulting (Taylor, 1979; Taylor, Crook and Sinton, 1994; Martinez and Taylor, 1996) especially in the eastern end, with associated normal faulting, typical of extensional plate boundary earthquakes.

Likewise, the Solomon Plate is being pulled forward to the northwest by its own sinking beneath New Britain, pulling open the Woodlark Sea and creating the Woodlark Basin. Earthquake activity in the Woodlark Basin indicates normal and strike-slip faulting within the east-west trending seismic zone, again typical extensional plate boundary activity.

8.3.3 Convergence

Minor plates buffer the collision zone within the region, from the Solomon Islands in the east and as far west as the Caroline Plate. Convergence involving actual contact between the two major India-Australia and Pacific Plates is not possible anywhere within the region, as shown in Figure 69.

Anton, Gibson and McCue (2008; their Figure 5) proposed that the region is a diffuse volume plate boundary that includes small plates or blocks with multiple faults. Figure 69 shows the region of the two main plates, made up of intertwining and co-existing blocks that represent the whole zone of activity as the collision zone.

To the northwest, the mostly offshore Solomon Plate is converging beneath the eastern New Guinea – New Britain – southern New Ireland and Bougainville region, marked by the New Britain Trench. There may also be southward convergence marked by the currently less active Trobriand Trough. It does appear that the subduction of the Solomon Plate within the region is resulting in the eventual and complete annihilation of the plate in the region, consequently resulting in intense earthquake activity at all lithospheric plate fronts.

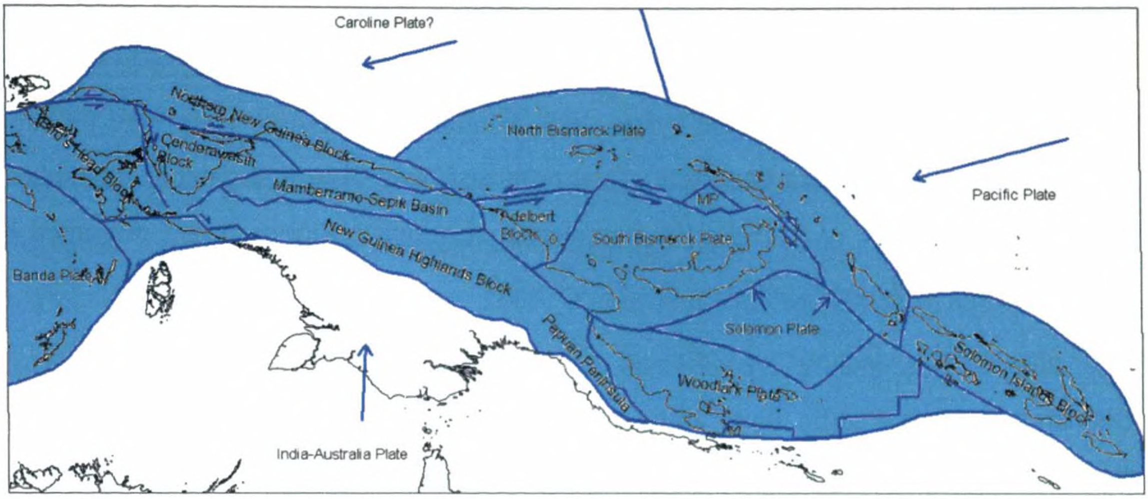

Figure 69: Collision zone of the Pacific and India-Australia plates.
Regions shaded in blue and representing a mega shear across the region (Anton et al., 2008).

The other zone of convergence is that between the South Bismarck and India-Australia Plate along northern New Guinea, marked by the New Guinea Trench (NGT). Geodetic observations through GPS measurements by Tregoning and Gorbatov (2004) provided conclusive evidence of southwestward subduction along the entire length of the NGT, in Indonesia and in PNG. Prior to this other workers have had slightly different views on the tectonic processes involved, for example Milsom *et al.* (1992) who concluded from sidescan radar imagery that the NGT is a relic feature and that convergence is taken up by crustal deformation with New Guinea. While Endaghl *et al.* (1998) identified a flat lying subducting slab far to the west at 138°E, Hall and Spakman (2002) found no evidence of subduction from their seismic tomography model.

Eastward from Wewak, the southern boundary of the South Bismarck Plate is prominently marked by the northwest trending Markham-Ramu Fault or suture zone, where southward over-thrusting of the coastal ranges of Adelbert-Finisterre-Sarawaget is occurring. It is proposed that the fault is locked at significant portions therefore possibly increasing the seismic hazard (Wallace *et al.*, 2004).

A significant evidence of convergence in this region is the migration of crustal folding and thrusting, more than 300 km from the northern coast of New Guinea to the region of the Papuan Fold Belt in PNG and Irian Jaya Fold Belt in Papua, Indonesia. The northwest-southeast striking features are the result of internal deformation of the India-Australia Plate front due to intense convergence across New Guinea. The seismic zone here probably better serve as the southern boundary of the proposed New Guinea Highlands lithospheric block, by Wallace *et al.* (2004), the boundaries of which are revised and presented by Anton *et al.* (2008).

The zone of less intense convergence in the region may be that between the North Bismarck and the Pacific Plate along the West Melanesian Trench. Seismicity in that region, outlined by a pronounce bathymetry depression, may be less intense but is active. Weissel and Anderson (1978) suggested the existence of North Bismarck Plate, but Curtis (1973), Krause (1973) and Taylor (1979) didn't concur. Tregoning (2002) concluded from geodetic data the independent existence of the North Bismarck Plate.

8.3.4 Extension/sea-floor spreading

The zones of crustal extensions responsible for basin development are the areas of the Woodlark Basin in the Solomon Sea, and Manus Basin in the Bismarck Sea respectively. Within these zones are the boundaries between the India-Australia and Solomon Plates, and North and South Bismarck Plates respectively.

Associated earthquake activity is shallow and fault plane mechanisms determined from first motion data appropriately consistent. As well, focal mechanism solutions show segments of sea-floor spreading being linked by segments of transform faulting.

The region west of Woodlark Basin and Rift system has been investigated in detail and discussed (e.g. Weissel *et al.*, 1982; Taylor *et al.*, 1999) as the zone of continental rifting, one of only known few fastest on Earth – in particular apart from the Gulf of Aden, the Red Sea, and the Gulf of California. The rifting develops in to full-scale sea-floor spreading towards the east within the Woodlark Basin (Ferris *et al.*, 2006).

8.3.5 Transform faulting

Transform faults are prominent geological features, many having been identified and known to have moved in recent times. In PNG, most of these zones are well-defined plate boundaries, apart from other zones of fracture.

One such zone is the Weitin Fault of southern New Ireland which was significantly displaced during the 16 November 2000 southern New Ireland Magnitude 8.0 (Mw) Earthquake (Itikarai and Tregoning, 2003; Anton and McKee, 2005a; Tregoning *et al.*, 2005). This left-lateral fault system marks the boundary between the Pacific and South Bismarck Plates.

The other zones of prominent transform plate boundaries are the Ramu-Markham Fault System and the Owen Stanley Range Fault System, which are boundaries of the India-Australia and South Bismarck Plates and India-Australia and Solomon Plates respectively.

Transform faults have also been identified within regions of sea-floor spreading, linking zones of crustal extensions, in the Woodlark Basin and Manus Basin (Taylor, 1979).

8.4 Earthquake distribution

Seismicity is envisaged to be one of the most intense in the world. In average, about two magnitude earthquakes of 7.0 and above occurred every year.

However, seismic stations coverage is still poor, making difficult earthquake location and magnitude determinations thus these having significant errors.

In terms of earthquake effects, damage is mitigated by the great depth of many PNG earthquakes, particularly those generated by subducting lithospheric slabs. Many earthquakes within sinking slabs or segments of slabs beneath Bougainville, northern New

Britain and the Markham, Ramu and Sepik Valleys are at depths that exceed 70 km (Ripper, 1992).

8.4.1 Lack of seismic coverage

Without local and regional seismic networks, earthquake locations by the global seismic network are not properly constraint and are known to be out of location by tens of kilometres, i.e. huge location errors, and incorrect magnitudes being assigned. Strong motion equipment to accompany local networks is to provide added constraint on local attenuation characteristics. The reason for this being that for a region of very complex geology and tectonics, where seismic attenuation is known to vary significantly from site to site, it has been envisaged that no one attenuation relationship exists for the whole of PNG. Ideally attenuation relationships must be developed for individual local sites.

8.4.2 Large earthquake location errors

Tregoning and Gorbatov (2004) expressed the need for improved seismic station coverage to appropriately enable delineation of features of seismicity at higher and better resolutions. The consequences of poor seismograph coverage had resulted in the huge errors in magnitude determinations, mostly at higher magnitude thresholds. Large errors in earthquake locations and poor depth constraints have also resulted.

Taking these in to account, earthquake data catalogues are certain to be incomplete for the 30 to 40 years of recording locally and regionally, and globally (very patchy with huge errors) since 1900. The longer the cataloguing period is extended, the more uncertainties and huge errors are allowed to creep in. For any work, the best data available would be that from about 1964 to current times, from when the regional and global networks of equipments improved enormously.

The findings include the confirmation of known concepts of seismicity of the PNG region including what is known about the existence of subduction zones, expressed clearly by Wadati-Benioff zones beneath New Britain and Bougainville. Depths of earthquakes here are as deep as to more than 600 km. The surface expression of the subduction zones is the New Britain Trench. While the subducting slab is a perfect Wadati-Benioff zone beneath New Britain, the slab is sinking vertically downwards west of Bougainville and includes a kink at intermediate depth. The possible explanation is being the effect of the buoyant OJP on the front of the southwest approaching Pacific Plate unable to subduct. It may be also proposed that possible doming and uplift of New Britain and southern New Ireland, and associated fault systems trending NW-SE, are the result of the effect of buoyancy exerted on the over-riding plate(s) at respective regions by the sinking Solomon Plate.

In the west, the sinking Solomon lithospheric slab beneath northeastern New Guinea is marked by intermediate depth seismicity. Above this is the shallow seismicity resulting from the collision of the South Bismarck Plate with the India-Australia Plate. Extending northwest through eastern New Guinea and east throughout New Britain is a shallow seismicity associated with plate convergence at respective locations. Shallow seismicity due to cross-fault activity also exists. These features exist throughout the entire New Guinea/Bismarck Volcanic Arc, and are a result of the plate front deformation and fracturing due to convergence with obvious accommodation zones. Cross-arc features are fault zones which act as terminus of rupture propagations along the main stress axes and orthogonal to the tectonic trends. They have orientations orthogonal to the strike of the main pattern of faulting. In the west, on the region of north coast of mainland PNG the axis of faulting is oriented east-west as documented by Anton and McKee (2005b), where it was noted the occurrence of two magnitude 6 earthquakes on an orthogonal feature which was assumed to terminate the rupture of the 8 September 2002 Wewak Earthquake.

8.5 The earthquake hazard

In this region of complexities, it is envisaged that no single attenuation relationship will apply over the whole region (Ripper, 1992). Ideally spectral attenuation relationships for the PNG region should be derived from analysis of local seismograms and strong motion accelerograms.

However, at this stage attenuation relationships that have been derived using data from regions with a similar tectonic environment outside of PNG are selected for use. These can be checked against the available PNG strong motion data, in a later stage of the project. These data include a collection of accelerograms recorded on medium or soft foundation, some of which have been analysed by the then Bureau of Mineral Resources, Geology and Geophysics (now Geoscience Australia) and others have been analysed by PMGO (Ripper, 1992).

8.5.1 Great PNG region earthquake doublets

The aftershock distribution of major earthquakes usually clearly show different tectono-structural elements involved in the regional stress re-adjustments. The region spanning the entire PNG region, from Papua Province, Indonesia in the west to Solomon Islands in the east, is known to have had quite a number of significant earthquakes.

Significant earthquake doublets have also occurred in the region, such as those discussed by Kagan and Jackson (1999). The well-documented earthquake doublet of the region in recent recorded history was the 14 July 1971 magnitude 7.8 and 26 July magnitude 7.6 earthquakes of northern Solomon Sea (Everingham, 1973b; 1975b; 1977). Lay and Kanamori (1980) and Schwartz, Lay and Ruff, (1989) analysed and described the source processes of these and other doublets in the region including those of 31 January 1974 (Ms=7.0) and 1 February 1974 (Ms=7.1), and 20 July 1975 (M~=7.9) and 20 July 1975 (Ms= 7.7). Listed also were other similar sequences that have occurred in the same area in 1919 – 1920 and 1945 – 1946, and from the data set Lay and Kanamori (1980) determined an apparent recurrence of 25 years. It is suggested from the analysis of sequences in this region the existence of relatively high, isolated high-stressed zones on the fault plane responsible for the occurrence of the doublets.

In more recent times had been the 16 November 2000 magnitude 8.0 (Mw) earthquake of eastern Bismarck Sea which ruptured south-eastward through southern New Ireland and beyond, and which was followed in a matter of hours by magnitude 7 earthquakes in the northern Solomon Sea and eastern New Britain respectively (Anton and McKee, 2005a; Tregoning *et al.*, 2005; Geist and Parsons, 2004; Itikarai and Tregoning 2003). The rupture associated with the first main earthquake of 16 November 2000 confirms that one component of the plate triple junction involves a dominantly strike-slip fault, consistent with the characteristics of the left-lateral fault system of south New Ireland.

However, regarding the occurrences of the November 2000 events and sequences didn't resemble any of the doublets and their sequences described by Kagan and Jackson (1999). In particular, the tight clustering in time and space of the great and the two large earthquakes which represent one of the most energetic episodes of seismic stress release recorded in PNG (Anton and McKee, 2005a). But even if both the large events had occurred at great distances from the great Mw 8.0 earthquake and both having generated their own aftershock sequences with many aftershocks occurring in coincidence with each and those of the great earthquake, Geist and Parsons (2004) determined that both earthquakes could not possibly qualify as another doublet of the region. They are worth a mention though.

Overall, some of these great earthquake sequences possessed features rendering them highly significant, not only locally, but also regionally and globally.

8.5.2 Surface effects of significant earthquakes

Observations and documentations of surface faulting from earthquakes in PNG have been few. Investigations have been limited as result of remoteness, landslides that follow earthquake shaking covering fault traces, possibly the general harsh environment making difficult accessibility and mostly with the lack of resources normally required to carry out investigations soon after the occurrence of significant events.

However, two significant observations of surface faulting following earthquakes have been made. The first was on mainland PNG in the Gusap Valley, on the southern foothills of the Finisterre Mountains following the M 7.1 earthquake (the second of a doublet) on 25 October 1993 (Tutton and Browne, 1994). The second was on southern New Ireland, where a displacement greater than 5 metres was observed on the Weitin Fault following the Mw 8.0 earthquake of 16 November 2000 (Itikarai and Tregoning, 2003; Anton and McKee, 2005a).

Further, there are known events associated with significant uplifts at the time of initial rupture or during large earthquakes. Carey (1990) related experiences at the time of the 1935 Torricelli Mountains Earthquake, during which items were thrown upwards, defying gravity, and Marshall (1937) documented extensive landsliding of whole mountainsides. Also at Gasmata in 1920, after a magnitude 7.7 earthquake water from the harbour rushed out and did not return, indicating permanent uplift.

Everingham (1974) indicated in a study that lists large earthquakes in the New Guinea – Solomon Island region, that uplift and subsidence characterise the entire region and occur at a significant rate, especially of coastal regions, at least during the Holocene.

Although significant Quaternary fault systems and regions of Quaternary uplift do exist in places in PNG, there may be little or no associated seismicity. Notably, these regions constitute a significant seismic hazard. Shallow seismicity is more a reliable indication of the location of geological features, particularly faults, especially where earthquake distributions occur linearly and continuously.

Most earthquakes on plate boundaries are usually deeper then those related to associated faulting, where the ruptures extend to within a few kilometres of the surface. The surfaces in many instances are not ruptured, making it impossible to identify continuous fault offsets. As well, earthquakes may have occurred offshore or there have been occurrences of numerous landslides and ground cracking, especially on hillsides making impossible identification of fault slips.

Many surface ruptures have not been observed, although they surely would have occurred. Remote locations, landslides covering fault traces, and the general harsh environments are probable reasons. Not all recognised or inferred Quaternary fault systems appear to be seismically active, but where a confirmed Quaternary fault appears to be inactive, a level of seismic hazard must be inferred. Active shallow fault systems are indicated by the contemporary seismic activity itself, despite non-recognition of specific active faults.

Table 9: Earthquakes with significant observed tectonic effects.
These data have been gathered by the Port Moresby Geophysical Observatory.

Date	Place	Mw	Effect
15/12/1907	Northern New Guinea	7.3	Subsidence
20/09/1935	Northern New Guinea	8.0	Uplift
13/01/1941	New Britain	7.0	Horizontal displacement
31/10/1970	Adelbert Range	7.0	Slumping; tsunami
25/10/1993	Eastern New Guinea	7.1	Vertical displacement
17/07/1998	Northern New Guinea	7.1	Submarine slumping; tsunami
16/11/2000	Southern New Ireland	8.0	5.5 m horizontal & 40 cm vertical displacements; tsunami
08/09/2002	Northern New Guinea	7.8	30-40 cm uplift; tsunami
01/04/2007	Gizo, Solomon Islands	8.1	3 m uplift; tsunami

8.5.3 Fracture zones

The seismicity is a result of active tectonics, thus the intensity of, and which is derived from the continually evolving lithospheric plate boundaries, marked by zones of crustal deformation, as well as zones of crustal fracture. Zones of fracture may be identified along zones of large shallow historical earthquakes. Presently many of these events are identified along the New Guinea/Bismarck Volcanic Arc, particularly those associated with significant events since 1900. The most noted having been the Gazelle Peninsula event of 1941 (Fisher, 1944), the 1935 Torricelli Mountains event (Carey, 1990), the Adelbert Range event of 1970 (Ripper 1977; Abers and McCaffrey, 1994), the New Britain of May 1985, the southern New Ireland of July 1985, the Vitiaz Strait of 1987 (Abers and McCaffrey, 1994), the Finisterre-Sarawaget Range of October 1993, the eastern Bismarck/southern New Ireland event of November 2000, and the Wewak Earthquake of September 2002.

Most of these earthquakes were accompanied by extensive landsliding of whole mountainsides. Others have resulted with significant tectonic effects in either subsidence or uplift, and/or horizontal and vertical displacements. The 1935 Torricelli Mountains earthquake, which denuded mountainsides of sediment and debris in millions of cubic metres (Marshals, 1937), was reported to have objects thrown upwards from resting positions (Carey, 1990).

For the Adelbert 1970 Earthquake, Ripper (1977) obtained an overthrust focal mechanism solution consistent with the northwest-southeast strike and trend of the plate boundary, but the aftershock series is elongated to the northeast through Karkar Island (Everingham, 1975; Abers and McCaffrey, 1994). The Vitiaz Strait earthquake of 1987 had a strike-slip focal mechanism trending N-S with aftershock sequence elongated in the same direction (King *et al.*, 1987; Anton, 1992; Abers and McCaffrey, 1994).

Two events notable for inconsistency in focal mechanisms with regard to the strike of cross-arc faults, but in the strike of plate boundaries at respective locations, were the 1985 central New Britain event and the 13 October 1993 Sarawaget-Finisterre Range earthquake (the first of the doublet). While they may not have exhibited fault orientations in the general trend of the plate boundary, these earthquakes are examples of the less popular view of the whole region being in a state of extension. For the New Britain earthquake, Mori *et al.* (1987) interpreted the focal mechanism as indicative of tensional stress across the New Britain Arc. The Sarawaget-Finisterre Range earthquake similarly represents the state of stress regime within the whole arc system that is tensional.

The western New Britain magnitude 6.4 earthquake of 19 July 2006 at 1148 UTC and an aftershock at 1809 UTC, both shallow events and both had strikeslip focal mechanism solutions, having northwest-southeast trending planes orthogonal to the strike of the volcanic frontal arc and the main seismic trend. The earthquakes were followed by a swarm of smaller size earthquakes in the area of the Sulu Ranges and Karai Volcanic centres that were accompanied by hot spring activity in the nearby fields, well away from the epicentres of the two earthquakes.

The strongest activity from the geothermal sites appear to be in the line of the locations of the magnitude 6.4 earthquake and its' magnitude 6 aftershock. This observation was confirmed with damage and felt effects at Silanga Catholic Mission, a location also in the line of the sites of intense geothermal activity and the earthquake locations, which is consistent with the northwest-southeast solutions of the earthquakes. This could be confirmation of a northwest-southeast trending fault in the area, typically consistent with trends of such features common within the New Guinea/New Britain Volcanic Arc.

8.5.4 Possible earthquake fault rupture lengths

Possible rupture lengths along plate boundaries are however restricted, to only a few hundreds of kilometres making almost predictable the potential maximum credible earthquakes. Great earthquakes that have occurred in the region have been those with magnitude 8.0 and only a little higher. The southern New Ireland Earthquake of 16 November 2000 has been such an example. This earthquake occurred in the zone connecting the Bismarck Sea Seismic Lineation and the New Britain Trench, in the northern Solomon Sea, rupturing a probable length of over 200 km.

The New Britain Trench zone, from Huon Gulf to southern New Ireland and the other arm of the trench from southern New Ireland to south Bougainville are such zones that can be recognized as having potential for great subduction earthquakes. The rupture of the full length of the trench during an earthquake originating from either end of the trench is restricted by the significant bend (~90°) on the trench in the northern Solomon Sea, therefore significantly reducing the rupture length to about half. Possible lengths of rupture could therefore total only to about 400 km, accounting for a possible magnitude high of 8.5.

Apart from the zone of the New Britain Trench, the New Guinea Trench is one other such zone that could account for possible rupture lengths of several hundreds of kilometres – at least up to 500 km. In the east, the other such zone is the seismic zone extending southeast from PNG across the Solomon Islands which in fact is the convergence boundary between the Pacific (Solomon Island Arc) and India-Australia Plates, capable of a rupture length of several hundred kilometres. Here though, the deepest part of the New Britain Trench doesn't continue and the collision is not geometrically straight, viewed from existing seismicity, topographic, bathymetric and free air gravity anomaly. Further, the seismicity doesn't outline northeast subduction that is continuous in length (Wadati-Benioff zone) beneath the approaching Pacific Plate or width extending the entire Solomon Island Arc. The Woodlark Basin being subducted northeastward at the trench, and it is not certain the effect of subduction in terms of the generation of large events from the existing stress regime. However, the rupture length possible could be as long to 600 km. The magnitude 8.1 earthquake of 1 April 2007 occurred in the zone of the trench that have not ruptured at least since the early 1900s, and ruptured a segment length of about 250 km. In fact it is note that the rupture propagated through the Woodlark Spreading Ridge but got restricted as it encountered the Woodlark Rise in the NW, south of Bougainville (USGS, 2007).

It cannot be concluded though, with confidence, that these rupture lengths will not be exceeded. There is no evidence that larger magnitude size earthquakes have not occurred in these regions. Further, it is well stated that earthquakes are known to have ruptured through geometrical complexities – a lot of which is noted to exist throughout the region. It may be difficult for the 90° bend of the New Britain Trench south of southern New Ireland, but other zones not so complicated are a good chance.

The analyses of the northern Solomon Sea great doublet of 14 and 26 July 1971 (Lay and Kanamori, 1980; Schwartz, Lay and Ruff, 1989) showed evidence of ruptures on both arms of the 90° bend, firstly of the Bougainville side and than the New Britain side. The great earthquake (Mw 8.0) of eastern Bismarck Sea and the huge sequence commencing on 16 November 2000 (Tregoning *et al.*, 2004; Geist and Parsons, 2004; Itikarai and Tregoning

2003; Anton and McKee, 2005a) ruptured in the SE direction to the northern Solomon Sea, and showed evidence of adjustments of structural elements on both arms of the New Britain Trench, first by the second large event of 16 November on the Bougainville side of the trench than by the third large event of 17 November on the New Britain side of the trench.

In recent times the magnitude Mw 8.1 Solomon Islands earthquake of 1 April 2007, a rupture length of 250 km was observed along a segment of the subduction zone that did not rupture previously. While the zone ruptured NW through the Woodlark spreading ridge, rupture process may have been restricted in the NW direction. NW progress of rupture may have been in fact restricted within the Woodlark Rise (USGS, 2007).

8.5 Results of the earthquake hazard analysis

The PNG region is seismically active and large earthquakes are frequent – resulting in the very significant hazard, manifested in the results so far contained in the thesis. The hazard was determined with the upgraded earthquake catalogue and improved methods. The work began with the determination of the hazard at specific locations, herein Port Moresby, Lae, Kokopo, Madang, Buka, Wewak, Kimbe, and Honiara. It is the aim to gradually improve coverage and include other sites in PNG, and eventually covering the whole region (Anton and Gibson, 2007; 2008).

This work is envisaged to replace results from previous studies, and facilitate the establishment of the basis for the revision of the seismic zoning for building construction in PNG. Since the 1970s, other seismic hazard analyses have been undertaken for various sites in PNG, particularly dams, mines and petroleum facilities. These have been mainly based on the limited and imprecise earthquake catalogues, without detailed consideration of regional geology, geophysics (gravity and magnetic data available) and geodesy (GPS measurements in particular), most of which did not exist (Anton and Gibson, 2007; 2008).

The seismotectonic map developed is largely based on the time and space distribution of past earthquakes, with additional constraint from regional geology, geophysics, geodesy, topography; maps of which are detailed in chapter 5. This usually involves division of the region into source zones, and the identification of active faults. For this study, the faults were not identified and associated hazard not analysed separately but combined as uniform zones of seismic distribution. The area or volume source zones and the active faults are each assumed to have uniform rates of seismicity. The zones identified are more detailed than those used in past studies, and for each depth layers included some tens of source zones (Anton and Gibson, 2007; 2008; Anton, Gibson and McCue, 2008).

The seismicity in each of the source zones were quantified, giving the rate of earthquake activity as a function of magnitude, with key parameters defining the relative numbers of small to large earthquakes, and the maximum credible earthquake magnitude in each zone. Quantification considered earthquake clustering, doublets and sequences including foreshocks and aftershocks.

Chapter 9 Conclusions

The significances of the findings are immense and will benefit PNG when embraced. Both the public and private sectors are envisaged to be the main beneficiaries, particularly in the area of town planning where earthquake engineering is involved. Earthquake hazard and risk mitigation become all too important as the region matures in to nationhood, and economic security becomes apparent as infrastructures such as roads and bridges become vulnerable to shaking and damage if measures are not taken to construct to earthquake specifications. The results obtained herein are to provide a guided approach in this endeavour, and earmarked to form the basis for the replacement of building code seismic zones.

9.1 The earthquake hazard

The seismic hazard is significant. While data catalogue is short (from about 1900), the location of the region within the very active plate boundary of the southwestern Pacific makes it all the more apparent the activity that is a daily occurrence. It is the understanding that the current tectonic activity is simply implying activity of the last 1 million years – which basically is the recent times. What is seen occurring currently will continue to happen for millions years. The young geology and evolving tectonics are the underlying causes of the seismicity that characterises the region as, intense.

Earthquake activity in the region is appropriately recognised as resulting from the evolving tectonics that began tens of millions of years ago but, classified as young compared to landmasses surrounding the region such as the Australian continent, and the OJP of oceanic origin dominating the eastern front of the collision with the Pacific Plate. Active subduction commenced about 6-5Ma in the northeast direction, after the arrival of the OJP in front of the Pacific Plate, which was then approaching southwest from the northeast. The central collisional zone of mountains of height above 3 km spanning the entire length of New Guinea Island is a manifestation of intense crustal deformation. The mountain building process is a result of the continuing collision of the respective major plates in the region, and especially faster rates of plate edge shortening and crustal rotation, and thickening.

Comparing seismicity in depth range with patterns outline by regional geology, geophysics (gravity and magnetics), geodesy (GPS), topographic and bathymetric data to define seismic source zones is envisaged to improve earthquake hazard analysis. The use of these data to develop a seismotectonic model, combined with improved assessment methods and better seismic data available should have an improved effect on the overall hazard determined. Better data catalogue now available, improved seismotectonic modelling, and improved assessment methods are essentially the differences to previous attempts on the earthquake hazard assessment. These ultimately making the findings presented herein the best, and carefully curved for use in the planning within the rapidly developing region.

It is the aim that the results endorsed in the thesis will be of an advanced improvement from numerous previous studies. The results determined and endorsed are a manifestation of this. It is an effort to stay in line and on par with the growth of the country that is seriously prone to earthquake shaking, in a region that is tectonically activity.

While the earthquake risk is gradually increasing in parallel with economy growth, the hazard has always existed and remains the same. The faster the growth rate, the faster the risk becomes. It is therefore imperative to determine the hazard with acceptable accuracy, and timely for use during planning of infrastructure in towns and sites of important national projects. The geographical location of the region is unfortunate to be earthquake-prone thus endangering and increasing the risks encountered by livelihood and infrastructure. Earthquake wave propagation paths encounter medium that is very complex and therefore intensity amplification or attenuation is complicated, and varied from site to site. For this reason, it is a requirement that proper seismic equipment coverage must exist. It is required that proper monitoring at local sites to determine ground and structural response to earthquake shaking, regardless of earthquake distance, must be accommodated for.

9.2 Summary of results

The results of this work will form the basis for the replacement of the existing outdated hazard maps.

Regions of high stress release were appropriately defined by low b-values, while those of low stress indicated otherwise. In general, it was the seismically active zones of subduction where stress accumulation is low that produced higher b-values as expected. These are the areas of the New Britain-Bougainville Arcs and New Guinea Trenches. Zones of sea-floor spreading in the Bismarck and Solomon Seas also produced higher b-values, as well as the active transform plate boundaries of southern New Ireland, and Yapen Fault zone in the west. West Woodlark Rift system of eastern Papuan Peninsula and the (east) Woodlark Spreading Centre also produced high b-values.

On the other hand, regions of arc-continental transition indicated higher stress evidenced by lower b-values. Potentially these are sites of future significant earthquakes. The zones include the Bird's Neck in the west, the Papuan Fold Belt, and the connecting Aru and Aure Troughs. Manus and New Britain Trenches indicate lower stress release and are potential for future significant earthquakes. Regions encompassing plate blocks of North Bismarck, South Bismarck and Bird's Head indicate lower stress release and are possible zones of future significant earthquakes, while the Solomon and Woodlark Plates indicate otherwise.

Ambiguous results shown for regions of the OJP front in the east and the foreland in the south may be a result of data error. While there exist no apparent cause for seismicity within these stable fronts, intra-plate earthquakes are known to have occurred due to evolving stress that typically dominates the region. Many of these earthquakes may as well be recognised as such, as they could be intra-plate events. Australia, for instance is known for its' intra-plate earthquakes, and the foreland craton shares geological affinity with Australia.

9.3 Recommendations

The thesis proposes a number of things to be achieved for the purpose of realising in full the value of the study. These include:

(1) Determine earthquake hazard at other additional sites, to improve the resolution and therefore better hazard mapping

(2) Improve on the seismotectonic model developed and hazard maps covering the whole geographic region

(3) Immediate use of the hazard maps to facilitate the replacement of the existing earthquake building code

(4) Replace seismic station network to improve data acquisition required which will in turn improve earthquake hazard analysis, and sustain maintenance of the network

(5) Develop plans for the future updates of the hazard map

(6) Acquire EZ-FRISK or similar tools for immediate use, and for future earthquake hazard updates

9.4 Future work

Determination of PNG earthquakes (epicentres, depths, magnitudes and mechanisms) using a local seismograph network will reduce the uncertainty and current scatter in epicentre and depth estimates, and hence allow delineation of active faults.

Future work will increase the resolution of the seismotectonic model, particularly further re-iteration of the analysis process to include more sites, and by computing the hazard contributions by specific active faults rather than assuming uniform area source zones.

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Appendices

Appendix 1: Some PNG locations mentioned in the thesis

Place	Lat (°S)	Long (°E)	Province	Remarks
Adelbert Range			Madang	Mountain Ranges NW of Madang
Alotau	10.35	150.45	Milne Bay	Town, capital of Milne Province
Asaroka	6.04	145.32	Eastern Highlands	Village/School outside Goroka
Banz	5.68	144.62	Western Highlands	Out station near Mt. Hagen
Bewani Mountains			West Sepik	Mountain range west of Aitape, south of Vanimo, at 3°S
Biak Island			Papua (Irian Jaya)	Island north off north of Papua (Irian Jaya), Indonesia
Buin	6.83	155.75	North Solomons	Town situated on the south coast of Bougainville Island
Buka Island			North Solomons	North-northwest of Bougainville
Buka (Passage)	5.43	154.67	North Solomons	Town on Buka Island
Bumayong	6.62	147.00	Morobe	School in Lae City
Busu	6.69	147.03	Morobe	Suburb of Lae City
Cape-Gloucester	5.45	148.43	West New Britain	District station
Cateret Island			North Solomons	Island northeast of Buka Island
Chuave	6.13	145.13	Chimbu	Patrol post
Dawgenda	6.12	146.38	Morobe	Village in the Finisterre-Sarawaget Ranges
Finisterre Range			Madang	Mountain ranges NW of the Huon Peninsula at about 6° south
Finschhafen	6.60	147.85	Morobe	Seismic station and town
Gazelle Peninsula	6.60	147.85	Morobe	Northeastern part of New Britain
Goroka	6.05	145.42	Eastern Highlands	Town
Guadalcanal Island			Solomon Islands	Island in the Solomon Islands
Gusap	6.05	145.95	Morobe	Village in the Markham Valley
Halopa	5.08	145.72	Madang	Village/School NW of Madang Town
Honiara	9.43	159.95	Solomon Islands	Capital of Solomon Islands
Hoskins	5.45	150.42	West New Britain	Airport
Huon Peninsula			Morobe	Area north and northeast of Lae, about 6°S

Jayapura	2.50	140.70	Irian Jaya	Capital of Irian Jaya, Indonesia
Kabwum	6.20	147.20	Morobe	Out station
Kaiapit	6.27	146.27	Morobe	Village
Kainantu	6.28	145.88	Eastern Highlands	Town southeast of Goroka
Karkar Island			Madang	Island north of Madang Town
Kavieng	2.59	150.81	New Ireland	Town and seismic station
Kokopo	4.35	152.27	East New Britain	New provincial capital
Kondiu	5.99	144.85	Chimbu	Village west-southwest of Kundiawa
Konga	6.66	155.48	North Solomons	Government station on southern Bougainville
Kimbe	5.65	150.17	West New Britain	Provincial capital on northern New Britain
Kundiawa	6.02	144.97	Chimbu	Town, provincial capital
Lae	6.73	147.02	Morobe	City, provincial capital
Langila	5.45	148.50	West New Britain	Seismic station at Cape Gloucester
Lihir Island			New Ireland	Island east of central New Ireland
Long Island			Morobe	Island in the Vitiaz Strait
Madang	5.23	145.83	Madang	Seismic station and town
Markham Valley			Morobe	Valley trending northwestwards from Lae, to about 6°S.
Mendi	6.13	143.65	Southern Highlands	Town and provincial capital
Minj	5.92	144.85	Western Highlands	Town near Mt Hagen
Motupena	6.51	155.32	North Solomons	Village on southwestern Bougainville
Mt Hagen	5.85	144.22	Western Highlands	City and provincial capital
Mt Ulawun	5.03	151.37	West New Britain	Volcano, near Ulamona and Bialla
Mutzing	6.32	146.27	Morobe	Village, near Kaiapit
Nadzab	6.58	146.71	Morobe	Airport and seismic station outside of Lae
Namatanai	3.65	152.45	New Ireland	Town on southern New Ireland
New Ireland			New Ireland	Island Province
Palmalmal	5.63	151.52	East New Britain	Government station on south New Britain
Pindiu	6.42	147.57	Morobe	District office on Huon Peninsula
Pomio	5.53	151.52	East New Britain	District office near Palmalmal
Popondetta	8.78	148.25	Oro	Town and provincial capital

Port Moresby	9.45	147.15	National Capital	City, National Capital and seismic station
Prince Alexander Range				East Sepik Mountain range located to the west of Wewak Town, at about 3.5°S
Rabaul	4.17	152.17	East New Britain	Town volcano complex and seismic station
Ramu Valley			Morobe	Northwestward extension of the Markham Valley, from about 6°S to 144°E
Sarawaget Mountains			Morobe	Mountain Ranges NW of Lae
Siassi	5.57	147.83	Morobe	Patrol post on Umboi Island
Siwai	6.55	155.42	North Solomons	District centre on southwestern Bougainville
Sovele	6.47	155.42	North Solomons	Village on southwest Bougainville
St. Mathias Group			New Ireland	Island group, northwest of Kavieng Town, north of 2°S
Tabele	4.10	145.01	Madang	Seismic station on Manam Island
Tabubil	6.35	141.29	Western	Mining town near Ok Tedi
Teptep	5.95	146.57	Morobe	Village in the Finisterre-Sarawaget Ranges
Tokaino	6.66	155.63	North Solomons	Village on southwestern Bougainville
Ulamona	4.99	151.27	West New Britain	Mission/Village near Ulawun Volcano and seismic station
Ulawun	5.06	151.30	West New Britain	Seismic Station, volcano near Ulamona
Umboi Island (Siassi Island)			Morobe	Island at extreme west of western New Britain
Vitiaz Strait			Morobe	The sea expanse between Huon Peninsula and Umboi Island
Vunapope	4.34	152.28	East New Britain	Mission, near Rabaul
Wantoat	6.14	143.47	Morobe	Village on the Sarawaget Range
Wau	7.32	146.72	Morobe	Town near Bulolo, seismic station
Wewak	3.57	143.63	East Sepik	Town and seismic station
Wide Bay			East New Britain	Bay on eastern New Britain.
Woaninara	6.79	145.88	Eastern Highlands	Government Station
Yonki	6.24	145.97	Eastern Highlands	Town and Hydro-electric dam

Appendix 2: Significant earthquakes in the PNG region to 2008

Year	Mon	Day	Hr	Min	Sec	Lat	Long	Depth	Ms	Mw
1763	9	12	0	0	0	-6.7	130	0		
1768	6	22	0	0	0	-7	150		7.5	
1841	11	26	0	0	0	-5	130	0		
1841	12	16	0	0	0	-5	130		6	
1851	5	4	0	0	0	-5	130	0		
1852	12	24	0	0	0	-5	130.5		7	
1857	4	17	0	0	0	-5.5	147		8	
1859	9	25	0	0	0	-5.5	130.5		6.6	
1864	5	23	0	0	0	-1	135		7.8	
1873	3	0	0	0	0	-5.5	146		8	
1875	0	0	0	0	0	0	150	0		
1878	2	4	0	0	0	-3	152.5	33	0	
1888	3	13	0	0	0	-5.6	148.1	0		
1895	3	6	18	25	0	-8.5	150	33	7.5	
1895	3	18	0	0	0	-8	150	0		
1899	10	19	9	16	0	-5	148	33	7.5	
1900	1	11	9	7	0	-5	148	33	7.4	
1900	9	10	21	30	0	-4	152	33	6.8	
1900	9	17	21	45	0	-5	148	33	7.5	
1900	10	7	21	4	0	-3.8	138	60	7.8	
1901	5	25	0	32	0	-10	160	33	7.5	
1901	8	10	10	27	0	-5	155	33	7.3	
1902	1	24	0	0	0	-8.3	151		7.8	
1902	1	24	23	27	0	-8	150	33	7.5	
1902	3	28	14	44	0	0	133	33	7.1	
1904	7	23	0	28	0	-5	133	33	7	
1905	1	13	13	18	0	0	143	33	7	
1905	3	4	23	17	0	-4	149	33	7	
1905	5	18	13	45	0	-4	149	60	7.5	
1905	5	18	13	45	0	-4	149	33	7.1	
1906	2	19	1	59	0	-10	160	33	7.5	
1906	6	1	4	30	0	0	145	33	7.5	
1906	9	14	16	4	0	-7	149	33	8.1	
1906	9	17	8	38	0	-4	149	33	7	
1906	10	2	2	52	0	-4	149	60	7.6	
1907	5	4	6	51	0	-7.5	153.7	60	7.6	
1907	5	7	10	16	0	-2.8	144.5	33	7	
1907	5	31	12	45	0	-5	161	33	7	
1907	12	15	17	35	0	-3.1	142.5	33	7.3	
1909	4	27	12	44	0	0	147	33	7.5	
1909	6	27	7	15	0	-10	162	33	7.1	
1909	12	9	15	33	0	-8	161	33	7.4	
1910	2	25	0	0	0	-4.2	152.2	33	6	
1910	12	4	11	0	0	-10	140	33	6.8	

1910	12	10	9	26	0	-11	162.5	33	7.4
1911	5	8	0	0	0	-6	151	0	
1911	5	8	0	0	0	-4.2	152.2	0	
1911	12	31	6	7	0	-2	143.5	33	7
1913	5	30	11	46	0	-5	154	60	7.6
1913	10	11	4	6	0	-7	148	33	7
1914	4	11	16	30	0	-12	163	33	7.1
1914	5	26	14	22	0	-2	137	60	8
1915	8	2	0	0	0	-5	155	0	
1915	11	6	0	0	0	-1	136		6
1916	1	1	13	20	0	-4	154	25	7.9
1916	1	13	0	0	0	-2	135		8.1
1916	1	13	6	18	0	-3	136	60	7.5
1916	1	13	8	20	0	-3	135.5	25	7.6
1916	8	3	1	30	0	-4	144.5	60	7.1
1917	7	29	21	52	24	-3.05	143.8	33	7.6
1918	7	3	6	52	0	-3.5	142.5	60	7.5
1918	10	27	17	6	0	-2	148	50	7.3
1919	5	6	19	41	0	-5	154	25	8.1
1920	2	2	11	22	18	-6.5	150	60	7.6
1922	1	19	21	58	50	-7	143	33	7.5
1923	11	2	21	8	6	-4.5	151.5	50	7.1
1923	11	4	0	4	30	-5	152	33	7.1
1926	1	25	0	36	0	-9	158		7.4
1926	3	27	10	48	0	-9	157		7.1
1926	4	12	8	32	0	-10	161	60	7.5
1926	9	16	0	0	0	-11.6	160	33	7
1926	10	26	3	44	0	-3.2	138.5	25	7.9
1927	8	10	11	36	0	-1	131		7.1
1930	9	30	21	20	45	-4.5	146	33	7
1930	12	24	0	0	0	-1.3	144.3	33	5.8
1931	8	7	2	11	0	-4	142		7
1931	10	3	19	13	0	-10.5	161.7	25	7.9
1931	10	10	0	19	0	-10	161	60	7.6
1934	2	28	14	21	0	-5	150		7.1
1934	7	19	0	0	0	-0.5	133.3	33	7
1935	9	20	1	46	33	-3.2	142.5	60	7
1935	12	15	7	7	0	-9.8	161	60	7.5
1936	2	16	12	46	0	-4.5	133		7.1
1936	4	19	5	7	0	-7.5	156	40	7.4
1937	5	28	0	0	0	-4.2	152.2	0	
1937	5	29	0	0	0	-4.2	152.2	0	
1938	2	1	19	4	0	-5.2	130.5	25	8.1
1938	3	6	1	56	0	-5.1	153.1	0	
1938	5	12	15	38	57	-6	147.7	60	7.5
1939	1	30	2	18	0	-6.5	155.5	25	7.8
1939	4	30	2	55	30	-10.6	158.5	25	8
1941	1	13	0	0	0	-4.5	152.5	33	7

1943	11	6	8	31	0	-6	134.3	60	7.5
1943	12	23	19	0	0	-5.5	153.5	50	7.3
1944	4	27	14	38	0	-0.5	133.5	50	7.3
1944	5	25	12	58	0	-2.5	152.8	60	7.5
1945	12	28	17	48	0	-6	150	60	7.8
1946	5	3	22	23	0	-6	154		7.4
1946	9	29	3	1	0	-4.5	153.5	60	7.6
1947	4	2	5	37	0	-1.5	136		7.3
1947	5	6	20	30	0	-6.5	148.5	60	7.5
1947	5	27	5	58	0	-1.5	135.25		7.3
1949	10	19	21	1	0	-5.5	154	60	7.1
1951	2	22	1	45	42	-3.6	142.6	33	0
1951	12	22	0	0	0	-9	157.9	0	
1952	6	22	21	41	58.7	0	153.6	45	6.9
1952	11	6	19	47	0	-5	145	50	7
1952	12	6	10	41	0	-8	156.5		7.1
1952	12	24	18	39	0	-5.5	152		7
1953	4	23	16	24	0	-4	154	60	7.5
1953	6	27	0	0	0	-2.4	147.4	0	
1955	9	8	0	0	0	-7	155.5	33	6.5
1955	10	10	8	57	47	-5	152.5	33	7.3
1956	7	18	6	19	0	-5.5	130	190	7.5
1957	6	22	23	50	0	-1.5	137	33	7.3
1959	8	17	21	4	0	-7.8	156.4		7.3
1959	8	17	21	24	40	-7.5	156	33	7.1
1960	6	11	0	0	0	-9	152.3	33	6.5
1961	1	5	0	0	0	-4.1	143	108	6.8
1961	2	6	0	0	0	-6.8	155.3	59	6.6
1961	3	5	0	0	0	-10.7	161.6	99	6.1
1961	3	15	0	0	0	-3.3	150.6	21	6
1961	5	7	0	0	0	-6	154.5	71	6.5
1961	7	7	0	0	0	-5.7	149.7	57	6
1961	8	1	5	39	49	-9.8	160.5	50	6.5
1961	9	20	0	0	0	-3.6	151	44	6.3
1961	10	10	0	0	0	-4.7	138.2	36	6.3
1961	10	26	0	0	0	-3.1	148.1	33	6.1
1961	12	14	0	0	0	-3.1	140.9	44	6
1962	6	18	0	0	0	-4.9	152	100	6.6
1962	7	30	0	0	0	-3.4	143.7	33	6.8
1962	12	12	0	0	0	-4.8	153.8	94	6
1963	2	13	0	0	0	-9.9	160.7	30	6
1963	8	14	0	0	0	-3.4	135.4	33	6.4
1964	2	14	0	0	0	-5.1	151.7	55	6
1964	4	24	0	0	0	-5.1	144.2	106	6.3
1964	6	28	0	0	0	-1.7	149.6	7	6.4
1964	7	6	0	0	0	-6.3	154.7	49	6.4
1964	7	8	0	0	0	-5.5	129.8	165	6.5
1964	9	5	0	0	0	-5.8	154	69	6.4

1964	9	12	0	0	0	-4.4	144	120	6.3
1964	9	16	0	0	0	-5.9	152	29	6
1964	10	2	0	0	0	-10.5	162.4	68	6
1964	11	17	8	15	39	-5.7	150.7	45	7.5
1964	11	18	0	0	0	-6	148.2	49	6
1964	11	19	0	0	0	-6	150.8	3	6
1964	12	24	0	0	0	-4.4	153.1	93	6
1965	1	10	0	0	0	-5.8	147.3	113	6.5
1965	2	2	0	0	0	-2.1	138.9	12	6
1965	2	25	0	0	0	-5.5	152	35	6.5
1965	3	4	0	0	0	-5.4	147	191	6.4
1965	5	6	0	0	0	-6.1	149.1	74	6
1965	7	6	0	0	0	-4.5	155.1	510	6.4
1965	7	17	0	0	0	-9.7	159.8	24	6.4
1965	8	5	0	0	0	-5.2	151.6	50	6.5
1965	8	12	0	0	0	-5.2	152.1	42	6.5
1965	9	11	0	0	0	-5.4	153	50	6.5
1965	9	12	0	0	0	-6.4	151.6	29	6.5
1965	9	22	0	0	0	-5.3	151.4	58	6
1965	9	25	0	0	0	-9.6	148.8	37	6
1965	10	17	0	0	0	-5	151.2	175	6
1965	11	21	0	0	0	-6.3	130.3	132	6.5
1965	11	27	0	0	0	-9.7	159.8	41	6
1965	11	27	0	0	0	-6.1	148.5	56	6
1965	12	7	0	0	0	-6.4	146.3	116	6
1965	12	26	0	0	0	-5.4	151.6	74	6
1966	2	22	0	0	0	-5.4	151.5	44	6.6
1966	5	2	0	0	0	-6	149.8	56	6
1966	6	15	0	0	0	-10.1	160.9	41	6
1966	6	15	0	59	0	-10.4	160.8	31	7.8
1966	6	15	0	59	0	-10.3	160.8	33	7.5
1966	6	15	1	32	0	-10.2	160.9	23	7.1
1967	1	13	0	0	0	-10.66	161.35	21	6.6
1967	3	17	0	0	0	-3.63	150.91	33	6.1
1967	3	19	0	0	0	-6.71	129.87	89	6
1967	4	9	0	0	0	-3.93	135.77	15	6
1967	4	10	0	0	0	-7.34	155.74	34	6
1967	4	10	0	0	0	-7.28	155.8	46	6.1
1967	4	29	0	0	0	-1.73	138.88	33	6
1967	5	5	0	0	0	-10.41	161.3	37	6.5
1967	8	13	22	15	10	-4.4	152.4	30	6.4
1967	10	12	0	0	0	-7.1	129.8	45	6
1967	12	25	1	23	0	-5.3	153.7	55	7.1
1968	1	19	0	0	0	-9.4	158.4	33	6
1968	2	12	5	44	0	-5.5	153.2	74	7.8
1968	5	28	0	0	0	-2.91	139.31	65	6
1968	5	28	13	27	0	-2.9	139.3	65	7.6
1968	6	1	0	0	0	-2.84	139.36	50	6

1968	7	29	0	0	0	-0.21	133.43	12	6
1968	8	18	0	0	0	-10.11	159.86	538	6
1968	9	27	0	0	0	-3.67	143.29	7	6.5
1968	10	10	0	0	0	-6	148.62	70	6
1968	10	23	21	4	0	-3.4	143.3	21	7.5
1968	10	23	21	4	0	-3.32	143.25	12	6.8
1968	12	7	0	0	0	-3.41	145.88	15	6.5
1969	1	5	13	26	0	-7.97	158.9	47	7.5
1969	3	9	0	0	0	-4.07	135.63	33	6
1969	3	9	0	0	0	-4.12	135.51	14	6.5
1969	3	10	0	0	0	-5.58	147.21	206	6
1969	4	16	0	0	0	-3.53	150.97	39	6.5
1969	6	14	0	0	0	-7.91	158.98	62	6.5
1969	8	5	0	0	0	-5.24	153.77	69	6
1969	8	8	0	0	0	-6.12	129.69	196	6
1969	9	6	0	0	0	-8.84	157.81	15	6
1970	1	6	0	0	0	-9.62	151.45	8	6
1970	6	12	0	0	0	-2.88	139.09	32	6.4
1970	6	25	0	0	0	-7.91	158.69	69	6.5
1970	7	19	0	0	0	-3.78	152.4	20	6
1970	8	3	0	0	0	-7.93	158.72	67	6.3
1970	8	28	0	0	0	-4.56	153.05	88	6
1970	9	23	0	0	0	-6.54	154.67	47	6
1970	9	23	0	0	0	-6.46	154.61	39	6.5
1970	10	2	0	0	0	-6.81	154.91	54	6
1970	11	8	0	0	0	-3.43	135.63	33	6.8
1970	11	12	0	0	0	-5.05	145.06	15	6.5
1970	12	28	0	0	0	-5.15	153.62	61	6.5
1970	12	29	0	0	0	-10.54	161.4	72	6.8
1971	1	1	0	0	0	-3.99	141.15	17	6
1971	1	10	0	0	0	-2.97	139.62	36	6
1971	1	10	0	0	0	-3.42	139.98	27	6
1971	1	10	0	0	0	-3.23	139.86	30	6
1971	1	10	7	17	0	-3.13	139.69	34	8.1
1971	1	15	0	0	0	-3.03	139.47	33	6
1971	1	25	0	0	0	-9.6	151.35	38	6.3
1971	3	13	0	0	0	-5.72	145.36	118	6.3
1971	7	14	0	0	0	-5.79	153.23	33	6.8
1971	7	14	0	0	0	-4.82	153.57	33	6.8
1971	7	14	0	0	0	-5.15	153.28	33	6.3
1971	7	14	0	0	0	-5.2	153.34	33	6.5
1971	7	14	0	0	0	-5.79	154.04	33	6.3
1971	7	14	6	11	29.1	-5.5	153.9	47	7.8
1971	7	14	7	41	0	-5.6	153.8	43	7
1971	7	18	0	0	0	-4.83	153.3	46	6.5
1971	7	19	0	0	0	-5.68	153.8	42	7
1971	7	19	0	0	0	-5.51	150.59	33	6
1971	7	26	0	0	0	-5.16	152.21	33	6.4

1971	7	26	0	0	0	-5.72	151.93	33	6
1971	7	26	0	0	0	-5.62	151.4	33	6
1971	7	26	0	0	0	-5.85	151.3	33	6.4
1971	7	26	1	23	21.2	-4.94	153.17	48	7.6
1971	7	27	0	0	0	-5.15	152.97	43	6.5
1971	7	28	0	0	0	-5.14	152.88	33	6.4
1971	8	9	0	0	0	-5.88	154.31	63	6.5
1971	8	9	0	0	0	-5.78	152.19	24	6
1971	8	13	0	0	0	-6.16	154.13	30	6
1971	8	13	0	0	0	-6.1	154.09	21	6
1971	8	23	0	0	0	-3.97	146.05	33	6.3
1971	9	14	0	0	0	-6.47	151.52	33	7
1971	9	16	0	0	0	-5.91	130.65	115	6
1971	9	25	4	36	14	-6.54	146.57	115	6.3
1971	9	27	0	0	0	-3.2	148.14	33	6
1971	10	4	0	0	0	-5.84	154.18	74	6.5
1971	12	4	0	0	0	-5.99	154.55	78	6.5
1971	12	11	0	0	0	-6.07	154.5	65	6.5
1971	12	26	0	0	0	-6.28	154.83	56	6
1971	12	30	0	0	0	-4.73	151.86	109	6
1972	1	7	0	0	0	-2.13	138.97	33	6
1972	1	18	0	0	0	-4.69	145.02	33	6.4
1972	1	18	0	0	0	-4.78	145.03	33	6.5
1972	1	19	0	0	0	-4.7	144.97	33	6.5
1972	2	19	0	0	0	-11.18	162.62	60	5.3
1972	3	25	0	0	0	-3.54	150.09	41	6.4
1972	4	28	0	0	0	-5.07	154.22	409	6.5
1972	5	5	0	0	0	-4.16	152.67	32	6.5
1972	5	7	0	0	0	-4.79	153.77	103	6
1972	7	30	0	0	0	-4.63	152.29	16	6
1972	8	4	0	0	0	-11.1	162.03	36	6
1972	8	4	0	0	0	-11.23	162.05	34	6
1972	8	5	0	0	0	-11.23	161.92	33	6
1972	8	5	0	0	0	-11.17	162.13	33	6
1972	8	6	0	0	0	-11.08	162.03	56	6.5
1972	8	17	23	44	5.9	-5.9	152.9	10	7
1972	8	18	0	0	0	-6.01	152.64	8	6
1972	8	19	0	0	0	-5.19	134.05	33	6
1972	8	30	0	0	0	-3.47	144.93	13	6.4
1972	9	3	0	0	0	-5.55	151.27	45	6
1972	9	11	0	0	0	-3.24	130.76	33	6
1972	9	24	0	0	0	-6.28	131.21	33	6.9
1972	10	6	0	0	0	-6.06	149.83	59	6.4
1972	10	28	0	0	0	-7.32	146.66	2	6
1972	10	30	0	0	0	-6.33	154.79	50	6
1972	11	21	0	0	0	-6.5	154.25	34	6.5
1972	12	4	0	0	0	-1.52	136.67	33	6
1972	12	6	0	0	0	-2.99	139.14	33	6

1973	1	10	0	0	0	-11.09	162.27	32	6
1973	1	18	0	0	0	-6.86	149.99	43	6.8
1973	4	17	0	0	0	-4.43	134.03	33	6.5
1973	5	12	0	0	0	-3.73	152.07	13	6
1973	6	9	0	0	0	-10.29	161.36	70	6.5
1973	7	31	0	0	0	-8.76	160.99	30	6.3
1973	8	13	0	0	0	-4.47	144.04	112	6.4
1974	1	30	0	0	0	-5.15	134.07	33	6.3
1974	1	31	23	30	5.8	-7.4	155.6	34	7
1974	2	1	3	12	33	-7.38	155.57	40	7
1974	2	4	0	0	0	-7.29	155.83	55	6
1974	3	9	0	0	0	-7.33	156.19	33	6.5
1974	3	9	0	0	0	-7.48	156.17	50	6.5
1974	6	27	0	0	0	-4.71	152.5	70	6
1974	7	19	0	0	0	-6.06	154.92	157	6.3
1974	10	23	6	14	0	-8.42	154.03	48	7
1974	11	19	0	0	0	-3.19	150.63	18	6
1974	11	27	0	0	0	-6.1	154.15	49	6
1974	12	3	0	0	0	-5.01	129.77	33	6.5
1975	1	14	0	0	0	-4.95	129.99	33	6.9
1975	2	7	0	0	0	-7.28	149.51	33	6.5
1975	3	17	0	0	0	-2.54	138.22	33	6
1975	4	9	0	0	0	-4.04	152.68	133	6.3
1975	6	16	0	0	0	-3.04	147.82	33	6.5
1975	6	23	0	0	0	-2.7	147.38	33	6
1975	7	11	0	0	0	-10.32	161.15	79	6
1975	7	20	0	0	0	-7.1	155.15	44	7.5
1975	7	20	0	0	0	-6.58	154.65	50	6.5
1975	7	20	14	37	39.9	-6.6	154.9	49	7.9
1975	7	20	19	54	0	-7.1	155.2	44	7.6
1975	7	21	0	0	0	-6.73	155.31	47	6.8
1975	7	21	0	0	0	-6.9	155.33	95	6
1975	7	22	0	0	0	-7.2	155.71	36	6
1975	8	6	0	0	0	-2.47	146.04	33	6.3
1975	12	25	0	0	0	-4.08	142.04	115	6.8
1976	2	6	0	0	0	-5.98	146.3	37	6
1976	3	13	0	0	0	-6.25	154.71	50	6
1976	4	6	0	0	0	-3.87	152.09	21	6.4
1976	4	10	0	0	0	-6.42	154.82	54	6
1976	5	23	0	0	0	-4.93	153.69	103	6
1976	6	3	0	0	0	-5.2	153.44	88	6
1976	6	5	0	0	0	-10.08	161.01	61	6.5
1976	6	6	0	0	0	-10.09	161.04	54	5.5
1976	6	16	0	0	0	-10.13	161.01	68	5.4
1976	6	25	19	18	0	-4.6	140.09	33	7
1976	7	17	0	0	0	-4.15	152.75	53	6.5
1976	9	14	0	0	0	-3.72	138.01	75	6
1976	10	5	0	0	0	-6.42	153	22	6.3

1976	10	12	0	0	0	-10.45	161.29	106	6.4
1976	10	29	0	0	0	-4.51	139.91	33	7
1976	10	29	2	51	0	-4.7	140.2	30	6
1976	11	1	0	0	0	-6.05	149.54	53	6
1976	11	18	0	0	0	-4.17	135.14	33	6.5
1976	11	18	0	0	0	-8.81	156.94	33	6.5
1977	1	6	0	0	0	-3.63	144.44	33	6.5
1977	4	20	23	13	10.3	-9.5	160.4	49	6.5
1977	4	20	23	42	50.5	-9.84	160.82	19	7.5
1977	4	21	0	0	0	-10.24	160.72	33	6
1977	4	21	4	24	0	-9.96	160.73	33	8.1
1977	4	21	4	24	9.6	-9.67	160.13	33	7
1977	4	22	0	0	0	-10.16	160.65	51	6
1977	6	18	0	0	0	-9.76	159.67	11	6
1977	7	2	0	0	0	-9.95	160.53	16	6
1977	7	29	11	15	0	-8.03	155.53	33	7
1978	1	25	0	0	0	-5.33	151.67	44	6.5
1978	2	2	0	0	0	-5.53	151.67	33	6
1978	3	4	0	0	0	-4.65	153.1	78	6
1978	4	3	0	0	0	-4.85	133.91	33	6
1978	4	11	0	0	0	-9.46	148.94	13	6
1978	4	29	0	0	0	-9.84	160.45	46	6
1978	7	22	0	0	0	-4.18	152.84	43	6
1978	8	3	0	0	0	-0.16	131.79	33	6
1978	8	5	0	0	0	-3.59	151.01	33	6
1978	9	1	0	0	0	-7.45	156.59	33	6
1978	11	4	0	0	0	-11.23	162.17	33	6.9
1978	11	4	0	0	0	-11.17	162.08	33	6
1978	11	5	0	0	0	-11.13	162.13	33	7.4
1978	11	7	0	0	0	-10.99	162.22	33	6
1978	11	9	0	0	0	-10.81	161.36	29	6
1978	11	27	0	0	0	-10.85	162.13	33	6
1978	12	1	0	0	0	-10.15	161.39	93	6
1978	12	21	0	0	0	-11.2	162.57	30	6.4
1979	3	9	0	0	0	-9.55	147.95	33	6.4
1979	6	25	0	0	0	-4.98	145.57	189	6.5
1979	6	25	5	29	0	-5.1	145.7	195	6
1979	7	9	0	0	0	-5.62	153.3	44	6
1979	9	12	5	17	51.4	-1.68	136.04	5	8.1
1979	10	17	0	0	0	-1.16	136.59	33	6
1979	10	23	0	0	0	-10.59	161.31	33	6
1979	10	23	0	0	0	-10.61	161.28	22	7
1979	11	6	0	0	0	-9.49	159.22	30	6.5
1980	2	12	0	0	0	-4.7	153.19	75	6
1980	2	22	0	0	0	-10.69	161.6	68	6
1980	2	27	0	0	0	-6.18	150.22	66	6.8
1980	2	27	0	0	0	-6.01	150.18	53	6.8
1980	3	29	0	0	0	-4.59	154.87	495	6

1980	5	14	0	0	0	-6	154.51	57	6.9
1980	6	18	0	0	0	-5.17	152.11	61	6.3
1980	6	25	0	0	0	-5.23	151.68	49	6.9
1980	7	16	0	0	0	-4.45	143.52	84	6.9
1980	7	21	0	0	0	-6.25	154.44	50	6
1980	9	26	0	0	0	-3.22	142.23	33	6.5
1980	9	28	0	0	0	-6.31	154.8	68	6.4
1980	12	21	0	0	0	-9.04	158.42	28	6.5
1981	1	19	0	0	0	-4.57	139.23	33	6.8
1981	1	19	0	0	0	-3.47	146.13	33	6
1981	1	19	15	11	0	-4.6	139.2	33	6.8
1981	2	24	0	0	0	-6.06	148.74	71	6
1981	3	21	0	0	0	-5.45	146.71	227	6
1981	5	28	0	0	0	-5.68	151.4	71	6.4
1981	8	7	0	0	0	-5.18	151.67	65	6
1981	10	4	0	0	0	-4.57	146.12	33	6.4
1981	10	9	0	0	0	-9.97	162.04	50	6.5
1981	11	6	0	0	0	-3.55	143.79	33	6.9
1981	12	6	0	0	0	-6.17	152.04	33	6
1981	12	11	0	0	0	-6.08	148.17	69	6.3
1982	1	13	0	0	0	-9.55	152.16	33	6
1982	1	14	0	0	0	-9.52	151.94	33	6
1982	1	15	0	0	0	-9.51	152.14	33	6
1982	3	27	0	0	0	-11.1	162.94	73	6
1982	8	12	0	0	0	-4.35	153.15	45	6.4
1982	9	14	0	0	0	-7.23	147.99	36	6.5
1982	9	21	0	0	0	-9.56	152.24	20	6
1983	1	8	0	0	0	-3.16	148.19	14	6
1983	1	16	0	0	0	-5.45	147.04	234	6.5
1983	3	11	0	0	0	-6.97	147.38	61	6
1983	3	18	9	6	6.1	-4.86	153.34	88	7.5
1983	3	23	0	0	0	-6.58	154.6	29	6
1983	3	23	0	0	0	-6.51	154.6	35	6.4
1983	4	24	0	0	0	-8.87	157.66	12	6
1983	5	10	0	0	0	-5.39	150.89	112	6
1983	5	10	0	0	0	-4.8	152.5	71	6.9
1983	8	23	0	0	0	-5.88	151.03	46	6.3
1983	9	24	0	0	0	-3.72	151.09	10	6
1983	10	8	0	0	0	-5.45	146.02	58	6
1983	10	15	0	0	0	-8.1	156.31	7	6.5
1983	11	20	0	0	0	-7.45	130.64	59	6
1983	11	25	0	0	0	-5.46	152	26	6
1983	12	15	0	0	0	-3.15	145.39	23	6.5
1983	12	20	0	0	0	-2.51	145.08	8	6
1983	12	20	0	0	0	-2.4	145.04	10	6
1983	12	21	0	0	0	-5.54	151.86	33	6.5
1983	12	21	23	32	0	-5.5	151.9	33	6.1
1983	12	22	0	0	0	-5.39	151.86	26	6.5

1983	12	22	1	2	0	-5.4	151.9	26	6.1
1984	2	8	0	0	0	-9.81	160.26	27	6.4
1984	2	17	0	0	0	-6.59	130.11	158	6
1984	3	27	0	0	0	-4.64	145.8	27	6.8
1984	3	27	20	7	0	-4.6	145.8	28	6.8
1984	5	30	0	0	0	-4.84	151.57	174	6
1984	7	5	0	0	0	-6.05	154.42	33	6.8
1984	8	11	0	0	0	-5.03	152.11	39	6
1984	12	2	0	0	0	-3.81	152.03	17	6
1984	12	21	0	0	0	-6.1	149.85	43	6
1985	2	23	0	0	0	-10.25	161.12	84	6
1985	5	10	15	35	0	-5.59	151.04	26	7.3
1985	5	10	15	36	0	-5.6	151.1	27	7
1985	6	5	0	0	0	-4.64	153.17	68	6.3
1985	7	22	0	0	0	-6.29	148.78	49	6.9
1985	8	26	0	0	0	-6.89	148.93	33	6
1985	9	10	0	0	0	-6.39	149.73	10	6.3
1985	9	15	0	0	0	-4.09	136.24	10	6.3
1985	9	15	0	0	0	-4.13	136.04	10	6.3
1985	9	15	2	42	0	-4.1	136.1	10	6.4
1985	9	27	0	0	0	-9.82	159.85	31	6.9
1985	9	27	3	39	0	-9.8	159.9	33	6.8
1985	11	17	9	40	0	-1.63	134.91	10	7
1985	11	17	9	40	0	-1.8	134.8	10	7.3
1985	11	22	0	0	0	-5.93	149.42	50	6
1986	1	22	0	0	0	-10.19	161	94	6
1986	2	24	0	0	0	-8.93	156.79	10	6
1986	3	7	0	0	0	-4.99	151.71	115	6
1986	3	13	0	0	0	-7.05	155.61	65	6
1986	3	24	0	0	0	-2.48	138.69	29	6.8
1986	4	20	0	0	0	-2.39	139.3	33	6.5
1986	9	11	0	0	0	-5.18	152.44	51	6.5
1986	10	14	0	0	0	-5.03	153.61	40	6.5
1986	10	17	0	0	0	-5.27	131.43	67	6.3
1986	10	24	0	0	0	-5.62	153.87	52	6.3
1987	1	3	0	0	0	-3.44	146.3	5	6
1987	1	3	0	0	0	-3.4	146.22	5	6
1987	2	7	0	0	0	-5.8	147.74	27	6
1987	2	8	18	33	0	-6.08	147.68	54	7.5
1987	2	8	18	34	0	-5.9	147.9	34	7.4
1987	3	16	0	0	0	-6.44	147.6	26	6
1987	5	6	0	0	0	-5.71	152.65	20	6.3
1987	6	9	0	0	0	-6.36	148.83	54	6.3
1987	6	17	1	33	0	-5.57	130.79	67	6.8
1987	6	18	0	0	0	-10.7	162.32	73	6
1987	6	27	0	0	0	-2.16	138.17	20	6.5
1987	8	18	0	0	0	-5.59	151.68	50	6
1987	9	17	0	0	0	-4.11	145.7	15	6

1987	10	3	0	0	0	-5.44	131.01		73	6.4
1987	10	12	13	57	0	-7.28	154.37		24	6.8
1987	10	16	20	48	0	-6.2	149.1		48	7.6
1987	10	25	16	54	0	-2.32	138.36		33	7
1988	3	18	0	0	0	-3.66	146.56		33	6
1988	4	8	0	0	0	-3.41	145.65		33	6
1988	4	8	0	0	0	-3.4	145.69		32	6.5
1988	4	25	0	0	0	-7.79	158.25		44	6
1988	7	5	0	0	0	-5.96	148.78		53	6.8
1988	7	5	20	32	0	-5.9	148.8		53	6.8
1988	7	23	0	0	0	-6.52	152.77		16	6.8
1988	7	25	0	0	0	-6.08	133.66		27	6.9
1988	8	10	0	0	0	-10.19	160.85		39	6.5
1988	8	10	4	38	0	-10.3	160.9		34	7.4
1988	10	4	0	0	0	-3.53	150.4		28	6
1988	11	14	0	0	0	-3.52	150.12		33	6.5
1988	11	18	0	0	0	-6.12	149.78		61	6.8
1988	12	30	0	0	0	-2.89	141.51		21	6
1989	1	10	0	0	0	-3.16	130.55		46	6.5
1989	1	17	0	0	0	-6.15	148.94		31	6.4
1989	2	4	0	0	0	-4.62	153.06		52	6
1989	2	14	0	0	0	-10.44	161.37		31	6.4
1989	3	10	10	14	0	-4.3	152.8		55	6
1989	8	1	0	18	0	-4.51	139.02		14	6
1989	8	1	0	18	0	-4.5	139		14	6
1989	9	4	0	0	0	-4.21	136.66		9	6
1989	9	4	5	21	0	-4.2	136.7		9	6
1989	10	18	0	0	0	-10.15	161.06		45	6
1989	10	27	21	4	0	-11.02	162.35		24	7
1989	11	6	0	0	0	-11.31	162.43		39	6
1989	11	19	0	0	0	-6.57	154.1		48	6
1989	12	7	0	0	0	-6.43	146.38		104	6.4
1989	12	30	0	0	0	-3.4	145.96		38	7
1990	5	2	0	0	0	-5.6	150.16		81	6
1990	6	7	0	0	0	-3.56	144.43		29	6.9
1990	6	15	0	0	0	-5.04	152.08		60	6
1990	6	23	0	0	0	-0.61	146.47		23	6
1990	7	10	0	0	0	-10.35	161.11		66	6
1990	8	17	0	0	0	-11.16	161.99		29	6.8
1990	9	9	0	0	0	-5.17	151.72		73	6
1990	9	23	0	0	0	-6.72	130.37		33	6.5
1990	11	22	0	0	0	-5.57	150.99		28	6.3
1990	12	24	0	0	0	-5.37	151.49		53	6
1990	12	30	0	0	0	-5.09	150.96		178	6.5
1991	1	3	0	0	0	-7.17	148.54		14	6
1991	1	9	0	0	0	-5.39	151.83		27	6
1991	1	25	0	0	0	-2.15	139.02	22	6	
1991	1	25	0	0	0	-2.27	139.2		33	6.4

1991	2	9	0	0	0	-9.85	159.17	10	6.4
1991	2	9	16	19	0	-9.92	159.13	10	6.9
1991	4	1	0	0	0	-4.91	152.01	89	6
1991	5	17	0	0	0	-4.39	142.71	59	6
1991	5	31	0	0	0	-6.04	130.59	33	6
1991	9	27	0	0	0	-3.35	137.56	52	6.4
1991	9	28	0	0	0	-5.86	151.08	33	6.5
1991	10	14	0	0	0	-9.01	158.6	32	6.3
1991	10	14	15	58	0	-8.7	158.49	33	7.3
1993	9	6	3	56	0.1	-4.64	153.23	49	6.6
1993	9	22	12	37	3.5	-6.47	154.9	27	6
1993	10	2	16	2	0.6	-3.44	148.8	36	6
1993	10	13	2	6	0.3	-5.89	146.02	25	7.1
1993	10	13	3	7	31	-5.93	146.15	33	6.6
1993	10	13	5	50	42.5	-6.01	146.06	33	6
1993	10	16	3	5	30.2	-5.9	146.2	27	6.5
1993	10	25	10	7	11.6	-5.88	145.93	18	6
1993	10	25	10	27	4.5	-5.91	145.99	30	7
1993	10	25	11	59	48	-5.86	146.02	26	6
1993	11	5	22	37	20.2	-3.19	148.34	14	6.1
1993	11	11	10	13	55.2	-4.54	153.15	45	6
1993	11	26	23	20	4.1	-9.6	158.15	17	6.1
1993	12	20	13	56	14.8	-6.88	131.34	7	6.4
1994	1	4	19	31	59.9	-4.3	135.15	11	6
1994	1	19	1	53	34.9	-3.18	135.97	23	6.8
1994	4	13	22	22	29.8	-3.14	135.97	28	6.5
1994	4	18	17	29	54	-6.47	154.93	26	6.8
1994	4	21	3	51	44.5	-5.7	154.12	28	6.9
1994	5	25	4	3	41.2	-4.2	135.49	33	6.5
1994	6	13	21	15	2.7	-5.47	151.84	17	6.1
1994	7	22	16	57	48.4	-7.78	158.42	19	6
1994	8	4	22	15	37.7	-6.34	131.57	33	6.1
1994	9	23	7	59	38.9	-3.38	148.54	33	6
1994	10	15	0	39	25.5	-3.8	152.15	8	6
1994	11	20	16	59	5.5	-2	135.93	16	6.3
1994	12	14	7	28	53.2	-9.52	159.41	16	6
1995	1	15	23	59	26.2	-5.25	152.04	62	6
1995	1	24	22	36	34.2	-5.9	154.49	24	6.1
1995	1	27	20	16	52.2	-4.43	134.48	22	6.8
1995	2	2	19	50	48	-6.23	148.79	57	6
1995	3	12	12	9	41.7	-5.35	146.73	217	6
1995	3	19	18	34	4.5	-4.23	135.01	19	6
1995	3	19	23	53	14.8	-4.18	135.11	33	7
1995	4	18	3	49	37	-2.06	140.46	20	6
1995	4	25	6	15	0.4	-5.9	147.42	22	6
1995	5	22	4	2	55	-9.66	151.51	29	6
1995	6	24	6	58	6.6	-3.96	153.93	386	6.8
1995	6	25	2	10	39.7	-3.32	150.46	32	6.3

1995	8	14	4 37	17.5	-4.84	151.51	127	6.6
1995	8	16	10 27	28.6	-5.8	154.18	30	7.8
1995	8	16	16 24	26.5	-5.43	153.77	18	6.8
1995	8	16	23 10	24	-5.77	154.35	33	7.1
1995	8	17	0 15	50.5	-5.93	154.21	14	6.4
1995	8	17	10 1	26	-5.17	153.45	21	6.5
1995	8	26	6 57	16.6	-5.64	153.54	17	6
1995	9	16	1 3	36.9	-6.32	155.21	151	6
1995	9	22	5 39	30.5	-6.05	146.54	45	6.1
1995	9	23	2 34	12.8	-5.97	146.63	27	6
1995	10	14	20 44	57.5	-6.43	154.56	18	6
1995	10	15	15 4	8.1	-6.51	154.63	14	6
1995	11	2	22 13	46	-6.73	130.29	104	6
1995	12	19	23 28	12.1	-3.7	140.23	63	6.6
1996	1	17	10 6	46.7	-4.4	140.07	109	6
1996	1	22	8 59	54.4	-2.98	141.65	35	6
1996	2	9	17 33	54.2	-6	146.63	68	6
1996	2	17	5 59	30.6	-0.89	136.95	33	8.1
1996	2	17	8 42	10.3	-0.84	136.59	33	6
1996	2	17	14 21	22.3	-0.57	135.84	19	6.5
1996	2	17	20 18	7	-0.92	136.23	31	6.5
1996	2	18	2 25	33.4	-1.34	136.46	10	6.5
1996	2	24	15 52	59	-0.87	137.35	33	6.1
1996	3	2	1 50	4.5	-5.97	146.57	58	6.1
1996	3	17	17 58	20.3	-6.27	147.9	33	6.1
1996	3	18	10 30	15.6	-6.17	147.81	33	6
1996	4	29	14 40	41	-6.52	155	44	7.5
1996	5	1	9 21	24.2	-6.66	154.85	33	6
1996	5	1	10 5	9.6	-6.74	154.9	33	6
1996	5	2	2 32	35.2	-6.44	154.58	33	6
1996	5	2	13 34	29	-4.55	154.83	500	6.5
1996	5	11	13 43	45	-6.61	155.04	33	6.3
1996	6	3	8 15	39.5	-9.31	157.17	33	6
1996	6	3	10 46	0.5	-9.27	157.2	33	6
1996	6	3	10 50	10.6	-9.32	157.24	10	6.1
1996	8	2	12 55	29.2	-10.77	161.45	33	7
1996	8	10	11 20	19.7	-4.94	152.13	33	6.1
1996	9	6	17 3	46.7	-7.31	155.89	33	6.1
1996	10	12	15 36	1.2	-7.25	155.47	33	6
1996	10	14	23 26	20	-7.13	155.57	24	6.9
1996	11	1	3 32	34.7	-1.3	149.52	33	6
1996	12	26	20 48	23.2	-2.24	138.94	33	6.3
1997	4	5	12 23	30.5	-6.49	147.41	69	6.5
1997	6	12	12 7	33.5	-5.95	147.03	33	6
1997	7	31	21 54	21.5	-6.64	130.92	58	6
1997	8	29	8 14	10	-3.56	144.36	22	6.9
1997	10	6	20 52	44.5	-9.3	158.69	33	6
1997	10	10	18 45	52.4	-9.32	158.73	33	6

1997	12	22	2	5	50	-5.49	147.87	179	7.1
1998	1	16	10	23	35.7	-5.87	146.39	33	6
1998	4	27	18	40	38.5	-2.99	136.28	53	6.1
1998	5	13	23	2	5.6	-5.15	151.71	61	6.5
1998	5	27	15	27	16.2	-5.84	149.7	33	6
1998	7	17	8	49	13.3	-2.96	141.93	10	7
1998	7	29	18	0	30	-2.69	138.9	33	6.6
1998	9	15	8	35	51.5	-5.62	151.64	83	6.3
1998	11	18	15	48	40.7	-3.32	130.77	33	6
1998	11	25	18	5	25.7	-7.86	158.62	47	6.1
1999	1	12	8	49	20.7	-5.42	151.68	42	6
1999	1	19	3	35	33.7	-4.6	153.24	114	7
1999	1	28	18	24	25.2	-4.58	153.66	101	6.4
1999	2	13	14	45	12.6	-3.56	144.83	10	6.3
1999	4	1	21	36	21.2	-4.36	152.71	33	6.1
1999	4	5	11	8	4	-5.59	149.57	150	7.4
1999	4	6	8	22	14.3	-6.53	147.01	33	6.4
1999	4	11	16	50	39.2	-6	148.49	58	6
1999	5	10	20	33	2	-5.16	150.88	138	7
1999	5	16	0	51	20.5	-4.75	152.49	73	7
1999	5	16	15	25	53.7	-2.64	138.22	59	6.4
1999	5	17	10	7	56.5	-5.16	152.88	27	6.9
1999	5	18	4	19	53.2	-5.65	148.53	127	6
1999	6	22	0	47	42.9	-4.51	133.95	33	6
1999	6	29	5	50	8.8	-9.47	147.85	33	6
1999	7	9	5	4	42.7	-6.51	154.94	29	6.3
1999	7	26	1	33	20.2	-5.15	151.94	69	6.1
1999	8	26	7	39	28.8	-3.52	145.66	33	6.5
1999	10	10	7	3	4.9	-1.99	134.28	33	6.1
1999	11	17	3	27	42	-5.98	148.82	47	7
1999	11	17	11	36	35	-6	148.8	45	6.3
1999	11	19	13	56	46.5	-6.35	148.76	33	7
1999	12	8	13	34	44.7	-9.84	159.96	33	6.1
1999	12	9	10	18	17.2	-6.03	148.14	58	6.4
1999	12	15	4	41	12.3	-5.79	150.97	33	6.3
1999	12	18	17	44	55	-2.42	139.68	16	6.1
2000	1	8	1	19	46.5	-9.81	159.81	33	6.4
2000	2	6	11	33	53	-5.66	150.88	33	6.8
2000	3	3	22	22	40.5	-6.77	143.75	10	6.5
2000	5	8	10	28	25.1	-4.49	150.01	500	6
2000	6	9	1	27	14.1	-5.14	152.56	33	6.3
2000	6	9	8	41	59.2	-11.35	161.92	33	6
2000	7	16	3	57	48.9	-7.75	150.8	33	6.5
2000	8	12	10	26	16.1	-3.01	136.12	33	6
2000	8	14	22	11	16	-9.36	153.82	10	6
2000	10	29	8	37	8.6	-4.77	153.95	50	6.9
2000	11	7	1	1	49.2	-5.54	151.59	33	6
2000	11	16	4	54	56	-3.96	152.27	33	8.1

2000	11	16	7 42	17	-5.18	153.05	33	7.8
2000	11	16	7 45	32.2	-4.9	153.2	33	7.1
2000	11	16	7 58	35.9	-4.84	153.23	33	6.8
2000	11	16	11 5	40.7	-5.25	152.91	33	6.1
2000	11	17	21 1	56.2	-5.45	151.68	33	8
2000	11	18	2 5	48.5	-5.09	153.05	33	6.9
2000	11	18	6 54	58.9	-5.14	151.73	33	6.8
2000	11	18	23 5	39.2	-5.4	153.49	33	6
2000	11	19	2 45	27.3	-5.12	151.65	53	6
2000	11	19	5 35	19	-5.66	151.76	33	6
2000	11	19	16 22	14.1	-4.79	153.16	33	6
2000	11	21	17 33	34.9	-5.32	152.12	33	6.1
2000	11	21	21 21	7	-4.93	152.76	33	6.1
2000	11	23	18 43	15.3	-4.6	153.08	33	6.4
2000	12	6	22 57	40.4	-4.18	152.77	31	6.5
2000	12	20	16 49	43.2	-9.23	154.33	33	6.5
2000	12	21	1 1	27.7	-5.74	151.13	33	6.5
2000	12	21	2 41	23.3	-5.3	154.03	385	6
2000	12	28	4 34	28.6	-4.04	152.38	33	6.1
2001	1	2	23 17	41.9	-11.16	162.44	33	6
2001	1	29	23 21	25.7	-0.68	133.33	33	6.1
2001	4	4	7 44	11.1	-5.18	132.37	33	6.4
2001	4	19	3 13	25.5	-7.45	155.89	12	6
2001	4	19	20 58	26.1	-7.31	155.96	20	6.1
2001	4	19	21 43	42.2	-7.41	155.87	17	6.6
2001	5	9	17 38	26.1	-10.32	161.23	67	6.3
2001	5	28	8 37	5	-6.61	132.35	33	6
2001	5	29	23 37	19.2	-7.02	155.04	14	6.4
2001	6	5	9 0	5.3	-6.88	146.39	10	6.4
2001	6	5	15 13	58	-6.82	146.41	10	6
2001	6	30	16 34	36	-6.41	146.76	103	6
2001	7	1	1 46	6	-4.31	152.96	28	6
2001	7	8	17 54	18.7	-6.66	152.11	10	6.1
2001	7	22	18 15	9	-5.15	132.34	33	6
2001	8	23	21 45	3	-3.37	146.31	10	6.1
2001	9	11	14 56	50.7	-0.58	133.17	33	6.5
2001	10	7	2 21	10.1	-3.21	142.98	10	6.1
2001	10	31	9 10	20.2	-5.86	149.78	33	6.9
2001	12	23	22 52	56.9	-9.65	159.53	33	7
2002	1	10	11 14	57.5	-3.12	142.29	11	6.6
2002	1	13	14 10	54.7	-5.54	150.85	33	6.4
2002	1	15	9 1	15	-5.49	151.06	33	6.1
2002	1	30	12 58	19	-6.25	150.84	33	6
2002	2	5	13 27	24.7	-5.34	151.3	39	6.5
2002	2	19	0 35	49.2	-3.82	150.95	33	6
2002	2	28	1 50	50	-5.6	151.25	45	6.4
2002	3	19	22 14	14.8	-6.49	129.9	148	6
2002	6	6	23 53	48.4	-0.88	148.33	10	6.3

2002	6	21	0	5	45	-4.47	146.76	33	6
2002	7	3	23	0	18.3	-5.03	147.34	31	6.1
2002	9	8	18	44	23.3	-3.27	142.85	13	7.8
2002	9	16	13	23	0.8	-3.26	142.57	10	6.3
2002	9	17	11	20	23.6	-3.23	142.77	10	6
2002	9	20	13	33	42	-1.58	133.92	10	6
2002	9	20	15	43	36.4	-1.54	134.35	10	6.4
2002	9	24	4	13	14.6	-10.51	161.13	33	6.1
2002	9	24	22	54	25	-10.51	161	33	6.3
2002	9	24	23	1	28.7	-10.59	161.16	19	6.5
2002	10	10	10	50	20.5	-1.76	134.3	10	7.6
2002	10	10	12	28	25.7	-1.51	133.97	10	6.6
2002	10	10	12	29	35	-1.4	133.93	10	6
2002	10	10	21	19	58.5	-1.48	134.11	10	6
2002	10	17	17	52	44	-3.6	140.23	33	6.3
2002	10	19	0	43	56.4	-3.67	140.31	33	6
2002	10	31	1	35	16.6	-3.44	148.64	10	6
2002	12	11	3	49	40	-3.81	135.12	10	6.3
2002	12	12	8	30	42.7	-4.79	153.27	34	6.6
2002	12	20	14	14	42	-3.08	147.94	33	6.4
2003	1	10	13	11	56.9	-5.31	153.7	71	6.6
2003	1	20	8	43	6	-10.49	160.77	33	7.8
2003	2	10	4	49	31.1	-6.01	149.79	33	6.3
2003	2	12	22	33	30.7	-3.65	144.24	10	6.1
2003	3	1	6	12	47.4	-1.7	134.31	28	6
2003	3	11	7	27	32.5	-4.69	153.24	40	6.8
2003	3	14	7	6	13.3	-0.41	132.95	33	6.3
2003	3	19	0	3	42.7	-9.35	156.48	33	6
2003	3	31	1	6	51.4	-6.2	151.3	33	6.1
2003	6	7	0	32	45.5	-5.09	152.5	33	6.8
2003	6	12	8	59	20.2	-5.99	154.76	186	6.3
2003	6	28	15	29	42.2	-3.33	146.15	10	6.3
2003	7	4	0	33	50	-5.47	151.69	10	6
2003	7	15	18	46	38	-3.83	152.17	33	6.5
2003	7	21	13	53	58.4	-5.48	148.85	189	6.4
2003	7	25	9	37	45.7	-1.53	149.69	24	6.5
2003	9	11	21	58	25.5	-8.2	156.16	10	6
2003	9	12	6	55	55.7	-5.27	151.5	50	6
2003	10	17	10	19	6.8	-5.47	154.16	133	6.4
2003	10	22	11	45	30.7	-6.05	147.72	52	6.3
2003	10	28	2	33	50.4	-5.35	151.45	55	6
2003	11	25	20	19	46.2	-5.54	150.84	33	6.5
2004	1	9	22	35	28.5	-6.03	149.43	33	6.3
2004	1	15	7	26	56.5	-3.49	150.99	33	6.1
2004	2	3	23	9	31.5	-3.73	140.36	45	6
2004	2	5	21	5	4	-3.62	135.52	24	7
2004	2	7	2	42	35.2	-4.01	135.02	10	7.3
2004	2	8	8	58	51.7	-3.67	135.34	26	6.9

2004	4	11	7 37	29.7	-3.75	140.06	20	6.1	
2004	4	22	14 16	3.4	-3.4	146.9	17	6	
2004	5	13	9 58	43.4	-3.58	150.73	10	6.3	
2004	6	25	2 35	7.6	-6.71	130.37	70	6	
2004	7	28	3 56	28.6	-0.44	133.09	13	6.5	
2004	10	6	22 30	56.9	-0.67	134.43	10	6.1	
2004	10	8	8 27	53.5	-10.95	162.16	36	6.9	
2004	11	5	5 18	35	-4.36	143.91	125	6	
2004	11	11	17 34	51.9	-11.13	162.19	10	6.6	
2004	11	16	10 6	54.5	-5.61	151.44	55	6	
2004	11	26	2 25	3.4	-3.57	135.43	10	7.1	
2004	11	28	7 36	44.5	-3.59	135.44	17	6.1	
2005	1	14	8 33	14.1	-4.31	152.76	10	6	
2005	1	22	20 30	17.2	-7.71	159.48	29	6.4	
2005	2	7	20 2	17.6	-4.53	153.19	36	6	
2005	2	23	11 33	57.5	-6.28	150.63	42	6	
2005	3	2	10 42	12	-6.53	129.94	201	7	
2005	3	6	4 40	4.5	-11.05	163.01	46	6.1	
2005	3	26	15 40	35	-4.89	129.92	10	6.1	
2005	4	11	12 20	5.9	-3.48	145.91	11	6.6	
2005	6	4	14 50	48.7	-6.34	146.81	43	6	
2005	6	15	10 13	59.2	-4.59	153.19	74	6.3	
2005	9	9	7 26	43.7	-4.54	153.46	90	7.6	
2005	9	16	0 31	42.7	-5.62	153.59	13	6	
2005	9	29	15 50	25.5	-5.46	151.82	37	6.6	
2005	9	29	18 23	26.2	-5.6	151.85	35	6.1	
2005	11	5	10 48	21.2	-3.16	148.14	25	6.4	
2005	11	22	15 11	31.5	-5.15	145.28	68	6.1	
2005	12	8	9 1	27.2	-5.41	146.94	218	6	
2005	12	11	14 20	43.7	-6.57	152.2	10	6.5	
2006	2	18	15 59	22	-5.19	152.05	44	6.1	
2006	3	24	12 27	5	-3.23	143.11	12	6	
2006	5	28	3 12	8.6	-5.72	151.13	34	6.5	
2006	07	19	11 48	58	-5.51	150.72	28	6.3	
2006	09	01	10 18	53	-6.77	155.54	49	6.6	
2006	10	17	01 25	12.23	-5.881	150.982	32	6.9	6.7
2006	11	06	20 56	51.11	-5.450	146.637	133		6.0
2006	11	07	17 38	33.80	-6.482	151.195	11	6.3	6.6
2006	11	12	18 21	26.14	-6.225	151.050	12	6.0	6.2
2006	11	13	16 12	28.98	-6.380	151.230	11	5.9	6.2
2006	12	27	20 15	38.64	-5.724	154.424	355		6.0
2007	01	17	04 28	26.66	-3.322	139.834	100		6.0
2007	04	01	20 39	58.71	-8.466	157.043	24	7.9	8.1
2007	04	01	20 46	19.35	-9.505	156.934	24		
2007	04	01	20 47	31.31	-7.169	155.777	10		
2007	04	01	21 11	33.15	-7.306	155.741	10		6.9
2007	04	01	21 15	22.70	-7.303	155.682	10		
2007	04	02	10 49	17.72	-7.225	156.243	34	5.8	6.1

2007	04	02	12 02	23.34	-8.706	157.620	14	6.1	6.2
2007	04	02	23 20	23.27	-8.617	157.386	18	6.0	6.2
2007	04	03	12 04	27.37	-7.857	155.801	8	6.0	6.1
2007	04	04	00 39	43.95	-7.141	156.047	10	5.7	6.0
2007	04	04	06 34	35.96	-7.760	156.490	17	6.3	6.4
2007	04	21	07 12	48.06	-3.548	151.266	407		6.1
2007	05	29	01 03	27.92	-4.587	151.841	132		6.1
2007	06	07	00 40	38.13	-3.316	146.761	4	6.2	6.2
2007	06	18	06 18	45.68	-3.550	150.962	9	6.2	6.3
2007	06	28	02 52	10.99	-7.979	154.635	18	6.7	6.7
2007	08	16	08 39	28.44	-9.834	159.465	15	6.7	6.5
2007	09	26	12 36	26.89	-4.990	153.500	40	6.6	6.8
2007	10	09	15 03	41.21	-4.808	152.892	39	5.7	6.0
2007	10	21	10 24	52.06	-6.310	154.770	46	5.7	6.0
2007	11	20	12 52	59.03	-6.907	155.672	52		6.0
2007	11	22	08 48	27.53	-5.757	147.098	53		6.8
2007	11	27	11 49	58.01	-10.950	162.149	16	6.7	6.6
2007	12	15	09 39	53.62	-6.622	131.090	57		6.4
2007	12	22	07 11	08.10	-2.407	139.067	20	6.1	6.2
2008	01	01	18 54	59.01	-5.878	146.884	34	6.1	6.3
2008	06	03	16 20	50.38	-10.509	161.273	84		6.2
2008	08	04	20 45	13.97	-5.916	130.195	173		6.3
2008	08	30	06 54	07.73	-6.153	147.289	75		6.4

Appendix 3: Modified Mercalli Intensity Scale, 1931, PNG version

I (1) Not felt, except under especially favourable circumstances on upper floors of tall buildings.

Tall trees (coconut trees) may move slowly in resonance. Still water in ponds, lakes, reservoirs may be set in oscillation.

II (2) May be felt lightly by a few persons favourable situated on upper floors of buildings.

Scarcely noticed.

Not felt outside.

III (3) Felt by several or many people indoors.

Nobody is frightened.

A few sleepers are awakened, especially on upper floors.

Hanging or suspended objects may swing (often drawing attention to the earthquake before it is felt).

The earthquake motion is often described as swaying or slow.

No noises heard.

Not felt outside.

IV (4) Felt by virtually everybody indoors.

Awaken many or most sleepers.

Excite a few people.

Noises are heard. Houses creak, dishes, glasses crockery, windows, doors rattle.

Sounds like gusts of wind may be heard

Hanging objects swing.

Liquids in jugs disturbed.

No breakages occur.

Earthquake motion may be abrupt, sharp jolting, rapid vibration.

Duration of motion may be estimated.

Felt outdoors, by a few or more people.

Water in domestic water tanks sloshes faintly.

No outdoor damage.

V (5) Awakens virtually everybody.

Felt by everybody indoors and virtually everybody outdoors.

Direction of motion can be estimated.

Rumbling sounds heard.

Frighten some people.

A few people run outdoors.

A few household breakages occur. Some items of glassware, crockery, etc., may be broken.

Small household objects and light furniture may be moved.

Hanging objects and doors swing considerably, pictures may be swung permanent out of position.

Houses shake or vibrate noticeably.

Water sloshes from domestic water tanks.

Animals become frightened.

Trees, bushes, branches shake noticeably (as in a moderate wind).

An occasional landslide may occur in steep, unstable high rainfall areas.

Standing motor vehicles may rock.

No building damage occurs.

VI (6) Felt by everyone except by some people in moving vehicles.

Many people are frightened and run outdoors.

There is general excitement.

Roaring sounds are heard.

There is household confusion. Objects fall from shelves, liquids spill from containers, pictures fall from walls, light furniture overturns, heavy furniture moves.

School bells and church bells ring.

Building damage occurs. Slight damage may occur to poorly built or weak structures.

A few village houses may be damaged. Some old domestic water tanks start to leak.

Outside, people feel a little unsteady on their feet.

The direction of motion can be estimated.

Some landslides occur in steep unstable, high rainfall areas.

No serious damage to ordinary well built structures occurs.

VII (7) Everybody is frightened. There is general alarm. Most people run outside.

People find it difficult to stand.

Explosion - like sounds may be heard.

It is noticed by people in moving motor vehicles.

Household chaos occurs. Furniture is damaged from being thrown about.

Some damage may occur to ordinary well built structures.

Free standing and exterior brick and cement-brick walls are cracked.

House stumps are cracked.

Poorly built walls may be considerably damaged.

Many domestic water tanks burst.

Some village houses collapse.

Electric power may be interrupted.

Waves appear on lakes, ponds, rivers. Water splashes over river banks.

River water becomes muddy. Sand and mud mounds shift horizontally.

Unconsolidated ground (such as filled in bomb craters, reclaimed land) cracks, settles, subsides.

Trees are shaken strongly. Damage occurs. Coconuts and branches fall.

No underground pipes are broken.

VIII (8) Alarm approaches panic. Everybody runs outside.

People fall over.

There is almost total household breakage of crockery and glassware. Furniture is broken.

Heavy furniture is overturned.

Buildings sway violently.

Extensive damage occurs to poorly built structures.

Free standing walls fall.

Some damage occurs to ordinary well built structures.

Panel walls are thrown out of frames.

Houses move on their stilts. Stilts are badly damaged.

Windows are broken.

No damage occurs to earthquake resistant buildings unless they are defective.

Almost all domestic water tanks are destroyed.

About half of village houses collapse.

Extensive landslides occur in wet mountainous country.

Landslides occur in cuttings and excavations.

Slumping of unconsolidated ground (filled in bomb craters, unsupported road edges, embankments, bridge approaches) occurs.

Cracks appear in the ground.

Underground damage may occur. Underground pipes may be cracked or broken.

IX (9) There is general panic.

People are thrown to the ground, out of chairs, out of bed.

Most houses built on stilts are considerably damaged.

Building foundations are damaged.

Considerable damage occurs to normal good-workmanship structures. Only light damage occurs to earthquake resistant structures unless defective.

Most village houses are destroyed.

River bank changes are extensive, landslides, cave-ins, sand liquefaction.

Wide spread landslides occur.

Ground is severely cracked, roadways are damaged, especially in embankments, bridge approaches, cuttings.

Broad open folds formed in cement and bitumen surfaces.

Dams, dykes are damaged.

Underground pipes are broken.

X (10) Objects may be thrown vertically into the air.

Serious damage occurs to engineering works (bridges, dams, reservoirs, cement irrigation ditches) and to earthquake resistant buildings.

Broad fissures and undulations form in ground surfaces.

Liquefaction of bearing soils may cause buildings to sink into the ground.

Underground pipes may be torn apart of crushed.

Landsliding is widespread.

XI (11) Damage is almost total.

XII (12) Damage is total.

(Ripper, 1979)

Appendix 4: Quick reference intensity scale for PNG

A quick reference Modified Mercalli earthquake intensity scale for PNG.

II (2)	Scale noticed. Not felt outside.
III (3)	Felt indoors, not outdoors, hanging objects swing, a few sleepers awakened.
IV (4)	Awakens almost all, felt by all indoors, excites a few. Noises are heard, houses creak, crockery rattles. Sounds like the wind. No breakages. Felt outdoors by a few.
V (5)	Felt by all, frightens some, rumbling sounds heard. Minor household breakages occur, small objects and light furniture moves. Houses vibrate, water sloshes from tanks. Animals frightened. Trees shake. Occasional landslides. No building damage.
VI (6)	General excitement. People are frightened and run out doors. Roaring sounds heard. Household confusion. Minor breakages occur. Objects fall, heavy furniture moves. School and church bells ring. Minor building damage to weak structures. Some water tanks leak. No damage to ordinary structures. Some landslides.
VII (7)	General alarm. Explosion sounds heard. Difficult to stand. Household chaos, furniture is damaged. Many water tanks burst. Some village houses collapse. Considerable damage to weak or poorly built walls. Tree damage occurs. Unconsolidated ground subsides slightly. Waves appear on larks vier.
VIII (8)	Panic. People fall over. Total household breakage of crockery. Furniture is broken. Buildings sway violently. Extensive damage to weak structures. Some damage to ordinary structures. Almost all water tanks destroyed. Half village houses collapse. Extensive landslides occur. Road edges, bridge approaches slump. Liquefaction effects occur.

(Ripper, 1979)