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RECORDS OF PREHISTORIC TSUNAMIS FROM BOULDER DEPOSITS – EVIDENCE FROM AUSTRALIA

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ABSTRACT

Detailed analyses of boulder deposits along 8000 km of coastal tropical Australia shows that prehistoric records of tsunami and tropical cyclone inundation can be differentiated from each other and tsunamis were larger before European settlement. The accuracy of equations used to derive these results was confirmed by the June 17 1998 tsunami event in Papua New Guinea, where flow depths of the tsunami and the size of transported clasts were surveyed. Regions that would appear safe from tsunami because of sheltering by the Great Barrier Reef or in shallow epicontinental seas such as the Gulf of Carpentaria have experienced 11 m and 3.5 m tsunami (wave height at shore) 400 yr B.P. For the Australian continent, and likely many other regions, written histories alone are too short to reasonably determine the physical vulnerability to this hazard.

INTRODUCTION

As along other rock-dominated coasts, the shores of the Australian continent have in numerous places boulder deposits whose sedimentological characteristics indicate that they were transported by waves. These characteristics include distinct imbrication of boulder clasts with seaward dips, low variance in the alignment of boulder A - axes, discrete trains of boulders extending inland, boulders deposited well above storm wave limits and the presence of marine fauna within the deposit. Boulder deposits displaying these characteristics have been reported in southeast Australia (Bryant et al., 1996), and they also occur along the north-east (Nott, 1997) northern and Western Australian coasts. All of these deposits display one or more of the characteristics of wave transported boulders.

Boulder deposits from Cairns in northeast Australia to near Carnarvon in central Western Australia, a distance of over 8,000 km, are described and age estimates presented. Morphological characteristics and hydrodynamic equations are used to determine the origins of these deposits. These data are used to estimate the magnitude and frequency of large waves (most likely tsunami) to have struck coastal regions of Australia over the last millennium.

NORTHEASTERN AUSTRALIA

Nott (1997) has described wave transported boulder deposits at five separate locations between Cairns and Cooktown along the northeastern Australian coast. These deposits all lie inside the Great Barrier Reef but here, and as occurred along the stretch of coast inside the 200 km long Ningaloo Reef in Western Australia in 1994, tsunami have been able to strike the mainland opposite sizeable gaps in the reef system (Fig. 1).

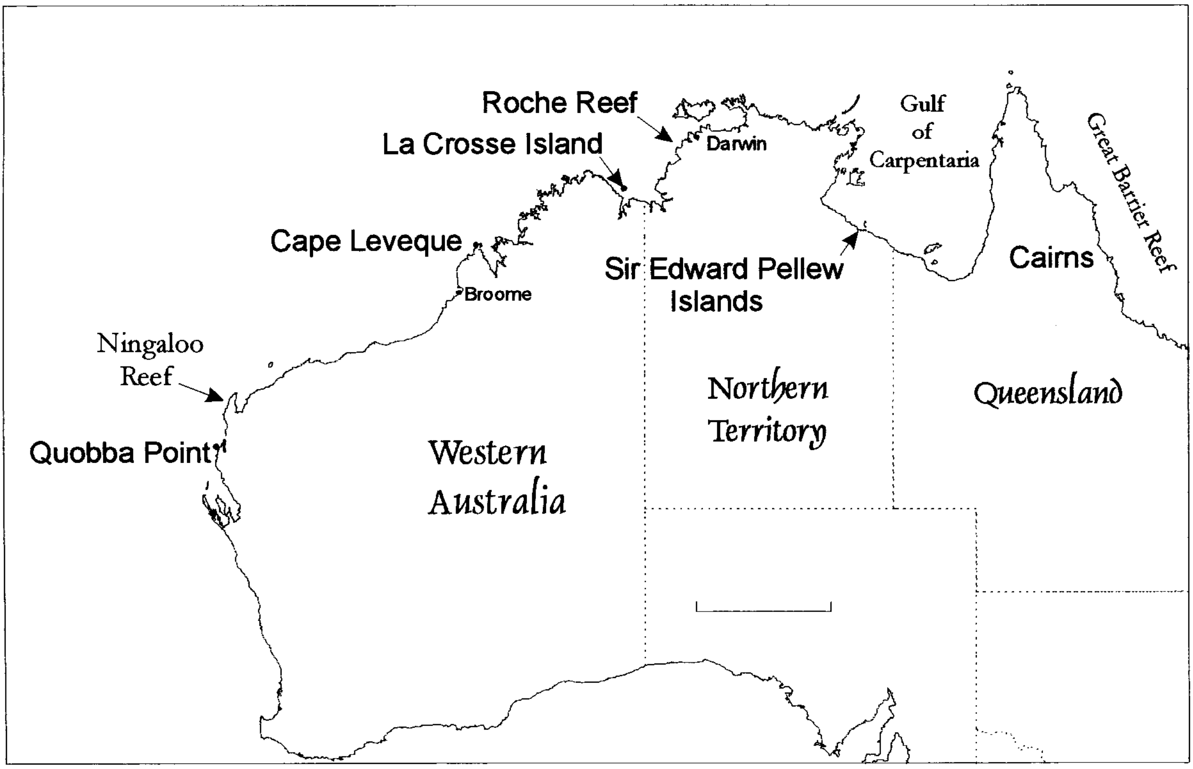

Figure 1. Location of sites mentioned in text. Scale equals 500km.

The boulders vary in size between sites with B-axes (A axis = long, B axis = intermediate, C axis = short) ranging from 2 - 6 m and the largest weighing over 200 tonnes. Large coral boulders (3 m B-axes) also occur preferentially on reef flats adjacent to the passages through the Great Barrier Reef. The ^{14}C chronology described in Nott (1997) showed that these coral boulders were transported onto the reef flats during the same event that deposited the accumulations of rock boulders along the mainland coast. Two large tsunami events have occurred in this region over the last millennium, the most recent being approximately 400 yr B.P.

GULF OF CARPENTARIA

Little West Island lies adjacent and to the north of West Island in the Gulf of Carpentaria. The latter forms part of the Sir Edward Pellew Group of islands (Fig. 1). The Gulf would seem to be an unlikely location either for the generation of tsunami, or passage of these waves from distant sources. However, the deposit on Little West Island presents unequivocal evidence of wave transported boulders. Quartzite boulders at this location are shaped as rectangular prisms, or slabs, and form a deposit that displays very clear imbrication and the majority of A-axes are aligned parallel to shore (Fig. 2).

Fig. 2. Imbricated boulders, Little West Island, Gulf of Carpentaria. These boulders form a ridge along the crest of the island approx. 8 m above sea-level (HAT). Note very clear imbrication of boulders. These boulders are composed of quartzite and could not have weathered into this depositional pattern.

The deposit occurs along almost the length of the island, at its crest approximately 7 m above highest astronomical tide. The size of clasts grade (A axes length and boulder volume) along the length and breadth of the island; in the latter case in the direction of wave transport. The largest clasts are in the centre of the deposit on its northern side. They have a mean B-axis length of 2.31 m and mean A-axis of 3.31 m (5 largest boulders) with the largest single boulder weighing approximately 129 tonnes. One boulder obviously broke in two upon deposition and one section now lies against the other; the two together as a single boulder would have measured 4.8 x 3. 9 x 1.2 m and weighed over 224 tonnes. The deposit is entirely clast supported with many of the blocks or boulders lying flat against each other. Towards the western end of the island the deposit grades into small boulder to gravel size clasts which in places lie within a matrix of shell, coral and sand. Elsewhere, however, sand and carbonaceous materials are absent from the deposit. Measurements of the strike of the boulders shows that the wave approached from a bearing of 330^{o} which is almost parallel to the trend of the coast along this side of the Gulf. Hence the wave(s) travelled along or perpendicular to the coast. The boulders have been plucked from the shore platform approximately 7 m below the main deposit and have been clearly overturned as shown by comparisons between the sedimentary structures in the boulders and exposures in the shore platform.

ROCHE REEF, NORTHERN AUSTRALIA

Roche Reef occurs approximately 10 km offshore from Fog Bay, 50 km south west of Darwin (Fig. 1). The reef is composed of rock that has been indurated by iron oxides to a depth of approximately 0.5 m. The reef is exposed sub-aerially at low tide. The largest single boulder here measures 2.6 x 1.9 x 0.5 m and weighs approximately 25 tonnes. The majority of these boulders are well imbricated with little variance in dip direction (standard deviation 7^{o}) and a mean bearing of 290^{o} .

LA CROSSE ISLAND, NORTHERN AUSTRALIA

LaCrosse Island lies within Cambridge Gulf, offshore from the mouth of the Ord River, in northern Western Australia (Fig. 1). The island is composed dominantly of quartzite. Joints within this rock are closely spaced (tens of centimetres) resulting in an abundant supply of boulders from the sparsely vegetated, relatively steep slopes. Several embayments around the island are composed of detrital boulder ridges that, in places, impound lagoons (Fig. 3). In most locations these boulder ridge sequences are composed of 7 - 9 consecutive ridges standing approximately 5 m above highest astronomical tide. Boulders within these ridges range in size from approximately 25 cm to 119 cm (A-axis). Five hundred measurements of individual boulders (all axes) revealed that there is a distinct sorting of each ridge into three zones, here called the lower, middle and upper ridge zones. Boulders in the lower zone have an average size of 119 x 91 x 56 cm, the middle zone 84 x 60 x 38 cm and the upper zone 42 x 27 x 20 cm.

Clasts of coral, buried within the boulder ridges were radiocarbon dated revealing ages spanning between 1, 280 yr B.P. to 5, 990 yr B.P. (uncorrected conventional radio-carbon years) (Table 1). Coral samples were excavated from a depth of between 50 to 100 cm below the crest of each ridge. None of the dated coral clasts was sampled from the crest of the ridge. All corals were excavated from at least 50 cm depth and were overlain by boulders. The dated ridge sequence did not reveal a chronological trend. The most seaward ridge contains coral dating to 5, 990 yr B.P. and likewise with the most landward ridge in the same sequence. Ridges in between reveal ages less than 2, 000 yr B.P. and 3,000 yr B.P. (Table 1). The scatter of ages between ridges and within each ridge suggests that either each ridge was not deposited sequentially (i.e. ridge 8 was not deposited before ridge 7 etc.) or ridges have been deposited sequentially (from ridge 8 through to ridge 1) but have been subsequently reworked by large wave events while maintaining their morphology.

Fig. 3. Oblique areal view of boulder ridges on La Crosse Island.

There is little doubt that large waves were responsible for deposition of these boulder ridges. The ^{14}C chronology indicates that waves overtop and rework the ridges and further evidence for over-washing comes from the unusual cone shaped depressions located on the crests of some of the ridges. These depressions are approximately 1 m deep and 2 - 4 m wide and appear to have been formed from the scooping or transport of boulders in a circular or spiral manner from the centre of the depression. Boulders around the lips of these depressions are frequently 'loose' and do sit in the typical imbricate or 'locked' position characteristic of the boulders making up the remainder of the ridge. In other words these 'loose' boulders have the appearance of being tossed or transported from within the depression. There is no evidence to suggest that these depressions have an anthropogenic or faunal origin. Another explanation is that these features were created by vortices generated within a high velocity fluid flow, quite possibly a result of large waves or storm surge moving rapidly over the formed ridges. Such features may therefore provide further indication of the depth of flow responsible for reworking clasts across these ridges. Similar vortice depressions were formed on the sand barrier at Sissano, Papua New Guinea during the

July 1998 tsunami event. The tsunami here had a flow depth of at least 15 m as it crossed the barrier and excavated depressions approximately 1 – 2 m deep and between 1 - 10 m across at the rear of the barrier.

CAPE LEVEQUE, NORTHWESTERN AUSTRALIA

Cape Leveque is approximately 200 km north of Broome in the Kimberley region of northwestern Western Australia (Fig. 1). Here boulders up to 4 m (B axis) and 5.5 m (A axis) have been transported across the shore platform and deposited at the base of a headland (Fig. 4). The deposit shows clear imbrication and the majority of boulders have their A axes aligned parallel to shore. The headland is composed of deeply weathered sedimentary rock of Cretaceous age and is capped by 'porcellanite', a rock formed within the profile as a result of silica mobilisation and precipitation during the weathering process. The weathering front occurs at approximately sea-level and the shore platforms around the base of the headland are composed of unweathered solid rock. The difference in lithology between the headland and the shore platform shows that clasts within the boulder deposit have been eroded from the shore platform and not from the headland itself. Large tsunamis have struck this site approximately 340 yr B.P. and 900 yr B.P. (Table 2).

Figure 4. Imbricated boulders at base of headland, Cape Leveque. Note distinct imbrication of virtually all boulders in deposit. Boulders could not have fallen to their present position as they are composed of different lithology to headland. Boulders have been plucked from shore platform to the right of person standing in background.

QUOBBA POINT, WESTERN AUSTRALIA

Quobba Point occurs just north of Carnarvon on the central Western Australian coast (Fig. 1). Large boulders (5 m B-axis, 6 m A-axis) have been tossed and scattered across a shore platform carved from horizontal to sub-horizontally bedded sandstone with occasional conglomerate lenses. An island, joined at low tide to Quobba Point, has much larger boulders strewn across it. Most of these boulders are on the eastern or mainland side of the island where the largest boulders have A and B axis lengths of 9 m and 6 m respectively. These boulders have been deposited by waves and not exhumed or left standing as residuals following deep weathering for in many cases the orientation of bedding within the boulders is discordant with bedding in the strata forming the shore platform or island surface.

WAVE HEIGHTS

It is possible to differentiate boulders transported by tsunami from those deposited by storm waves through the use of hydrodynamic equations (Nott, 1997). Tsunamis are capable of transporting considerably larger boulders at the shore than storm waves. Storm waves are limited in their transporting capacity because of their considerably lower velocity compared to tsunami and also the depth of water required at the shore to sustain such a wave upon breaking. Typically, water depths are very shallow or effectively 0 m at the high tide mark unless increased by a storm surge. But there is a physical upper limit to the height / depth attainable by storm surges and they must be at least 1.2 times the wave height in order to sustain that storm wave. Tsunami, however, can surge across a dry bed or shore. As shown in Table 3 the hydrodynamic equations suggest that the boulders at each of the sites reported here are too large to have been transported by storm waves and that tsunami have been responsible.

The accuracy of the tsunami wave height equation was tested by comparing it to measurements of tsunami flow depths and the size of concrete slabs transported by the June 17 1998 tsunami event at Sissano, Papua New Guinea. Tsunami flow depths were at least 15 m at or adjacent to the shore and 5 m high 400 m inland. A calculated wave height of 4.9 m was required to overturn the largest (3.15 x 1.22 x 0.23 m) of the transported slabs at the latter location.

The ability of storm surge and waves to transport boulders of various sizes was also recently tested when Tropical Cyclone Vance crossed the Western Australian coast on March 22nd 1999. The central pressure of this storm was 915 hPa as it crossed the coast and produced 300 km/hr winds near the eye. Historically, Vance was the most intense tropical cyclone to cross the Australian coast. It generated a surge of between 2.5 – 4 m. Despite a wide variety of boulder sizes available for possible transportation by the waves and surge, the largest boulders moved were considerably smaller than any of the clasts within the boulder assemblages reported within this study (Table 3). Storm waves are, however, capable of transporting quite large individual boulders. But where such events have been reported the boulders were left as isolated single entities and did not form distinct sedimentary assemblages such as the boulder trains, imbricated boulder fields or boulder ridges reported here.

Table 3 shows that the boulders on Little West Island were transported by a tsunami at least 3.4 m high at the shore. To transport the same boulders a storm wave would need to be tens of metres high and be accompanied by a surge of at least equal height. A surge of this magnitude is highly unlikely to occur; indeed a tropical cyclone of 920 hPa central pressure at this location can only produce a 6 m high surge under optimum conditions (G. Hubbert pers. comm. 1992). This would be close to the maximum achievable surge at this location.

Tsunamis also appear responsible for deposition of the boulders on Roche Reef. The equation for tsunami wave height indicates that a wave of at least 5.3 m is responsible for transport of the boulder with the smallest volume (1.3 m^2) and that waves of lesser height were capable of transporting boulders of greater volumes. This is because the length of the C-axis is the critical variable for initiation of boulder transport for boulders of similar sizes. The drag force required to initiate movement is inversely proportional to the length of the C-axis. The smaller the area of C-axis exposed the greater the drag force required assuming that boulders are overturned through the B-axis or the A-axis is parallel to the wave front.

The smallest boulders analysed in this study occur within the boulder ridges on LaCrosse Island. Despite their relatively small size the hydrodynamic equations suggest that they to are too large to have been deposited by storm waves. However, a caveat should be placed on the use of these particular equations at this site for the boulders here are semi-round to round in morphology and hence could be transported more easily than the block shaped boulders at the other sites. Unlike the other sites, storm waves and surge therefore cannot be entirely eliminated as a possible transporting mechanism here.

Tsunamis at least 2 – 4 m in height were required to transport the boulders at Cape Leveque and Quobba Point. These are minimum wave heights and other deposits on the headland 30 m above the boulder deposits (Table 2) indicate that even larger tsunamis have occurred here in the past. It may be that these larger tsunamis were the waves responsible for deposition of the boulders at Cape Leveque.

TSUNAMI SOURCES

The Western Australian coast is recognised as the most tsunami prone region of Australia because of its proximity to the seismically active Indonesian archipelago. It is possible that the tsunamis that deposited the boulder assemblages along the northern and western Australian coasts were generated by very large earthquakes or submarine volcanic eruptions near Indonesia. In 1977 and 1994 earthquakes near Indonesia generated tsunamis of 4 m run-up height at Cape Leveque and elsewhere along the W.A. coast. The 1994 earthquake measured 7.7 (M_w) and had an epicentre in the Timor Trench. A tsunami of 2 - 3 m run up height along the W. A. coast resulted from the 1883 Krakatoa volcanic eruption. These waves, however, were smaller (as they were run-up heights as opposed to wave heights at the shore) than the minimum wave heights suggested to have deposited the boulders along this coast. At Cape Leveque and Quocca Point these modern tsunamis did not move any boulders.

Historical data indicates that few tsunami have reached the Gulf of Carpentaria. Modelling experiments of tsunamis generated by large earthquakes near Indonesia predict waves that enter the Gulf of Carpentaria (Blackford, 1994) Interestingly, the models show that once in the Gulf the tsunamis refract and travel along the west coast of the Gulf from north to south at a bearing identical to the wave approach responsible for deposition of the boulders on Little West Island as indicated by their dip direction.

It has often been assumed that the mainland coast of northeastern Australia is protected from tsunamis by the Great Barrier Reef. However, as demonstrated by (Nott, 1997) sizeable gaps in the reef have allowed tsunami to reach the sheltered waters adjacent to the mainland. Modern examples of tsunami passing through gaps in coral reef systems have occurred at Ningaloo Reef in Western Australia in 1997 and 1994, Flores Island Indonesia (Minoura et al., 1997) and Nicaragua (Satake et al., 1993). The source of the tsunamis striking northeastern Australia are presently unknown. Large subduction zone earthquakes near the Solomon Islands or near Vanuatu are possible source areas and bolide impacts into the ocean cannot be discounted.

Whatever the sources of the tsunami which have impacted this extensive area of the Australian continent the propagating mechanisms were undoubtedly considerably greater in magnitude than any such mechanisms that have occurred over the last few centuries.

CONCLUSION

Like paleohydrological studies of terrestrial floods, coastal boulder assemblages are useful for estimating the magnitude and frequency of pre-historic ocean waves and their effects. Analyses of wave transported boulder deposits from Cairns in northeast Australia to approximately Carnarvon in Western Australia, a distance of over 8,000 km, show that pre-historic tsunamis striking this extensive coastline were considerably larger than those since European settlement. This study has also demonstrated that seemingly protected regions of the Australian coast such as areas inshore of extensive barrier reefs and in the epicontinental sea of the Gulf of Carpentaria are also prone to tsunamis of considerable magnitude.

That large tsunami have not struck the Australian coast during historical times has led other workers to conclude that the intraplate setting of this continent renders it relatively safe from tsunami hazard. However, the results presented here show that the historical record alone is insufficient to determine the tsunami hazard risk to coastal communities. The geological evidence shows that large tsunamis have struck extensive areas of the Australian continent at least twice during the last millennium with the most recent occurring just prior to European settlement. The recognition that such high magnitude events have occurred in the relatively recent past, prior to written records, indicates that these regions are potentially at risk from this hazard in the future.

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Code	Loc.	Situat.	Age (C14 conv.) (yrs B.P.)	95.4% (2σ) Cal. age range (yrs BP)	Rel. area	Code	Loc.	Situat.	Age (C14 conv.) (yrs B.P.)	95.4% (2σ) Cal. age range (yrs BP)	Rel. area
ANU9635	L.I.	Ridge 1	5990 ± 70	6993 - 6667	1.0	ANU9639	L.I.	Ridge 5	4730 ± 70	5591 – 5428 5427 - 5318	0.624 0.376
ANU9636	L.I.	Ridge 2	4070 ± 70	4819 – 4719 4734 - 4415	0.163 0.837	ANU9632	L.I.	Ridge 6	5660 ± 60	6621 – 6598 6565 - 6305	0.034 0.966
ANU9628	L.I.	Ridge 2	2490 ± 70	2735 – 2429 2417 - 2362	0.866 0.134	ANU9640	L.I.	Ridge 6	4280 ± 60	5032 – 5014 4980 – 4795 4765 - 4624	0.018 0.710 0.272
ANU9629	L.I.	Ridge 3	4810 ± 70	5658 – 5447 5406 - 5326	0.861 0.139	ANU9633	L.I.	Ridge 7	5990 ± 80	7148 – 7131 7017 - 6641	0.011 0.989
ANU9637	L.I.	Ridge 3	5750 ± 80	6730 – 6397 6367 - 6349	0.984 0.016	ANU9641	L.I.	Ridge 7	2880 ± 70	3237 – 3229 3213 – 2844 2823 - 2804	0.007 0.982 0.012
ANU9630	L.I.	Ridge 4	2690 ± 60	2927 - 2735	1.0	ANU9634	L.I.	Ridge 8	4590 ± 60	5465 – 5206 5195 - 5048	0.642 0.358
ANU9638	L.I.	Ridge 4	1280 ± 60	1292 - 1070	1.0	ANU9642	L.I.	Ridge 8	5900 ± 70	6887 – 6813 6812 – 6536 6513 - 6512	0.115 0.878 0.007
ANU9631	L.I.	Ridge 5	3400 ± 70	3828 – 3788 3781 – 3738 3737 - 3475	0.088 0.070 0.842	ANU8848	L.W.	Boulder ridge	4810 ± 190	5928 – 5033 5013 - 4981	0.989 0.011

Table 1. Carbon 14 results from La Crosse Island (LI) and Little West Island (LW). Calibrated age ranges determined using Stuiver et al. (1998). Coral fragments on La Crosse Island were well buried under boulders. Two separate coral fragments were extracted from individual ridges except for ridge 1. Ridge 1 lies at shore and ridge 8 inland. The scatter of ages between ridges and within each ridge suggests that either each ridge was not deposited sequentially (i.e. ridge 8 was not deposited before ridge 7 etc.) or ridges have been deposited sequentially (from ridge 8 through to ridge 1) but have been subsequently reworked by larger wave events while maintaining ridge morphology. The youngest age (1,300 yr B.P. – ridge 4) suggests a maximum age for the event if all ridges were deposited during one event. These ages have not been corrected for marine reservoir effect.

Code	Location	Material	Situation	Age (C14 conventional) (yrs B.P.)	95.4% (2σ) Cal. age range
Beta 98467	Cape Leveque	Oyster	h'land 22m a.s.l	330 ± 50	488 - 301
Beta 98468	Cape Leveque	Shell	h'land 30m a.s.l.	350 ± 60	504 - 305
Beta 98469	Cape Leveque	Oyster	h'land 20m a.s.l	330 ± 60	502 - 294
Beta 98472	Cape Leveque	Oyster	h'land 20m a.s.l.	340 ± 50	491 - 306
Beta 98470	Cape Leveque	Shell	h'land 20m a.s.l	1110 ± 60	1152 - 930
Beta 98471	Cape Leveque	Shell	h'land 20m a.s.l	920 ± 60	939 - 711
Beta 98473	Cape Leveque	Oyster	h'land 20m a.s.l	890 ±60	922 - 701

Table 2. Carbon-14 results from carbonate deposits on headland, Cape Leveque. Calibrated ages are age ranges relative area under probability distribution = 1.00. Ages calibrated using Stuiver et al. (1988). The height of these deposits above sea level suggests the waves responsible were larger than those calculated in Table 1. For example boulders at Cape Leveque require a minimum wave height of 2 – 4 m yet carbonate deposits sit 30 m a.s.l. The height of these deposits suggests that a minimum wave height of 6 m was necessary as tsunami run-up elevations can be up to 5 times that of wave height at the shore (Camfield, 1980). These ages have not been corrected for marine reservoir effect.

Loc.	a-axis (m)	b-axis (m)	c-axis (m)	Vol. (sq.m)	tsunami (m)	storm (m)	Loc.	a-axis (m)	b-axis (m)	c-axis (m)	Vol. (sq.m)	tsunam i (m)	storm (m)
Roche	2.6	1.9	0.5	2.5	3.7	56	Leveque	4.2	2.1	1.6	14.1	1.8	28
Roche	2.5	1.8	0.6	2.7	2.9	45	Leveque	5.6	2.7	1.2	18.1	3.7	57
Roche	2.2	1.3	0.7	2.0	1.5	23	Leveque	4.3	2.8	1.9	22.9	2.6	40
Roche	2.2	2.1	0.3	1.4	5.3	81	Leveque	4	2.3	1.1	10.1	2.9	45
Roche	2.3	1.8	0.7	2.9	2.5	39	Leveque	3.6	1.8	0.9	5.8	2.2	34
L.I.	1.59	1.39	0.59	1.3	1.8	28	Quobba	6.3	4.8	2.6	78.6	5.2	81
L.I.	1.44	1.39	0.59	1.2	1.7	27	Quobba	5.3	3.6	2.1	40.1	3.8	58
L.I.	1.34	1.29	0.59	1.0	1.5	24	Quobba	5.1	3.7	2.3	43.4	3.6	56
L.I.	1.29	0.79	0.64	0.7	0.6	10	Quobba	4.5	2.8	1.9	23.9	2.6	40
L.I.	1.49	1.09	0.39	0.6	1.7	26	Quobba	4.1	2.5	1.4	14.4	2.7	42
L.W.I	2.75	1.78	0.55	2.7	3.1	48	Exmouth	0.9	0.6	0.52	0.3	0.4	6
L.W.I	2.9	1.9	0.6	3.3	3.3	51	Exmouth	1.02	0.65	0.55	0.4	0.5	7
L.W.I	2.9	1.6	0.8	3.7	2	30	Exmouth	0.56	0.45	0.43	0.1	0.3	4
L.W.I	2.7	2.67	1.1	7.9	3.4	52	Exmouth	0.58	0.47	0.37	0.1	0.4	5
L.W.I	3.4	2.3	1.65	12.9	2	31	Exmouth	0.60	0.35	0.32	0.1	0.2	3

Table 3. Boulder sizes and heights of waves (tsunami and storm) required to transport boulders. See Nott (1997) for details on derivation of equations and text for details. Equations derived for block shaped boulders hence some caution needs to be placed upon interpretation of results for La Crosse Island (L.I.) as these boulders are semi-rounded.

Equation to determine tsunami wave height surging onto coast $h = (\rho s - \rho w)/(4\rho w)\ .\ 2a/[(ac/b^2).Cd + Cl]$

Equation for storm wave overturning boulders $h = (\rho s - \rho w)/\rho w\ .\ 8a/[(ac/b^2).Cd + Cl]$

where h = wave height at breaking point and where ρ_w= density of water at 1.02 x 10^3 kgm^{-3}, ρ_s = density of boulder at 2.7 x 10^3 kgm^{-3}, Cd = Coefficient of drag = 1.2, Cl = Coefficient of lift = 0.178, a = a axis of boulder, b = b axis of boulder, c = c axis of boulder.

PREDOMINANCE OF LONG PERIODS IN LARGE PACIFIC TSUNAMIS

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ABSTRACT

Large Pacific tsunamis, which include the 1952 Kamchatkan tsunami, the 1960 Chilean tsunami, and the 1964 Alaskan tsunami, were translated into amplitude spectra, with the most predominate periods being shown as space distributions with the amplitude on a global scale. As a result it was found that long periods of 49, 56, and 102 minutes were predominant in the distributions, with the amplitudes of these long periods showing large values in directions perpendicular to fault strikes on the other side of the globe. These long periods can be explained by the arrival of predominant phases beginning 50-110 minutes after the initial waves and can be attributed to waves reflecting away from the continental coast closest to the sources. For the 1960 Chilean tsunami, predominant periods and the spectral amplitude at islands were compared with the lengths of these islands. It was found that the predominant periods displaced to the long sides with increase of the island length and the amplitude responses could be approximated by a resonance curve of the island in relation to the incident wave of the long period, giving a time of approximately 60 minutes. Thus the global distribution of both the predominant period and the amplitude can be understood primarily as a radiation effect of reflected waves and subsequently as a resonance effect of the tide station. Differences in the observed predominant periods between these continental tsunamis and island arc tsunamis were demonstrated.

Introduction

Large tsunamis of the Pacific Ocean propagate on a global scale. In particular, the Chilean tsunami on May 22, 1960, which struck the Hawaiian islands and Japan, was unusually large (e.g. Cox and Mink, 1963,The committee for field investigation of the Chilean tsunami of 1960,1961, Berkman and Simons, 1964). Before the tsunami, Miyoshi (1955) remarked of the large amplitude observed at Talcahuano, Chile in the Kamchatkan tsunami on November 4,1952 and suggested that a lens-effect of a shallow region could cause a conversion of wave rays. Later, the Alaskan tsunami of March 28, 1964 also propagated to Chile and Antarctica with considerable amplitude (U.S. Department of Commerce, 1967). Thus, there have been three large tsunamis of global scale at least in the mid-twentieth century, which include the 1952 Kamchatkan tsunami, the 1960 Chilean tsunami, and the 1964 Alaskan tsunami. It can be seen from the tide-gage records when observing the tsunamis on a global scale that there were extremely large waves propagated from one side of the globe to the other (U.S. Department of Commerce, 1953, 1967, Berkman and Simons, 1964). It is important to examine this global behavior observed in the tide-gage records to determine the amplification mechanism.

Spectral analysis is a powerful method for finding characteristic properties, and many studies have utilized spectral analysis to more closely analyze characteristics of tsunamis. These studies include spectral analyses of many tsunamis at the same stations or a particular tsunami (Takahashi and Aida, 1963, Sanchez and Farreras, 1983, Soloviev and Kulikov, 1987, Abe, 1990, Baptista et al., 1992, Oh and Ravinovitch, 1994), temporal variations in spectra (Loomis, 1966), shelf effects in spectra (Abe and Ishii, 1983), and the separation of source spectra from observed spectra (Abe,1996, Ravinovitch, 1997). Similar spectra have frequently been observed for different tsunamis at the same station. Thus, one of the most difficult problems in interpreting the observed spectra is how to find a relation between the source and local conditions. From this standpoint we will translate the spectra of three tsunamis into the spectra on a global scale and then provide an interpretation.

Predominant frequency

Worldwide tide-gage records of these three tsunamis were published by U.S. Department of Commerce (U.S. Department of Commerce, 1953, 1967, Berkman and Simons, 1964). Japanese records were published by a survey group for the 1960 Chilean tsunami (The committee for field investigation of the Chilean tsunami of 1960 ,1961), Japan Meteorological Agency (1954) and Sendai Meteorological Observatory (1964). Water levels recording the tsunamis were digitized from the arrival time (in hour units) for 6 hours with time intervals of 1 minute. We carefully selected the stations to cover all the Pacific Ocean to avoid local oscillations. As for Japanese stations facing the open sea, Onahama in Honshu, Aburatsu in Kushu and Miyakozima Island in the Southwest islands, were selected. Excluding off-scaled station, stations were used 39 for the 1952 Kamchatkan tsunami, 40 for the 1960 Chilean tsunami and 54 for the 1964 Alaskan tsunami. Tidal levels were excluded using smoothed curves. The method of spectral analysis used was the same as that used in the previous studies (Abe and Ishii, 1983, Abe, 1990). The effect of the tide-gage response is neglected in this analysis. The spectra are shown for a frequency range from 0.01 to 2 mHz (period range from 8.3 to 1667 minutes) with an interval of 0.01 mHz.

The space distributions

A part of the obtained spectra is shown in Fig. 1. In the spectra, the most predominant period, that is the period of peak amplitude , is noted along with the peak amplitude. Space distributions of the predominant periods along with the amplitudes are shown in Fig. 2.

1 1952 Kamchatkan tsunami

On the whole, predominant periods of 42-56 minutes prevail at the observation stations. These periods are long in comparison with those of usual tsunamis, which will be described in more detail later. At three stations, however, Midway Island, Port Huenem and Caldera, relatively short predominant periods of less than 16.7 minutes(1 mHz) were observed. Port Huenem has Santa Cruz Island approximately 30 km distant from the coast, and Caldera has San Ambrosio Island approximately 1000 km from the coast. At these locations the arrival of waves was possibly refracted by the island slopes. We noticed that these three stations were located within 30 ° to the perpendicular direction of the seismologically estimated fault strike. Based on Kanamori's estimate (1976) of the direction of the fault strike as 214 ° , the perpendicular direction toward open sea can be assumed to be 124 ° . It is known that a short-period component is predominant in the perpendicular direction compared to the parallel direction in the direct waves of a tsunami (e.g. Yamashita and Sato,1974). In the perpendicular direction, the amplitudes of the long period are larger than those of short periods. The 92-minute predominant period at Talcahuano, for which Miyoshi(1955) noticed the large amplitude, had an amplitude of 0.51 m-sec. The most frequently observed period is 49

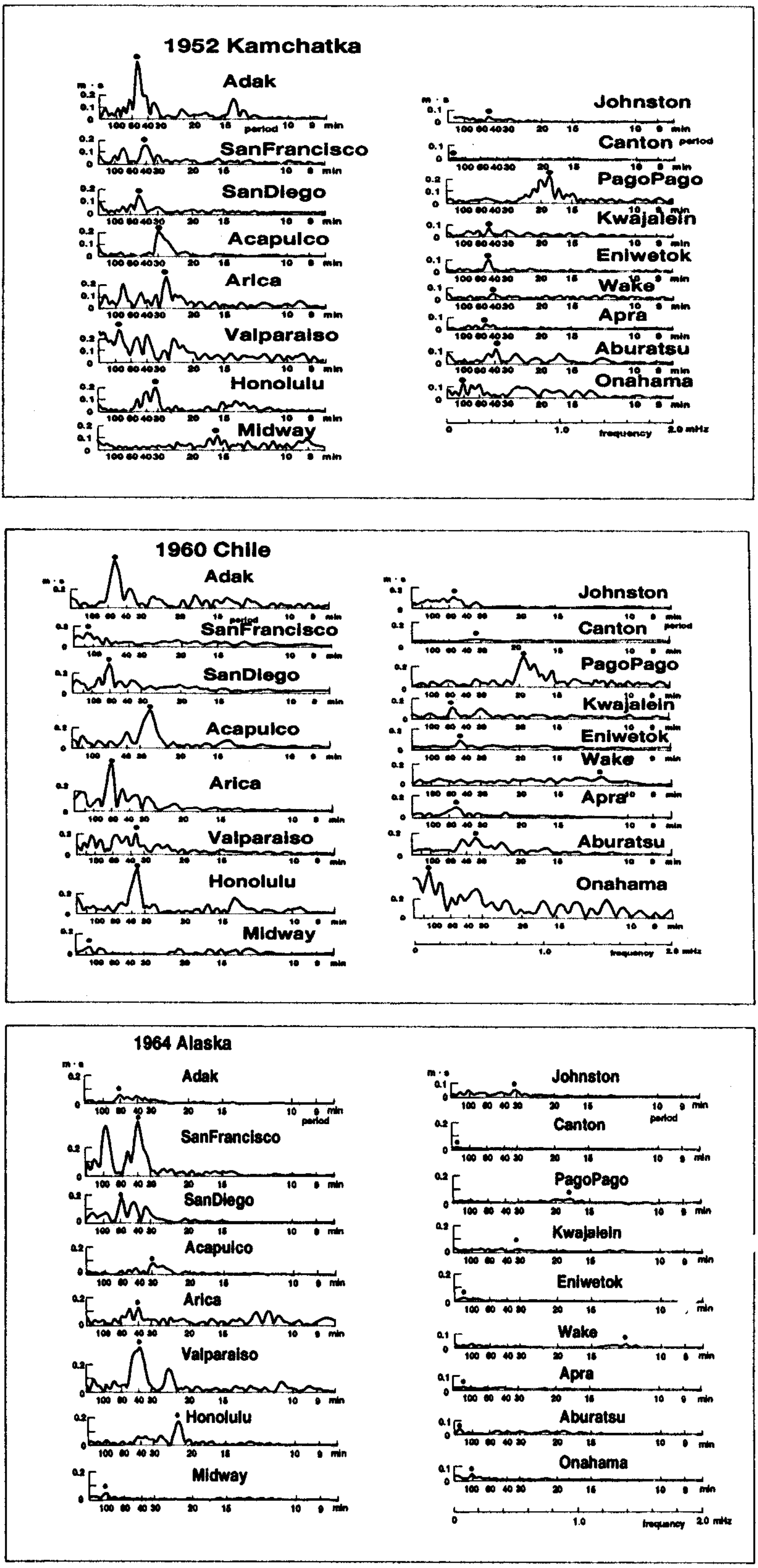

Figure 1. Predominant periods in tsunami spectra (●).
1952 Kamchatkan tsunami (top), 1960 Chilean tsunami (middle) and 1964 Alaskan tsunami (bottom).

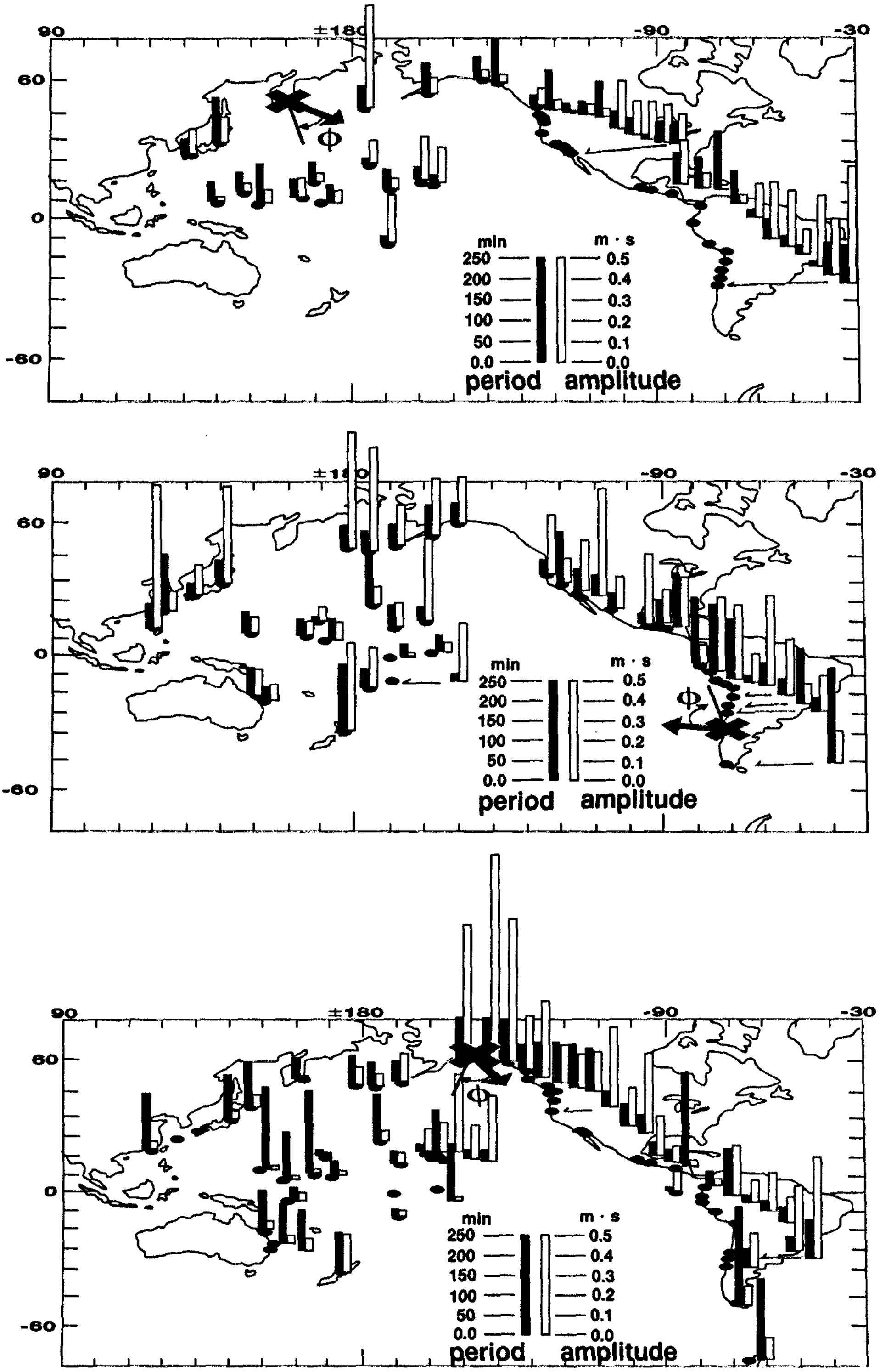

Figure 2. Predominant period (closed bar) and the amplitude (open bar) along with the epicenter(×) and the normal direction in relation to the fault strike (thick arrow). 1952 Kamchatkan tsunami (top), 1960 Chilean tsunami (middle), and 1964 Alaskan tsunami (bottom).

minutes, and the average of all the predominant frequencies is 37 minutes.

2 1960 Chilean tsunami

In the 1960 Chilean tsunami, the most frequently observed predominant periods, 56 minutes, and the average predominant period is 49 minutes with a small deviation. As short period predominance occurred at Wake Island but the amplitude was small. Long period predominances can be observed at Hondagua (64 minutes) in Luzon and Onahama (139 minutes) in Honshu with large amplitude. All these stations are located at directions within 20 ° from one of perpendicular directions (280 °) to the fault strike, 190 ° (Kanamori and Cipar, 1974). Thus, the long-period predominances were widely observed and the long-period waves with large amplitude were observed at the perpendicular direction..

3 1964 Alaskan tsunami

In the 1964 Alaskan tsunami, the most frequently observed predominant period is 104 minutes, and the average is 49 minutes with a large deviation. Short period predominances were observed at small islands such as Wake and San Cristobal, but the amplitudes were small. It should be noted that very long periods were observed at many places in the northwest Pacific, and waves with large amplitude were observed at stations nearest to the source. It is also notable that waves with moderate amplitude occurred at Nawiliwili in Hawaii and Talucahuano in Chile. Talcahuano can be considered to be located approximately perpendicular to the fault strike, as the fault strike was 240 ° (Kanamori, 1971), and Talcahuano is located only 28 ° from the perpendicular.

4 Low-frequency predominances

The spectral amplitude versus the length of the predominant period is plotted for each tsunami as shown in Fig. 3. The most common periods were 42-56 minutes for the 1952 Kamchatkan tsunami, 42-56 minutes for the 1960 Chilean tsunami, and 83-138 minutes for the 1964 Alaskan tsunami. These periods are long in comparison with those of frequently observed tsunamis, with periods of 8-20 minutes(0.83-2.1 mHz). Thus, it can be concluded that long periods or low frequencies characterize these tsunamis.

5 Azimuth distribution

The predominant period and the amplitude are plotted to illustrate the differences between the perpendicular directions and azimuthal angles of stations for each tsunami,

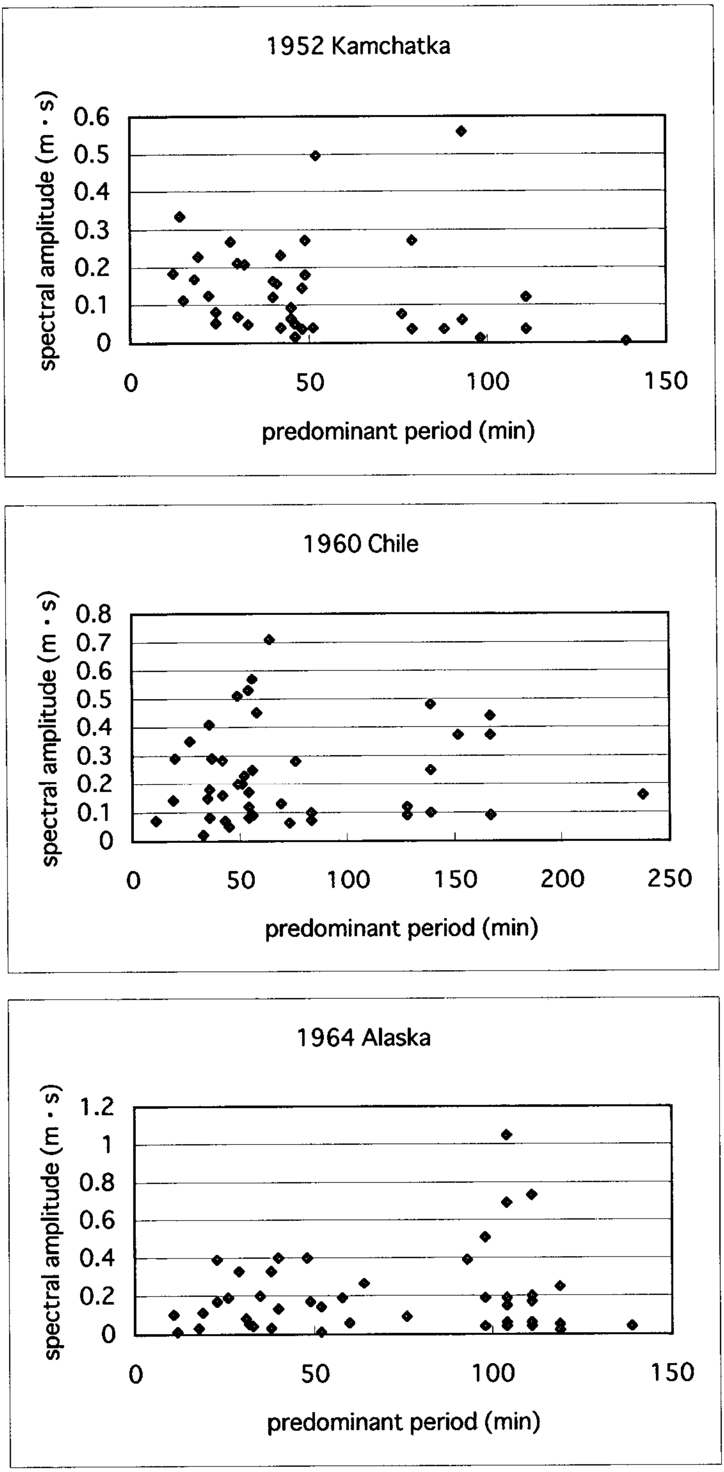

Figure 3. Spectral amplitude versus the length of the predominant period. The 1952 Kamchatkan tsunami (top), 1960 Chilean tsunami (middle) and 1964 Alaskan tsunami (bottom).

respectively (Fig. 4). In every case, a strong radiation toward the outer sea perpendicular to the fault strike was assumed because large amplitudes were observed in the perpendicular direction. The predominant period range from short to long in the perpendicular direction. It is notable that the shortest periods in the predominating periods are found within 30 ° of the perpendicular direction in all the tsunamis. In the 1964 Alaskan tsunami, the distribution is split into two groups because of the wide area with no station between Antarctica and the Hawaiian Islands. The eastern distribution illustrates refractions of the wave due to an extension of the shallow seas accompanied by an extension of the eastern coast. There are some differences between the perpendicular direction of the station and the direction of large amplitude. We must therefore interpret that the coast receiving large-amplitude waves shifted from the perpendicular direction.

6 Shift of the predominant period and increases in the amplitude

Variations in the predominant period and the spectral amplitude are examined for the epicentral distance, which is an approximated source distance. The variations in the azimuthal direction within 30 ° of the perpendicular directions are shown in Fig. 5 for the 1952 Kamchatkan tsunami, the 1960 Chilean tsunami, and the 1964 Alaskan tsunami, respectively. In all cases, the predominant periods increased with increases in the propagation distance. Moreover, the amplitude increased with increases in the propagation distance except in the last case, in which the amplitude decreased on average but showed a very large value on the opposite side of the globe. It is difficult to believe that this increase with distance without limit could occur because of the law of energy conservation. It is natural to consider the increase to be caused by the coast preventing propagation to a more distant place. The reason why the predominant period increased is a selective trap of a short period component into islands in the path of the wave. All the observation points in the way are located on small islands. Energy traps alongside islands have been discussed by Longuet-Higgins(1967). The trap is consistent with long period predominances at distant stations. It is interesting in the amplitude distribution that the maximum values are observed on opposite sides of the globe in all cases. The stations are Talcahuano in Chile, Hondagua in the Republic of the Phillipines and Talcahuano in Chile for the 1952 Kamchatkan tsunami, the 1960 Chilean tsunami, and the 1964 Alaskan tsunami, respectively. The predominant periods are 93, 64, and 94 minutes long and the azimuthal differences from the perpendicular directions are 4 ° , 8 ° , and 28 ° for the Kamchatkan, Chilean and Alaskan tsunamis, respectively. It is particularly noticeable that the directions almost coincide with the perpendicular

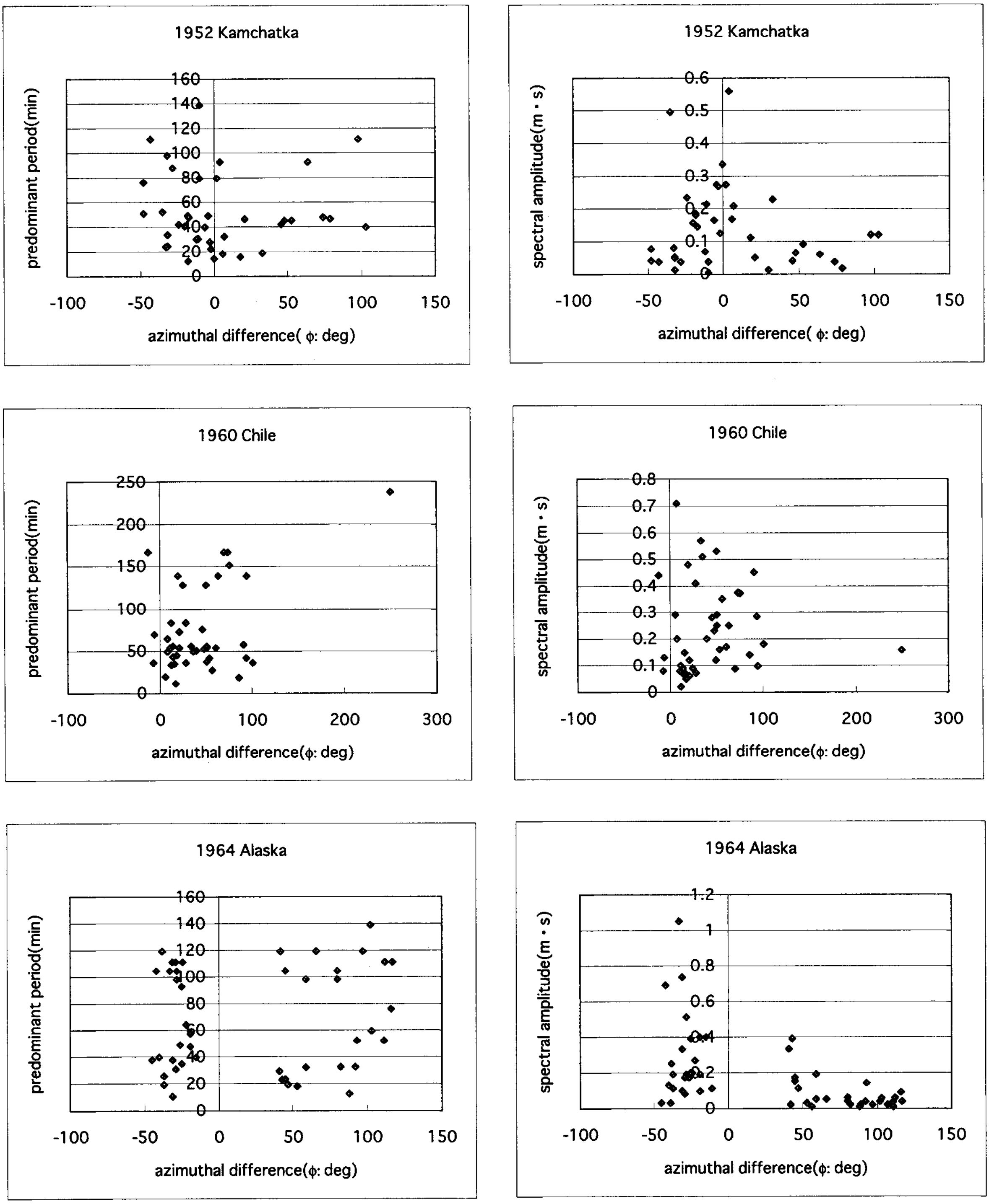

Figure 4. Azimuthal difference dependences of the predominant period (left) and the amplitude(right). The angle is defined in Fig. 2.
Top:1952 Kamchatkan tsunami, Middle:1960 Chilean tsunami,
Bottom:1964 Alaskan tsunami.

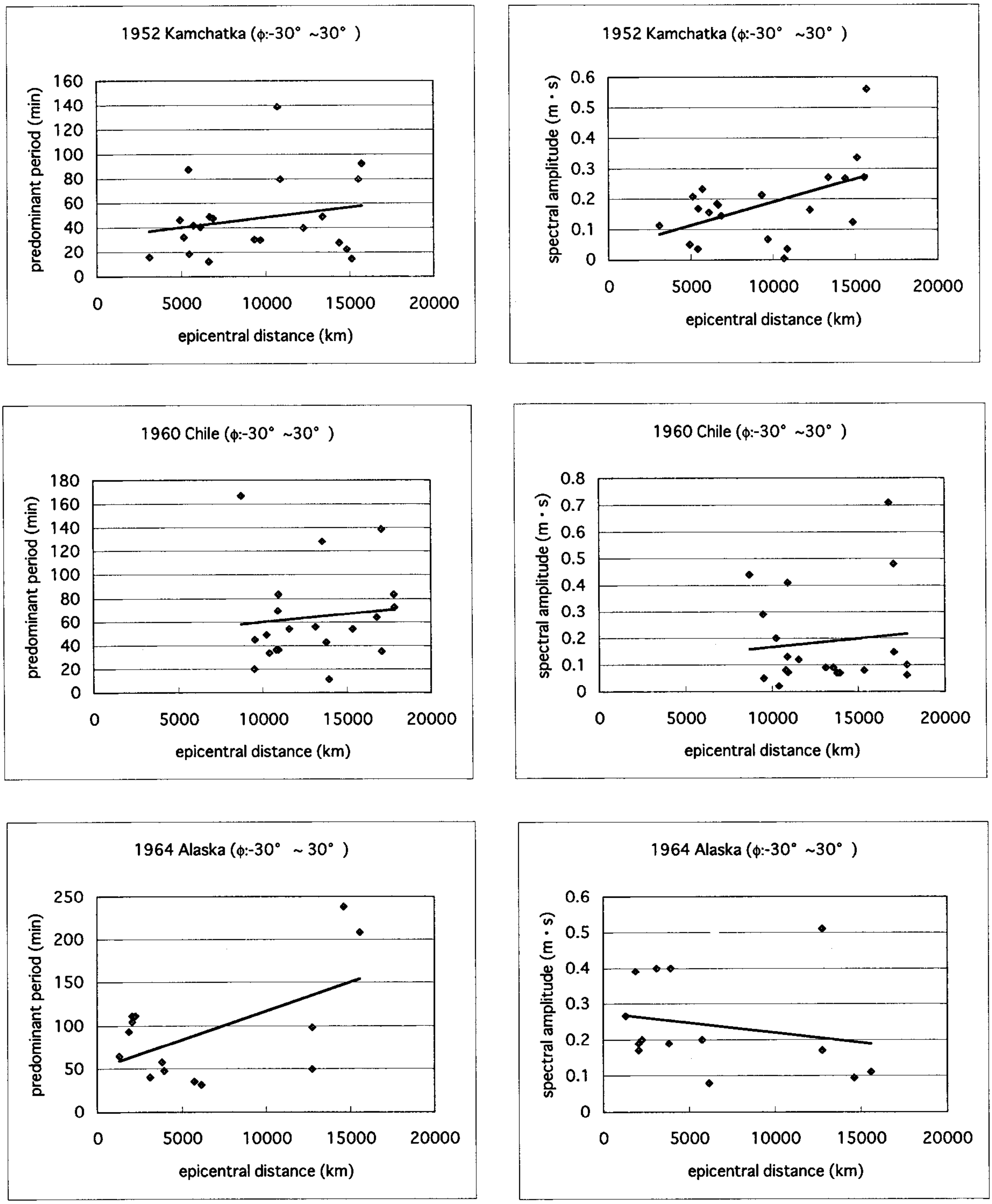

Figure 5. Epicentral distance dependences of the predominant period (left) and the amplitude (right). Solid lines are fitted to the data.
Top:1952 Kamchatkan tsunami, Middle:1960 Chilean tsunami,
Bottom:1964 Alaskan tsunami.

directions in the former two tsunamis..

Reflected waves

These tsunamis have their sources on a continental shelf and continental slopes off continents. Since the coastlines are comparatively simple, it is likely that the coasts work as perfect reflectors of tsunamis radiating parallel to trench axes. The hypothesis regarding the reflection of tsunami was formulated by Cochrane and Arthur(1948) and this phenomenon was identified by Shimozuru and Akima(1952). Abe(1991) was subsequently able to explain the second waves of the 1983 Japan Sea tsunami, the 1952 Kamchatkan tsunami and the 1964 Alaskan tsunami as reflected waves from the coasts. The source of the 1952 Kamchatkan tsunami was the continental slope, and that of the 1964 Alaskan tsunami was the continental shelf. Using the same method as that of Abe (1991), we can propose a reflector model for the 1960 Chilean tsunami. According to a tectonic deformation derived by Plafker (1972), we can assume a displacement field for the upheaval on the continental slope. The model and the observed wave are shown in Fig. 6. According to this model, the reflected wave is expected to follow the initial one with a time interval of 56 minutes. As for the other two tsunamis considered here, the reflected waves can be assumed to have time intervals of 55 and 102 minutes after Abe's model (1991). These time intervals are regarded as periodicities of the same time intervals in the spectra, and the periods are represented in Fig. 2 as the most frequently observed predominant periods. The intervals are 55 minutes (0.30 mHz), 56 minutes (0.30 mHz) and 102 minutes (0.16 mHz). These values are approximately equal to the most frequently observed predominant periods of 49, 56 and 102 minutes. Without question, we can identify the periods in the observed time histories as in Fig. 7. It is interesting in the figure that reflected waves predominate with the propagation time, that is the propagation distance. This corresponds to the increase in the predominant period with distance in the spectra as described previously.

Amplification on resonance

It is known that the same predominant period has been observed for different tsunamis at the same station(e.g. Takahashi and Aida,1963). In this case we can also find such similarities. For example, PagoPago experienced the predominant periods of 19, 20, and 18 minutes for the 1952 Kamchatkan tsunami, the 1960 Chilean tsunami and the 1964 Alaskan tsunami, respectively. The values differ from the most frequently observed values of 49,56, and 102 minutes in these tsunamis, with the small deviations from the average of 19 minutes representing excitations of a local oscillation with the natural

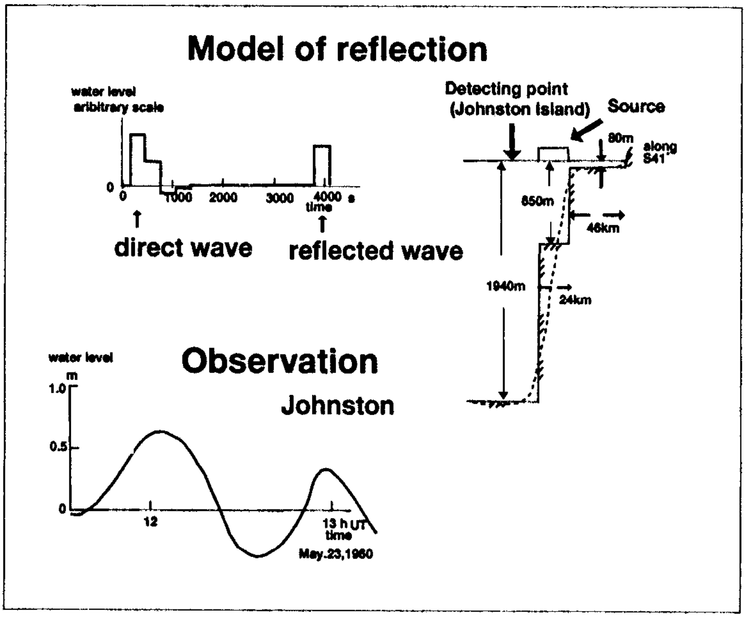

Figure 6. Model of reflection in the 1960 Chilean tsunami and the waveform observed at Johnston island. The same time scale is used for the comparison.

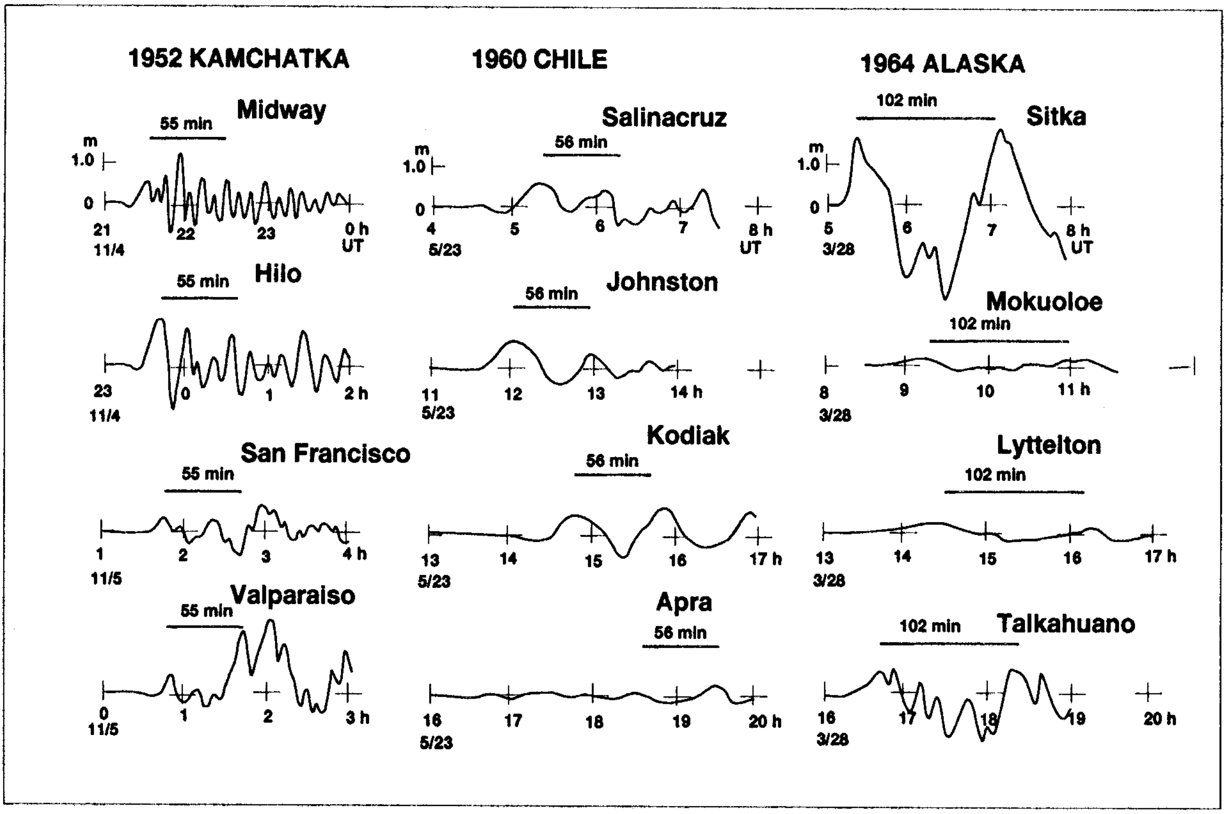

Figure 7. Observed waveforms showing the periods (bars) predicted in reflection models.

period. Other examples of stations observing almost the same predominant periods are Adak, Onahama, SanDiego, and Acapulco. We examined the station dependence of the predominant periods. Thus, seven island stations having similar propagation distances located opposite to the source of the 1960 Chilean tsunami were selected, and we show the relation between the island length and the observed predominant period in Fig. 8. A clear length dependence of the predominant period, with the period increasing with island length, can be seen in the figure. These results suggest that the predominant period is modified by local oscillations in the amplitude. In the resonance curve, a peak at period of about 60 minutes can be seen. The period is nearly equal to the most frequently observed period of 56 minutes. The result can be interpreted as a resonance of the island to the incident tsunami of the period. Since this figure is actually a part of Fig. 3, we can understand the distributions in Fig. 3 as period-response curves.

Comparison of continental tsunamis with island arc tsunamis

The long period predominance is explained by the long time intervals of 55-102 minutes between the initial and reflected pulses. The reflectors were continental coasts close to the sources. The time intervals correspond to the turn-around times of initial pulses on the shelves. Our justification of this assumption can be checked in comparison with island arc tsunamis without reflected waves from the continental coast. As the island arc tsunamis we take the Aleutian tsunamis of April 1, 1946 and March 9, 1957 and the Sanriku tsunami of March 2, 1933 (Fig. 9). The tide-gage records (Green, 1946, Homma, 1950, Fraser et al., 1959) were digitized and translated into spectra by the same method described above and the observed spectra were compared with those of the continental tsunamis as shown in the same figure. The predominant periods were 15 minutes at Hilo for the 1957 Aleutian tsunami and 13 minutes at Honolulu for the 1946 Aleutian tsunami. These tsunamis are considered to be typical because of the short period predominances. On the other hand, these periods were 29 minute at Hilo for the Alaskan tsunami and 32 minutes at Honolulu for the Kamchatkan tsunami. It is easy to see that the Aleutian tsunamis had no clear reflectors like the continental coast. It can be concluded that the reflected waves play a role in elongating the predominant period. The Sanriku coast acted as a reflector in the Sanriku tsunami, and the predominant period of 41 minutes that was observed at San Francisco could very possibly have been due to a reflected wave from the coast. The amplitude, however, was small. As a result it can be concluded that the phase was weak, perhaps suggesting that the curved coast of Sanriku characteristic of an island arc did not work as a good reflector of reflected wave. At the same time, it should be noticed that a large-scale earthquakes generated these

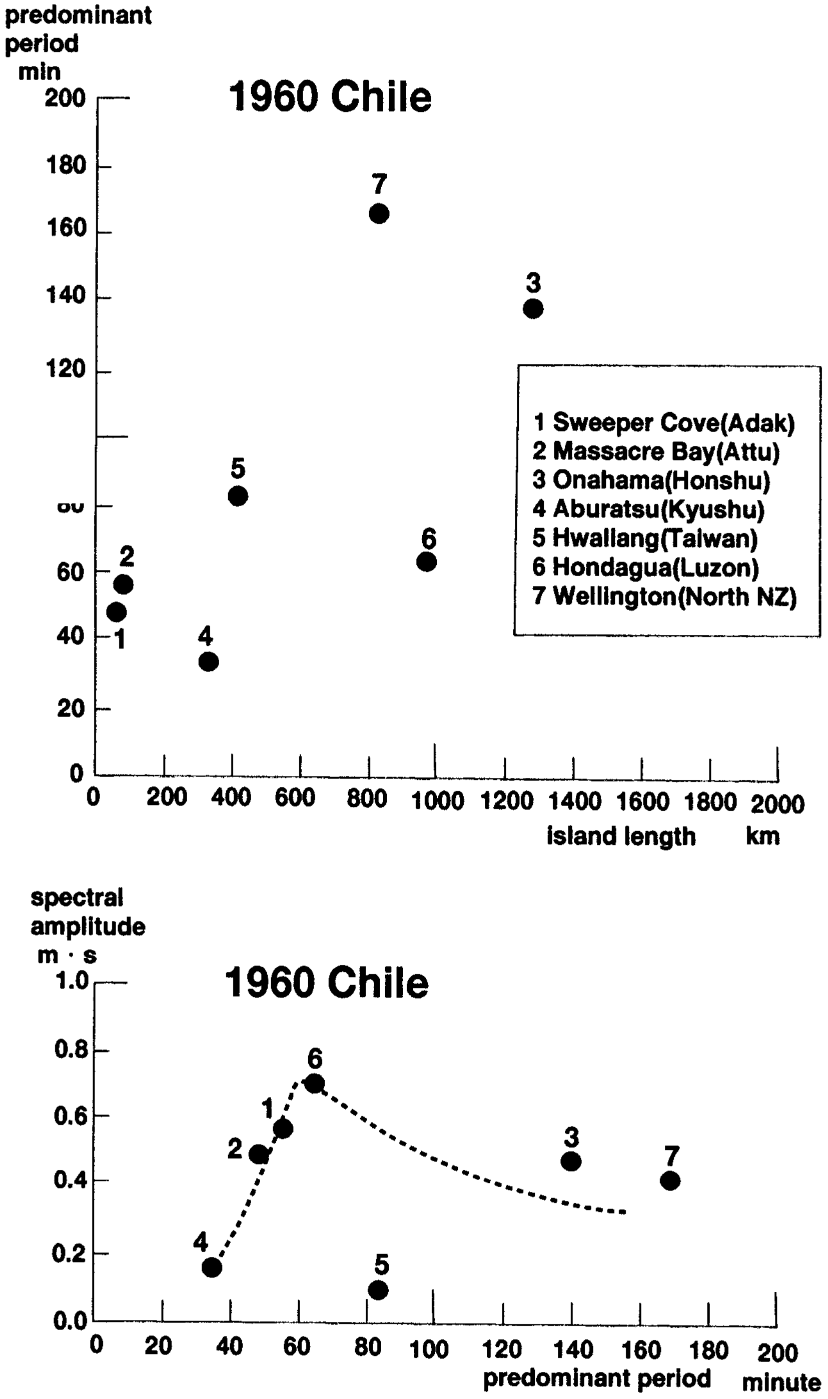

Figure 8. Island-length dependence of the predominant period in island stations across the Pacific Ocean (top) and the resonance curve, which is a part of Fig. 3 (bottom). Numerals in the figures correspond to the observation points shown in the rectangle.

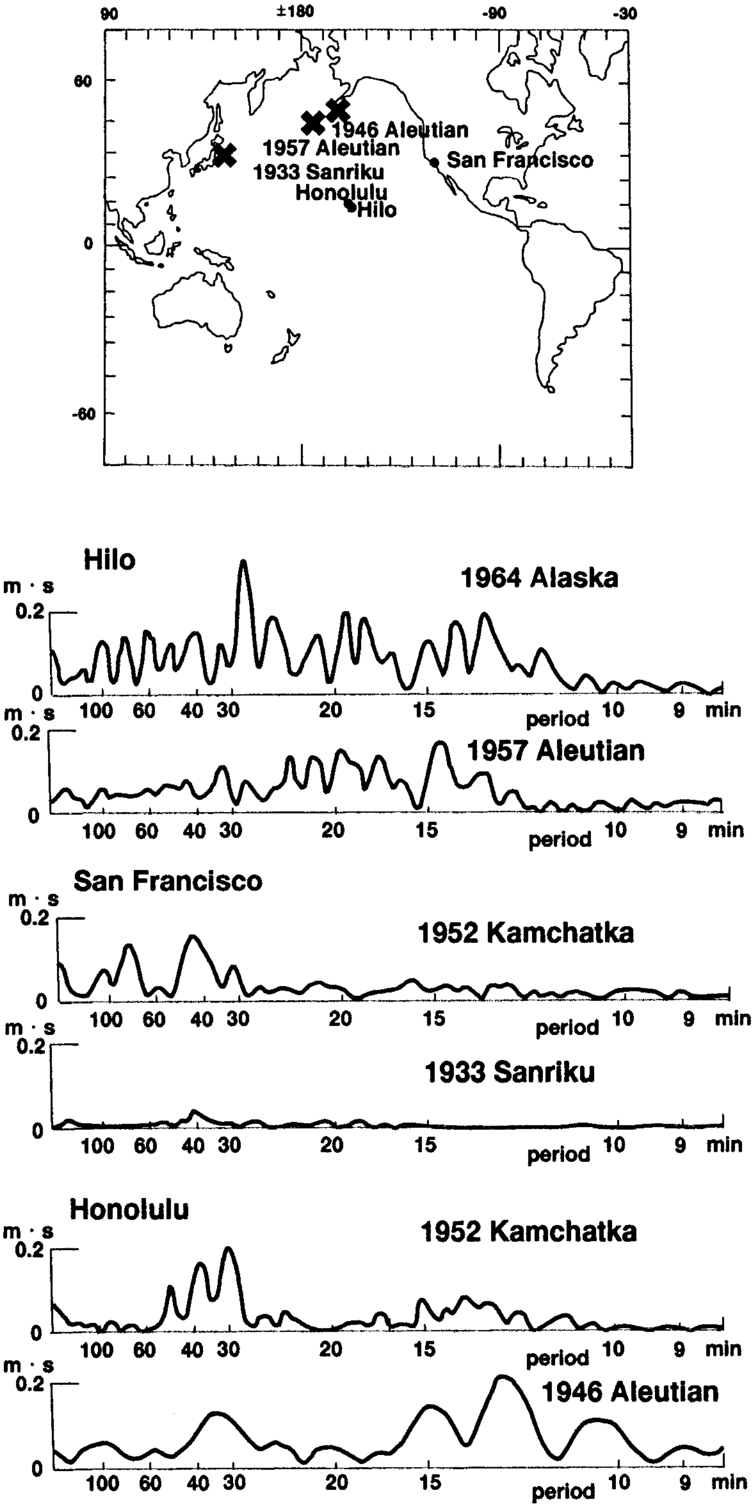

Figure 9. Comparisons of spectra at the same stations between continental tsunamis and island-arc tsunamis. Sources of the island-arc tsunamis and stations are indicated in the map above. Spectrum of the 1946 Aleutian tsunami atHonolulu is reproduced from Åbe (1996).

three tsunamis. The seismic moments reached 3.50×10^{22}, 2.70×10^{23}, and 7.50×10^{22} N-m and the lengths of the proposed faults are 650, 800, and 500 km for the 1952 Kamchatkan earthquake, the 1960 Chilean earthquake, and the 1964 Alaskan earthquake, respectively (Kanamori,1971,1976, Kanamori and Cipar,1974). The long fault lengths are considered to contribute to the reflected waves remaining coherent on a large scale. The above results suggests that the long period predominances are caused by reflected waves from the continental coasts.

Discussion

The response of tsunamis to islands has been studied by Homma (1950), Williams and Kartha (1969), Vastano and Reid (1967,1970), and Van Dorn (1970). In most of these studies high frequency waves of 0.83 -2.0 mHz have been noted due to typical periods of 8-20 minutes in the tsunamis. This period ranges is characteristic of usual tsunami, which bring a strong amplification of tsunamis in a small-scaled island or bay. The two Aleutian tsunamis are included in this category. The model study reported by Van Dorn (1970) suggests that there was no interaction of long-period waves 42-170 minutes with Wake Island. Based on these findings, we can possibly conclude that the amplitude of 42-minutes predominant period in the 1952 Kamchatkan tsunami was not amplified locally but attributed to the source.

Numerical simulations of the Kamchatkan (Abe, 1979), Chilean (Ueno, 1965,Goto et al., 1990) and Alaskan tsunamis (Hwang et al., 1972, Goto et al., 1988) have been attempted. In these numerical approaches, high levels in the maximum level distributions tended to concentrate in the directions perpendicular to fault strikes. These results are supported by our azimuthal distributions of the spectral amplitude. The spectral amplitude in the predominant period is different from the maximum level in the time history but the former is correlated to the latter, which will be shown in a future paper.

Finally, we will discuss about the lens-effect proposed by Miyoshi (1955). The azimuthal distribution showing a concentration of large amplitudes in the perpendicular directions is explained by the superposition of waves radiating parallel to the fault strikes and does not require further explanation by another mechanism such as the lens-effect. In a numerical simulation, Imamura et al.(1990) have shown an increase in the maximum levels around the shallow seas of the Pacific Ocean in comparison with those of the assumed sea region with a constant depth. The shift to longer predominant periods in the ocean provide a proof of trapping and refraction phenomena, suggesting that the lens-effect is a factor during propagation. The lens-effect could contribute to modifying the observed azimuthal distributions of simple forms showing the maximum values in the perpendicular directions, but clear proof to this effect has not been found. In the 1952 Kamchatkan tsunami, we described large amplitude waves observed at continental coasts located at rear sides of small islands. This is the lens-effect of small scale. But the predominant periods of 12-14 minutes were small. It is too small to give some effect to our main conclusion that is a long-period predominance in the perpendicular direction. It is reasonable to conclude that the observed azimuthal distributions can primarily be attributed to sources including nearby coasts.

Conclusion

Spectral analyses of three large tsunamis, including the 1952 Kamchatkan tsunami, the 1960 Chilean tsunami, and the 1964 Alaskan tsunami, were carried out, and space distributions of the predominant periods and amplitudes were obtained. The results revealed long period predominances of 49,56,102 minutes in all the tsunamis. The amplitude of the long period component increased with increases in propagation distance toward coasts on opposite side of the globe with long periods predominating in particular in directions perpendicular to the fault strikes. The predominant periods could be explained by the time intervals between initial waves and waves reflecting from the continents based on several models. The spectral amplitude observed at some islands varied with the predominant period and the distribution was represented by a resonance curve. The continental tsunamis were compared with island arc tsunamis without any reflected waves and it was shown that the long period predominances are peculiar to continental tsunamis and contribute to the global radiation.

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TSUNAMI MITIGATION FOR THE CITY OF SUVA, FIJI

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ABSTRACT

At about 12.30pm (local time) on 14 September 1953, the City of Suva was devastated by an ML 6.5 earthquake and associated tsunami of local origin. The earthquake source was about 25km SW of the City with the tsunami generation attributed to submarine landslides (turbidity currents). The City CBD, main industrial area and shore and harbour facilities were severely damaged. As part of the UNDHA – South Pacific Programme Office "South Pacific Disaster Reduction Programme", within the auspices of Pacific Region IDNDR and the 1994 Yokohama Statement, the "Suva Earthquake Risk Management Scenario Pilot Project" (SERMP) was facilitated for the Government of the Republic of Fiji. SERMP considered mitigation measures for both earthquake and tsunami impacting upon the City of Suva, with the scenario event based on the real experience of the 1953 Suva earthquake and tsunami.

A specific tsunami mitigation methodology was developed involving a multidisciplinary approach with multi-agency cooperation to address, in both quantitative and qualitative terms, the premise

RISK = HAZARD ● VULNERABILITY.

The hazard and vulnerability assessments are integrated to provide the risk assessment which is then considered in terms of Fiji's emergency management requirements. The outcomes include hazard, vulnerability and risk zonation maps with associated commentaries, estimates of relevant tsunami parameters and possible damage situations. Practical applications of these results, in terms of community vulnerability and reduction of potential losses, and including a simulated tsunami exercise, have been a major element in this project. It was concluded that a significant risk of local tsunami does exist for the City of Suva and its harbour environs

This information resource has been implemented for Fiji's National Disaster Management Office in terms of disaster planning, response actions, training and community education. Currently, Fiji is developing its own regional tsunami warning system. Recent tsunami disasters, like that in Aitape, Papua New Guinea, in July 1998, serve to reinforce the vital need for mitigation measures in these vulnerable coastal communities of Pacific Island nations.

INTRODUCTION

Earthquakes are the most devastating natural phenomena known to human civilisation. They strike without warning, impact all levels of society and take a toll in human life, personal injury, property damage and the socio-economic fabric. Their consequences affect both the built and natural environments. Some major earthquakes cause associated tsunamis which can further affect coastal precincts and island communities. The Republic of Fiji and, in particular, its capital city of Suva are considered to be so vulnerable. Recent history attests to this, with the memory of the devastating 14 September 1953 Suva earthquake (Richter Magnitude ML 6.5) and its associated tsunami.

With the world's modern and expanding societies, many recent earthquake and tsunamis are clear testament to the immediate need for earthquake mitigation. This need has been most aptly facilitated during this present decade, 1990 - 2000, by the United Nations International Decade for Natural Disaster Reduction (IDNDR). Herein, the issues of awareness, risk assessment, preparedness and warning for earthquake and tsunami are being addressed, the premise for mitigation measures.

At the IDNDR Mid-Term Conference in Yokohama, Japan, in May 1994, one of the outcomes from the "Yokohama Strategy and Plan of Action" has been the actions taken by the island nations of the world, with particular reference to the Pacific Island Countries (PIC) of the South Pacific. Many national and local agencies, both Government and non-Government, expressed the need to better understand the implications of potentially damaging earthquakes and tsunamis on their communities.

The Republic of Fiji took up this challenge. At the 3rd Pacific Regional IDNDR Meeting held in Suva in September 1994, the premise of earthquake and tsunami mitigation for Fiji was seriously considered. The Government of the Republic of Fiji Ministry for Regional Development and Multi-Ethnic Affairs National Disaster Management Office (NDMO), in cooperation with the UN Department of Humanitarian Affairs South Pacific Programme Office (UNDHA-SPPO) (now United Nations Development Programme – South Pacific Office, UNDP-SPO), inaugurated this SUVA EARTHQUAKE RISK MANAGEMENT SCENARIO PILOT PROJECT (SERMP) through the UNDHA's South Pacific Disaster Reduction Programme (SPDRP). At this meeting, international support was afforded by the International Association for Earthquake Engineering (IAEE) "World Seismic Safety Initiative" (WSSI), an approved IDNDR Demonstration Project. SERMP considered risk assessment and mitigation measures for both earthquake and tsunami.

This paper relates to the issues for tsunami, taken from the SERMP Final Report (CERA, 1997) for the City of Suva (Figure 1).

1953 SUVA EARTHQUAKE AND TSUNAMI

At 12.28pm on 14 September 1953, the Republic of Fiji experienced its most devastating earthquake and associated tsunami of modern times. These events were located about 15-20 km southwest of the City of Suva, off the coast near Navua. The most severe damage, resulting from both events, was concentrated in Southeast Viti Levu, particularly in the City of Suva and surrounding areas.

The initial studies were undertaken by Houtz (1962) and Houtz and Wellman (1962). A Richter magnitude ML 6.75 was assigned to the earthquake. The effects of the earthquake were felt up to 250 km from the epicentre (representing the majority of the Republic of Fiji) with damage reported from several urban and rural centres in Viti Levu, albeit concentrated in southeastern Viti Levu. Tsunami waves were reported at distances up to 180 km from the epicentre, with the most severe effects in southeastern Viti Levu, particularly in Suva Harbour, along the adjacent foreshores of Suva Peninsula and Rewa River Delta, and on the coastal areas of Kadavu Island to the south.

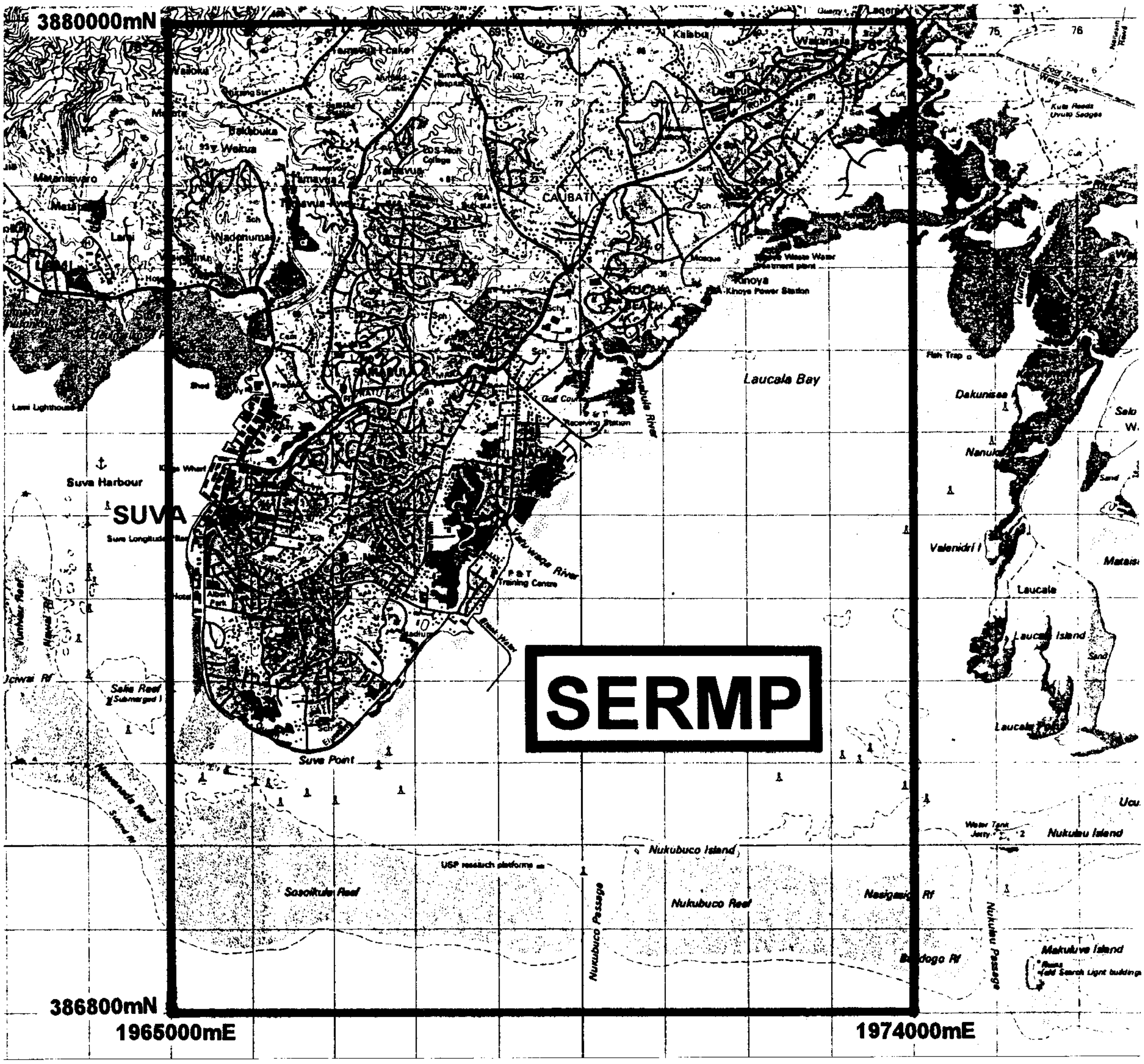

Figure 1 : Location Area for Suva Earthquake Risk Management Scenario Pilot Project (SERMP) - The City of Suva, Fiji

Wave heights were greater than 3m with travel times (time of arrival after the initial earthquake shock) of 5 - 15 minutes. Collateral damage from the tsunami waves occurred along the Suva City foreshores, along the coast from Suva to Navua, in Suva Harbour and on the reefs. Economic losses were assessed at (1953) F£250,000. A significant toll on the human population was also taken - 8 deaths (three due to the earthquake and five drownings in the tsunami) and 61 reported injuries from the earthquake.

These initial studies, together with the other later ones (Soloveiv and Go (1984); Everingham, 1984) unfortunately did not provide the information in a form suitable for vulnerability assessments, and hence they were not appropriate for disaster management authorities. As part of SERMP, Rynn and Prasad (1999) undertook a review of all available data to define the required earthquake / tsunami scenario, compile the risk assessments and provide "real experience" information for future mitigation strategies.

The seismological parameters are :

earthquake : origin time : 0028 hours 14 September 1953 (UT)
12.28pm 14 September 1953 (local)
epicentre : 18.2^{0}S, 178.3^{0}E
focal depth : 10 km
magnitude : (revised) Richter ML 6.5, Mw 6.5

tsunami : source : submarine canyons off coast of Southeast Viti Levu near Naqara
mechanism : submarine sediment slumping (turbidity current)
wave height : > 3 m
run-up : max 2 m
magnitude : I 1.5 - 2.0.

The earthquake isoseismal map for the Fiji Islands and the tsunami inundation map for the City of Suva are shown in Figures 2 and 3, respectively. This information provided the basis on which the scenario earthquake and associated tsunami for SERMP was to be defined.

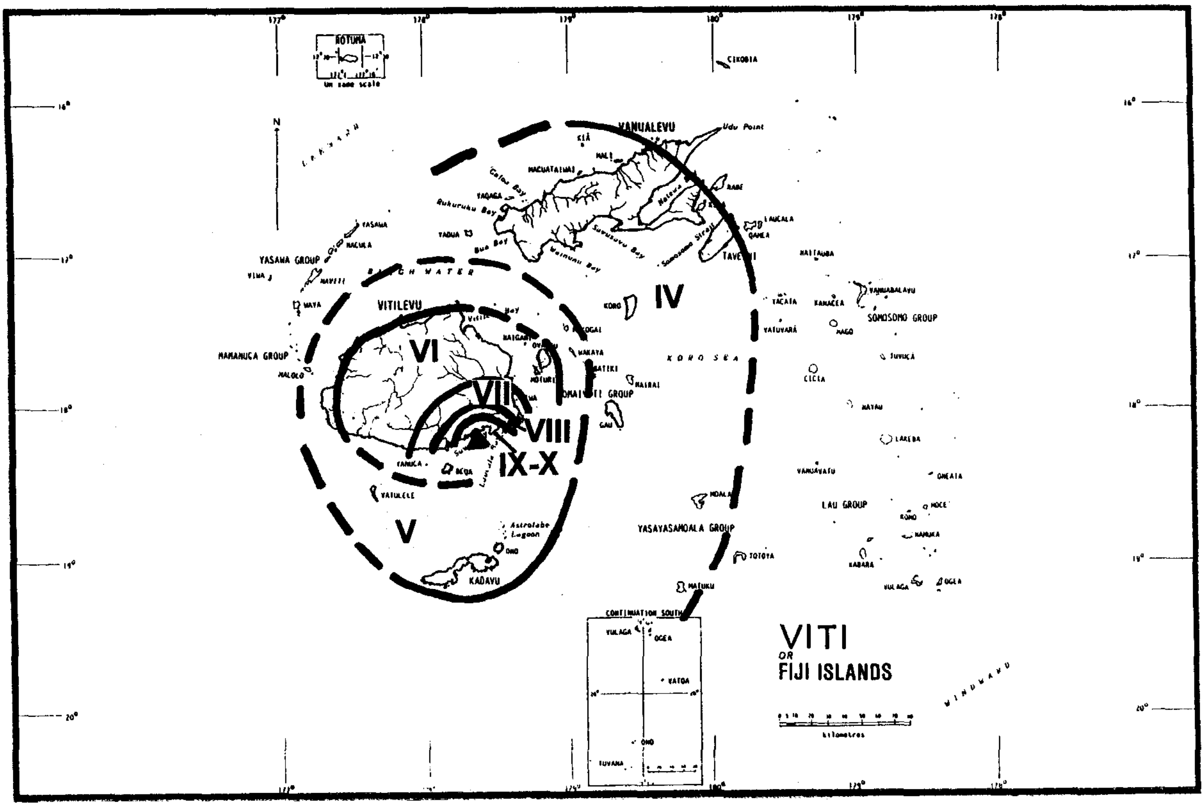

Figure 2 : Isoseismal Map of 14 September 1953 Suva Earthquake Mw 6.5 for the Republic of Fiji – Built Environment
(From Rynn and Prasad, 1999)

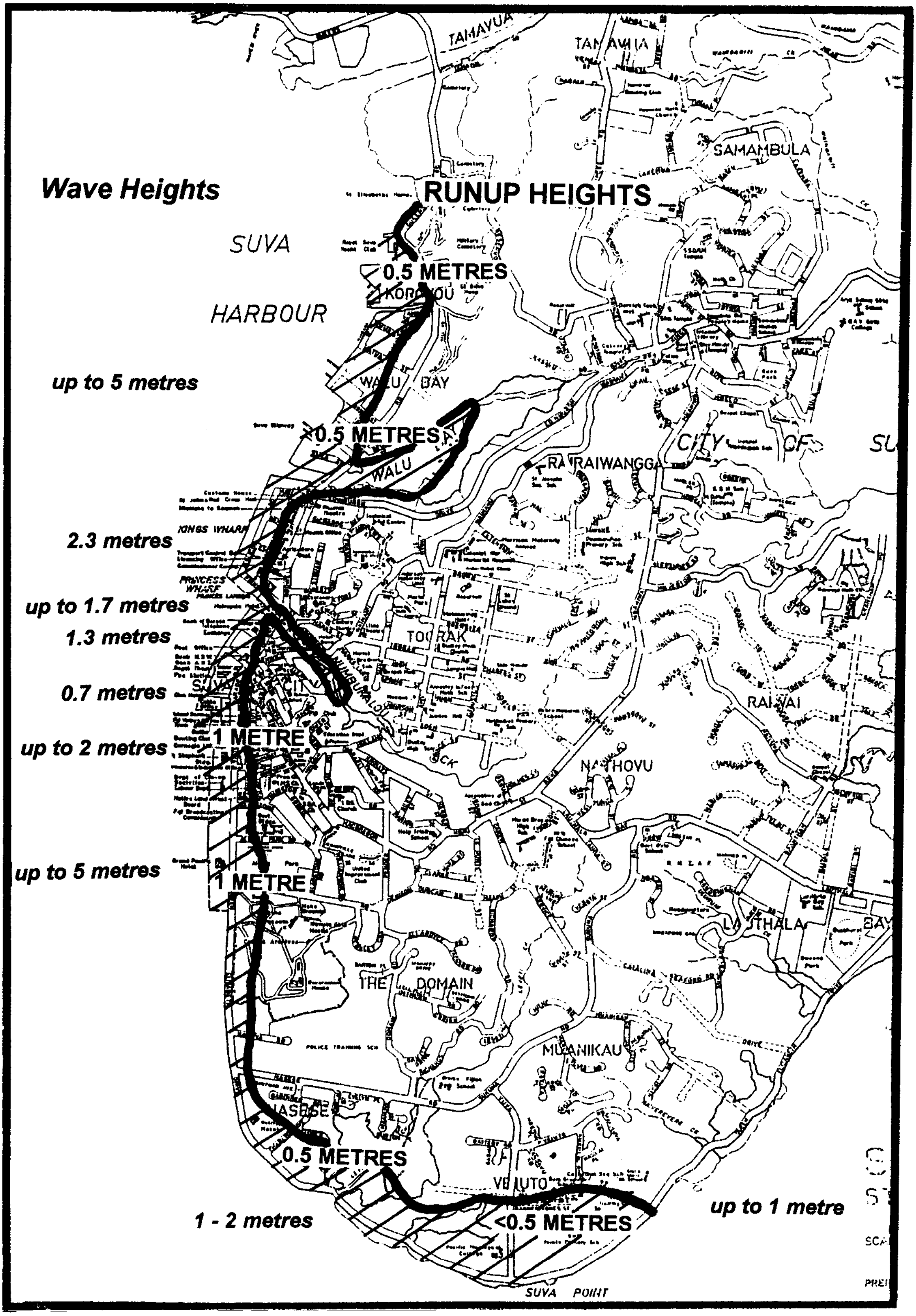

Figure 3 : Inundation Map with Run-up (m) and Wave Heights (m) of 14 September 1953 Tsunami (Suva Earthquake) for the City of Suva (From Rynn and Prasad, 1999)

SUVA EARTHQUAKE RISK MANAGEMENT SCENARIO PILOT PROJECT (SERMP)

SERMP was undertaken over the period 1995 through 1997. It has been coordinated by the Ministry of Regional Development and Multi-Ethnic Affairs through the National Disaster Management Office (NDMO). UNDHA-SPPO facilitated the project under its SPDRP by providing management support and linkages to regional technical organisations (such as SOPAC, SPC, SPREP), Emergency Management Australia (EMA) Australian IDNDR Coordination Committee and relevant international geological, seismological and disaster management agencies. This pilot project involved a multidisciplinary and multi-institutional approach involving forty-six (46) Fiji Government agencies, Non-Government Organisations and professional bodies, and international consultancies with the Centre for Earthquake Research in Australia (CERA), Brisbane, Australia and the Institute for Geological and Nuclear Sciences (IGNS) Wellington, New Zealand. The tsunami mitigation part also involved collaboration with the US National Oceanic and Atmospheric Administration (NOAA) tsunami laboratories in Boulder and Seattle and the International Tsunami Commission (ITC).

When the concept of SERMP was being considered in late 1994, the importance of the information from this 1953 event being integrated into mitigation strategies was fully realised. Today, more than 45 years later, the City of Suva is a thriving metropolis. The City and environs has undergone a great transformation with massive population increase (from about 35,000 in 1953 to about 300,000 in 1997) and consequent infrastructure expansion. As the capital city of the Republic of Fiji, most of the commerce, a large volume of industry and all diplomatic missions are located therein. As well as serving Fiji, Suva is today the hub of economic activities for other nations in this part of the South Pacific. The vulnerability, in all aspects, of Suva and environs to a similar earthquake and associated tsunami striking in the future is patently evident.

Integral in this project has been the development of an **earthquake and tsunami mitigation strategies** suitable to the needs of PIC, with the emphasis on a major urban area and its rural environs. As such, the City of Suva, Fiji, was considered to be most appropriate for this initial pilot project. The concept is that of a pilot project to provide necessary and sufficient information resources from which NDMO will be able to implement emergency management procedures to reduce the potential toll and damage from future earthquakes and associated tsunamis that may impact on communities in Fiji. The prime concerns were the vital involvement of relevant Fijian agencies and the consideration of the indigenous and ethnic populations.

It must be fully recognized that the aims, significance and objectives of SERMP emphasise that of a **PILOT PROJECT** to strictly address the associated elements of **AWARENESS** and **PREPAREDNESS** to mitigate the earthquake and tsunami hazards. The outcomes are thus required to provide the platform whereby Fiji is able to continue investigations to improve national mitigation strategies - that is, the "way-forward".

The direction for SERMP was stated in terms of six (6) **PROJECT COMPONENTS** (for both the earthquake and associated tsunami hazards relative to The City of Suva) :

1. HAZARD ASSESSMENT
2. VULNERABILITY ASSESSMENT
3. DISASTER MITIGATION MEASURES
4. EMERGENCY RESPONSE PLANNING
5. PUBLIC AWARENESS AND POLICY SUPPORT
6. DISSEMINATION OF FINDINGS.

TSUNAMI MITIGATION APPROACH IN SERMP

The potential for devastation to coastal communities, particularly small island nations, from tsunamis was recognised within the IDNDR initiative (Bernard, 1993). Such devastation has been witnessed during the Decade with, for example, the 1992 Nicaragua, 1992 Flores (Indonesia), 1993 Okushiri (Japan), 1994 East Java (Indonesia) and, most recently, 1998 Aitape (Papua New Guinea) tsunamis. The historical record provides many more cases, even for Fiji with the 1953 tsunami impacting the City of Suva

For SERMP, the premise was to consider a potential tsunami associated with the scenario earthquake – as was the case with the 1953 Suva earthquake and associated tsunami – that is, to consider a locally generated tsunami. Hence, consideration of potential tsunami effects related to distant tsunamigenic sources (for example: earthquake occurrences around the Pacific Ocean Basin) are not included in the scope of work of this pilot project.

The methodology has been developed in terms of the three INDNDR/STC targets – risk assessment, mitigation measures, warning systems – and was based upon the Australian IDNDR project "Contemporary Assessment of Tsunami Risk and Implications for Early Warnings for Australia and Its Island Territories" (Rynn and Davidson, 1999; loc. cit). This was adapted to the situation of the City of Suva and local requirements.

Tsunami risk is is assessed by a deterministic approach according to (as defined in Figure 4) :

TSUNAMI RISK = HAZARD ● VULNERABILITY,

(a) for the HAZARD assessment :
- Preparation of a data-base of historical and archival information (MRD files, newspapers, archives, anecdotal information, literature survey) of relevant Fijian tsunamis, with the emphasis clearly on the 1953 event (Rynn and Prasad, 1999)
- Analyses of these data, which are essentially a "scaling up" of the 1953 event to
  - define the scenario tsunami
  - prepare the tsunami hazard map ;

(b) for the VULNERABILITY assessment :
- Based on the earthquake vulnerability assessment, define the vulnerable elements on the coastal, island and reef environments and in Suva Harbour
- Prepare vulnerability charts and matrices;

(c) for the RISK assessment :
- integrate these hazard and vulnerability assessments for the risk assessment.

This information resource was then used as the basis for tsunami mitigation strategies as required by Fiji's Natural Disaster Management Office (NDMO) – in terms of emergency management, disaster plans, community vulnerability, education, training, community awareness, tsunami exercises and recommendations for future studies – in both the terrestrial and marine environments of the City of Suva. It is noted that these strategies are integral with those for earthquake mitigation in the context of SERMP (CERA, 1997a).

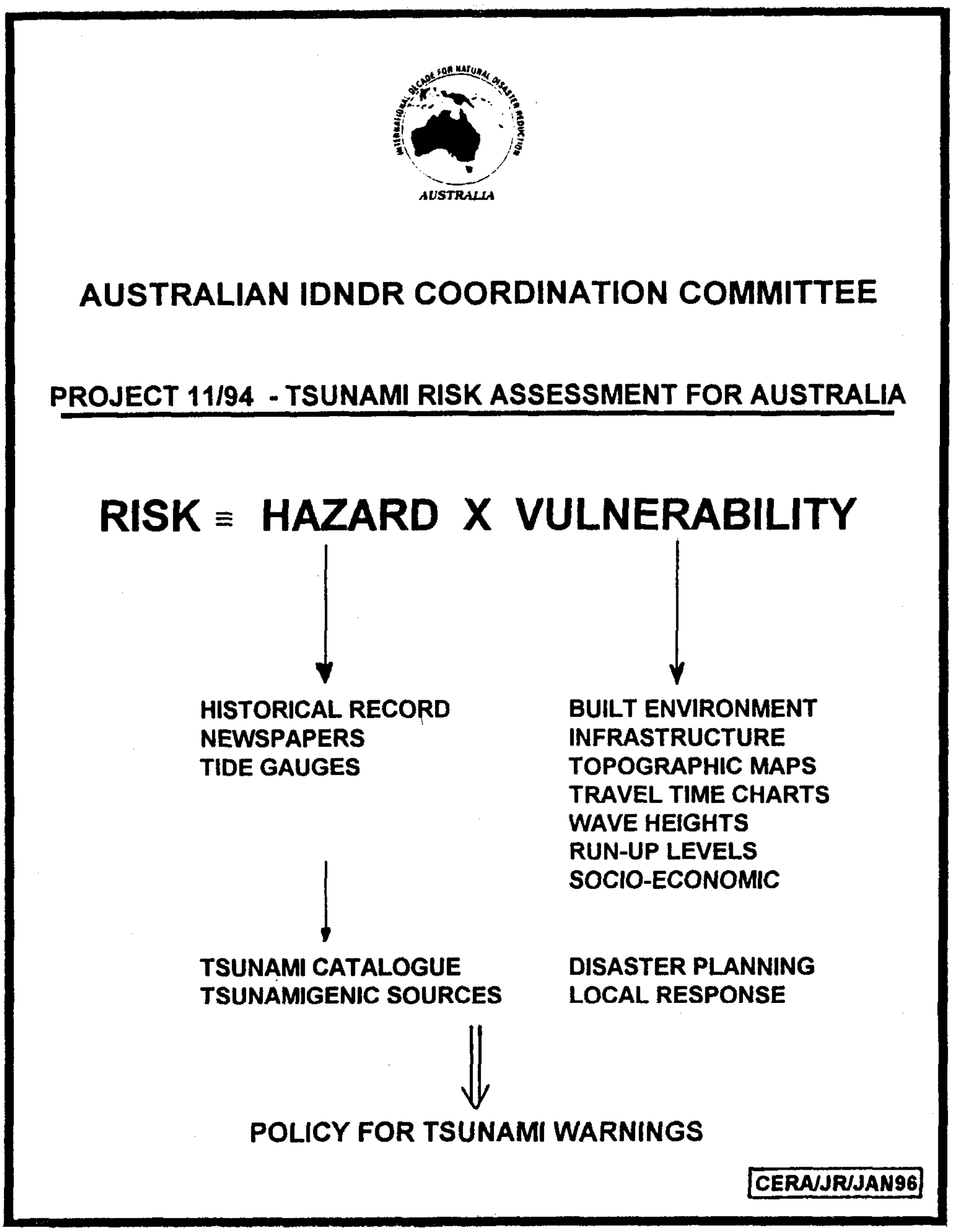

Figure 4 : The Approach for Tsunami Risk Assessment (Per SERMP; CERA, 1997a)

TSUNAMI HAZARD ASSESSMENT

The tsunami hazard for the Fiji region of the South Pacific (Fiji, Vanuatu, Samoa, Tonga) has been well recognized with vulnerability being considered as at high levels (for example : Carter et al, 1991; Rynn, 1995). The most recent and comprehensive tsunami catalogue for Fiji is that compiled by Everingham (1987) for the period 1853 - 1981. Eleven tsunamis have impacted upon the coastal areas of the main islands and on the small islands. The largest, and indeed the only tsunami to have caused damage, was that associated with the 1953 Suva earthquake (Houtz, 1962 : Houtz and Wellman, 1962 : Rynn and Prasad, 1999).

Scenario Tsunami

Relative to the SERMP scenario earthquake epicentre (18.2°S, 178.3°E – Figure 5; Mw 7.0), the tsunamigenic source (area of generation) for SERMP is taken to be similar to that for the 1953 event (as determined by Houtz, 1962, and Houtz and Wellman, 1962), as shown in Figure 5. The parameters are

tsunami source region : Coincident with the steepest portion of the marginal shelf which drops abruptly from 200 to 600 fathoms parallel to the south coast from Suva to Beqa Is; For Suva, origin at entrance to Suva Harbour
mode of generation : High velocity turbidity current (submarine landslides of seafloor sediments of marine chasms)
potential wave heights : Reefs at entrance to Suva Harbour - up to 20 m
Suva Harbour (waves) - up to 3 m
Suva Harbour foreshores - up to 3 m
Laucala Bay foreshores - up to 2 m
run-up (maximum) : Suva Harbour foreshores - 5m contour
Laucala Bay foreshores - 1m contour
tsunami intensity : $I = 0.5 - \log_2 H$ (Pelinovsky, 1996)
with H = average maximum run-up height > 3m
I (max) = 2.5.

Tsunami Hazard Map

The SERMP tsunami hazard map, given in Figure 6, has been empirically defined using a deterministic approach, based upon potential maximum wave heights for the scenario tsunami essentially "scaled-up" from the 1953 event observations of Rynn and Prasad (1999). The definition of the tsunami hazard zones, as preliminary estimates, is given in Table 1. For the terrestrial environment ("ON LAND") - foreshores around Suva Peninsula - the hazard is presented as inundation levels, in terms of run-up heights at specified land contours.). For the marine environment ("ON WATER") - Suva Harbour, Laucala Bay, Reefs - the hazard is given in terms of potential maximum wave heights.

TABLE 1 : TSUNAMI HAZARD ZONES DEFINITION (PRELIMINARY)

CHARACTERISTIC	TSUNAMI HAZARD ZONE		
	HI	MED	LO
ON LAND			
INUNDATION LEVEL-MAXIMUM (M CONTOUR)	5	3	1
RUN-UP HEIGHT-AVERAGE (M)	>3	1 - 3	0 - 1
TSUNAMI INTENSITY (I)	>2	1 - 2	0
LIKLIHOOD OF TSUNAMI	YES	YES	POSSIBLE
DAMAGE OBSERVED IN 1953 TSUNAMI	SEVERE	MINOR	NONE
COAST ADJACENT TO TSUNAMIGENIC SOURCE	YES	YES	NO
ON WATER			
WAVE HEIGHTS (M)	>2	1 - 2	<1
REEF DAMAGE	SEVERE	MINOR	NONE

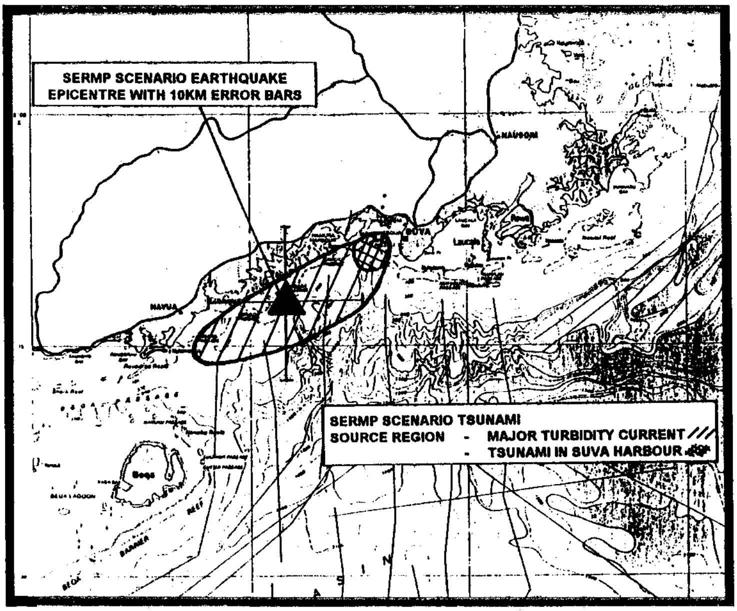

Figure 5 : Scenario Tsunami Source Region (Per SERMP; CERA, 1997a)

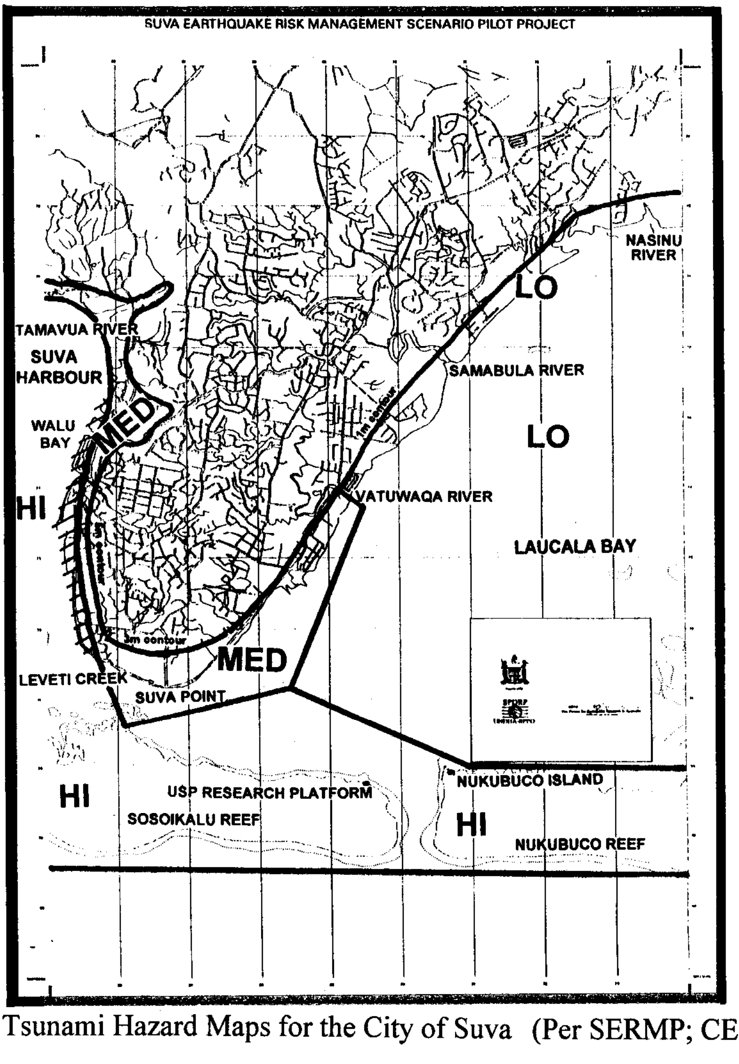

Figure 6 : Tsunami Hazard Maps for the City of Suva (Per SERMP; CERA, 1997a)

TSUNAMI VULNERABILITY ASSESSMENT

The vulnerability inventory for both the built and natural environments prone to potential tsunami damage was developed for suburbs of the City of Suva around the shores of Suva Peninsula and for Suva Harbour. Potential damage is related to the hydrological controls of wave action (surging), flooding and debris deposition, and consequent geological controls to damage by liquefaction, cracking and slumping. These result in structural damage to buildings, water damage to contents, flooding damage to infrastructure (roads, bridges, water supply, sewerage, wharves, sea-walls), damage to navigational aids and reef damage. There is the potential for "seiching" in the shallow harbour areas where, alternately (from the tsunami waves), water is drained from the harbour and then flooded to depths greater than high tide levels (as was the case in the 1953 event). This has the potential for threat to human life (death and injury) from people collecting fish from the harbour seafloor. In the Harbour, waves are a threat to shipping (sinking, striking wharves) and fishermen (drownings).

The vulnerability assessment is expressed as details of elements of the built, natural and human environments vulnerable to potential tsunami-related damage as given in Table 2. These are considered in terms of the Tsunami Hazard Zones of Figure 6 for the terrestrial environments around the foreshores of Suva Peninsula - western side (Tamavua River to Suva Point - in respect of Suva Harbour); and eastern side (Suva Point to Nasinu River - in respect of Laucala Bay) - and the marine environments of Suva Harbour, Reefs and Laucala Bay.

TSUNAMI RISK ASSESSMENT

By integrating the hazard and vulnerability assessments, the tsunami risk assessment is presented in terms of zonation and inundation maps (Figure 7) and associated commentaries (Table 3). The interdependence of such a locally generated tsunami with the scenario earthquake (a single tsunamigenic source) is again noted. In respect of the SERMP scenario tsunami source area to the WSW of The City of Suva (Figure 5), and the observations of the effects of the 1953 event (Rynn and Prasad, 1999), the tsunami risk zones have been related to the terrestrial environments along the western and eastern foreshores of the Suva Peninsula (Zones A-D), and the marine environments of Suva Harbour, near-shore Reefs and Laucala Bay (Zones Am - Cm). Characteristics of these Zones, in terms of inundation levels and vulnerability levels, are given in the COMMENTARY of Table 3.

PRACTICAL APPLICATIONS

The key factors to reduce potential losses due to tsunami are AWARENESS and PREPAREDNESS. The practical applications of this tsunami risk assessment, in both quantitative and qualitative terms, for implementation into mitigation strategies for the terrestrial and marine environments include :

1. BUILDING CODES
2. GIS MAPPING
3. LAND-USE PLANNING
4. DISASTER PLANNING
5. EMERGENCY MANAGEMENT
6. EMERGENCY PERSONNEL TRAINING
7. RESCUE AND RESPONSE
8. INSURANCE NEEDS
9. COMMUNITY EDUCATION
10. SIMULATED TSUNAMI EXERCISES.

TABLE 2

VULNERABILITY ELEMENTS RELATIVE TO SERMP SCENARIO TSUNAMI

(A) TERRESTRIAL ENVIRONMENT : FORESHORES AROUND SUVA PENINSULA

VULNERABLE ELEMENT	TSUNAMI EFFECTS			
	WAVE ACTION		FLOODING	
1. WESTERN SIDE - TAMAVUA RIVER TO SUVA POINT (AROUND SUVA HARBOUR)				
	Waves up to 3 m breaking over sea wall and onto foreshore roads causing damage, deposition of debris and flooding	• SUVA CENTRAL WALU BAY KOROVOU THE DOMAIN NASESE	Inundation possibly up to 5m topographic contour flooding infrastructure and buildings and causing problems for emergency services and distress to the public (commercial and residential)	• SUVA CENTRAL WALU BAY KOROVOU THE DOMAIN NASESE VEIUTO
(a) BUILT ENVIRONMENT				
CRITICAL FACILITIES				
NDMO			Store	• WALU BAY
NFA			Fire Headquarters	• WALU BAY
POLICE			Headquarters	• SUVA CENTRAL
PORT FACILITIES	Wharves, jetties, slipways, Rockabili Container Terminal	• WALU BAY SUVA CENTRAL KOROVOU	All facilities - wharves, jetties, slipways, building, Rockabili Container Terminal	• WALU BAY SUVA CENTRAL KOROVOU
ENGINEERING SERVICES			PWD workshops	• WALU BAY
			Telecom workshops	• WALU BAY
			Marine Department	• WALU BAY
COMMUNICATIONS			Telecom Headquarters	• SUVA CENTRAL
INFRASTRUCTURE	*[Refer to Earthquakes Vulnerability Inventory Table 12, Pages 123-129]*		Roads at elevations lower than 5m contour, including CBD, Walu Bay and Korovou industrial areas, Government Buildings, educational institutions and residential areas	• SUVA CENTRAL WALU BAY KOROVOU THE DOMAIN NASESE VEIUTO
ROADS	Roads adjacent to seashore			
	Stinson Parade	• SUVA CENTRAL		
	Victoria Parade	• SUVA CENTRAL		
	Queen Elizabeth Drive	• THE DOMAIN NASESE VEIUTO		
	Queens Road (Forster Rd)	• KOROVOU		
BRIDGES	Bridges may be subject to the combined effects of wave action and flooding resulting in possible damage from geological controls of liquefaction of abutments, partial collapse of embankments and debris deposition			
			Tamavua River	• KOROVOU
			Walu Bay	• WALU BAY
			Nubukalou Creek	• SUVA CENTRAL
			Turner Bridge	• NASESE
WATER			Flooding of services and equipment - for the foreshore areas to 5m contour in suburbs from KOROVOU to VEIUTO	
SEWERAGE			Flooding of services and equipment - for the foreshore areas up to 5m contour in suburbs from KOROVOU to VEIUTO - a public health hazard	
DRAINAGE			Flooding of dams and debris deposition within - for foreshore areas up to 5m contour in suburbs from KOROVOU to VEIUTO - a public health hazard	
SEAWALL	overtopping, damage to seawall and debris deposition	• SUVA CENTRAL THE DOMAIN NASESE		
OIL/FUEL TERMINALS	damage to wharf facilities, terminal equipment	• WALU BAY	damage to terminal equipment, fuel storage and products; pollution	• WALU BAY
MILITARY				
NAVY	wharves, slipways, buildings, facilities, equipment, ships, communications	• WALU BAY	buildings, facilities, equipment, ships, communications	• WALU BAY
ARMY	wharves, buildings, facilities,equipment	• WALU BAY	buildings, facilities, equipment	• WALU BAY
SHIPPING				
AT BERTHS (CARGO, TOURIST, INTER-ISLAND, NAVY, FISHING, RECREATIONAL)	damage to shipping	• WALU BAY SUVA CENTRAL SUVA CENTRAL	facilities, equipment, marinas	• WALU BAY SUVA CENTRAL KOROVOU
BUILDINGS				
INDUSTRIAL, COMMERCIAL	damage to structures and contents	• KOROVOU WALU BAY SUVA CENTRAL	damage to structures and contents	• KOROVOU WALU BAY SUVA CENTRAL
GOVERNMENT			damage to structures and contents	• KOROVOU SUVA CENTRAL THE DOMAIN NASESE
EDUCATIONAL			damage to structrures and contents	• SUVA CENTRAL THE DOMAIN NASESE VEIUTO
RESIDENTIAL			damage to structures and contents	• SUVA CENTRAL THE DOMAIN NASESE VEIUTO
VILLAGES AND SETTLEMENTS	damage to structures and contents	• KOROVOU	damage to structures and contents	• KOROVOU

TABLE 2 (Continued)

(b) NATURAL ENVIRONMENT				
SEASHORE	damage to shore areas, near-shore reefs, debris deposition - from Tamavua River to Suva Point			
RIVER MOUTHS	possible wave surges Tamvua River	• KOROVOU		
SWAMPS			flooding - Tamavua River mouth Walu Bay Leveti Creek	• KOROVOU • WALU BAY • NASESE
(c) HUMAN FACTORS				
SH IPPING	on beach ships at berth - injuries	• KOROVOU WALU BAY SUVA CENTRAL		
SEASHORE	drowning	• KOROVOU WALU BAY SUVA CENTRAL		
SOCIO-ECONOMIC	damage to fishing and recreational ships at berth	• KOROVOU WALU BAY SUVA CENTRAL	damage to businesses and loss of human life	• KOROVOU WALU BAY SUVA CENTRAL
			damage to personal effects in private residences from Tamavua to Suva Point	• ALL SUBURBS
2. EASTERN SIDE - SUVA POINT TO NASINU RIVER (AROUND LAUCALA BAY)				
	Waves possibly up to 1m breaking over the in-shore fringing reefs. Note that these reefs may act to suppress any large waves	• VEIUTO MUANIKAU LAUCALA BAY MUANIVATU VATUNAQA LAUCALA BEACH KINOYA	Dependent on wave heights on the shoreline, hence flooding could be miner with maximum inundation of the southern end of the Suva Peninsula, possibly to the 1m contour	• VEIUTO MUANIKAU LAUCALA BAY MUANIVATU VATUWAQA LAUCALA BEACH KINOYA
(a) BUILT ENVIRONMENT				
CRITICAL FACILITIES				
COMMUNICATION - FINTEL - TELECOM			International communications Transmitter	• VATUWAQA • MUANIVATU
INFRASTRUCTURE				
ROADS			Roads adjacent to seashore (minor flooding and debris deposition) Queen Elizabeth Drive	• VEIUTO MUANIKAU LAUCALA BAY
			Local roads near shore	• VATUWAQA LAUCALA BEACH KINOYA NADAWA
BRIDGES			Nolverevere Creek Vatuwaqa River Bridge No.2	• MUANIKAU • VATUWAQA
SEWERAGE			PWD Treadtment Plant	• KINOYA
POWER			FEA Power House	• KINOYA
BREAKWATER	possible damage	• LAUCALA BAY		
BUILDINGS				
COMMERCIAL			Stock Quarantine	• MUANVATU
EDUCATIONAL			Schools, Colleges, Seminaries USP, School of Maritime Studies Telecommunication Training Centre	• VEIUTO • LAUCALA BAY • MUANUATU
RESIDENTIAL			Private housing	• VEIUTO MUANIKAU MUANIVATU VATUWAQA LAUCALA BEACH KINOYA NADAWA
VILLAGES AND SETTLEMENT			Kinoya Village Baniose Settlement	• KINOYA • LAUCALA BAY
RECREATIONAL			Parks Fiji Golf Course	• MUANIKAU LAUCALA BAY MUANIVATU • VATUWAQA
(b) NATURAL ENVIRONMENT				
RIVER MOUTHS	Possible wave serges Vatuwaqa River Samabula River Nasini River	• MUANIVATU VATUWAQA • LAUCALA BEACH • NADAWA	Damage to river banks Nolverevere Creek Vatuwaqa River Samabula River Kinoya Creek Nasinu River	• MUANIKAU • MUANIVATU VATUWAQA • LAUCALA BEACH • KINOYA • NADAWA
			minor flooding Vatuwaqa River mouth Samabula River mouth	• MUANIVATU VATUWAQA • VATUWAQA LAUCALA BEACH
(c) HUMAN FACTORS			Water damage to private residences from Suva Point to Nasinu River	

TABLE 2 (Continued)

(B) MARINE ENVIRONMENT

TSUNAMI EFFECT		VULNERABLE ELEMENTS	
		SUVA HARBOUR	LAUCALA BAY
WAVE ACTION			
WAVE HEIGHTS	- OPEN WATER	up to 3 m	up to 2 m
	- REEFS	up to 20 m - Sosoikula, Nawanada, Vunivau, Nawai Reefs	up to 20 m - Nukubuco Reef
	- ISLANDS		up to 15 m - Nukubuco Island
DAMAGE	- REEFS	• overtopping by waves • cracking • displacement of coral blocks • breaking off of coral and coral blocks • debris flowing in Harbour	
	- SEA BOTTOM	• scouring of sand and coral • debris deposition	
	- ISLANDS		• Nukubuco Is - overtopping, flooding, erosion, damage to facilities
	- PASSAGES	• Levu Passage - possible damage	• Nukubuco Passage - possible damage
SHIPPING	- TYPE	• International (cargo, trourist / Intra-island / Local (fishing, recreation) / Fiji Navy	• local (fishing, recreation)
	- EFFECT OPEN WATER	• larger swell conditions • local boats overturned, swamped	• possible slighter larger than normal swells
	- EFFECT AT BERTHS	• all ships - damage to both wharves / jetties and ships by hitting adjacent wharves • local boats overturned, swamped • Navy - probable damage to ships and dock facilities	• if any, very minor
INFRASTRUCUTRE	- NAVIGATIONAL AIDS	• probability of serious damage making them inoperative • serious effects of safety of shipping and personnel	• possibility of minor damage
	- WHARF FACILITIES	• probability of serious effects to wharves, facilities, wharfs infrastructure, shipways, jetties, marinas,personnel	• possible damage to Breakwater
	- ROCKIBILI	• probability of wave action causing flooding and hence damage to Rockibili Container Terminal	
	- USP RESEARCH PLATFORM		• overtopping, flooding, probable severe damage
SEICHING	- SHIPPING	• fishing and recreation • drowning • personal injuries due to damage to shipping	• fishing and recreation • possible drowning
	- SEICHE	• drowning • people trying to collect fish from sea bottom	

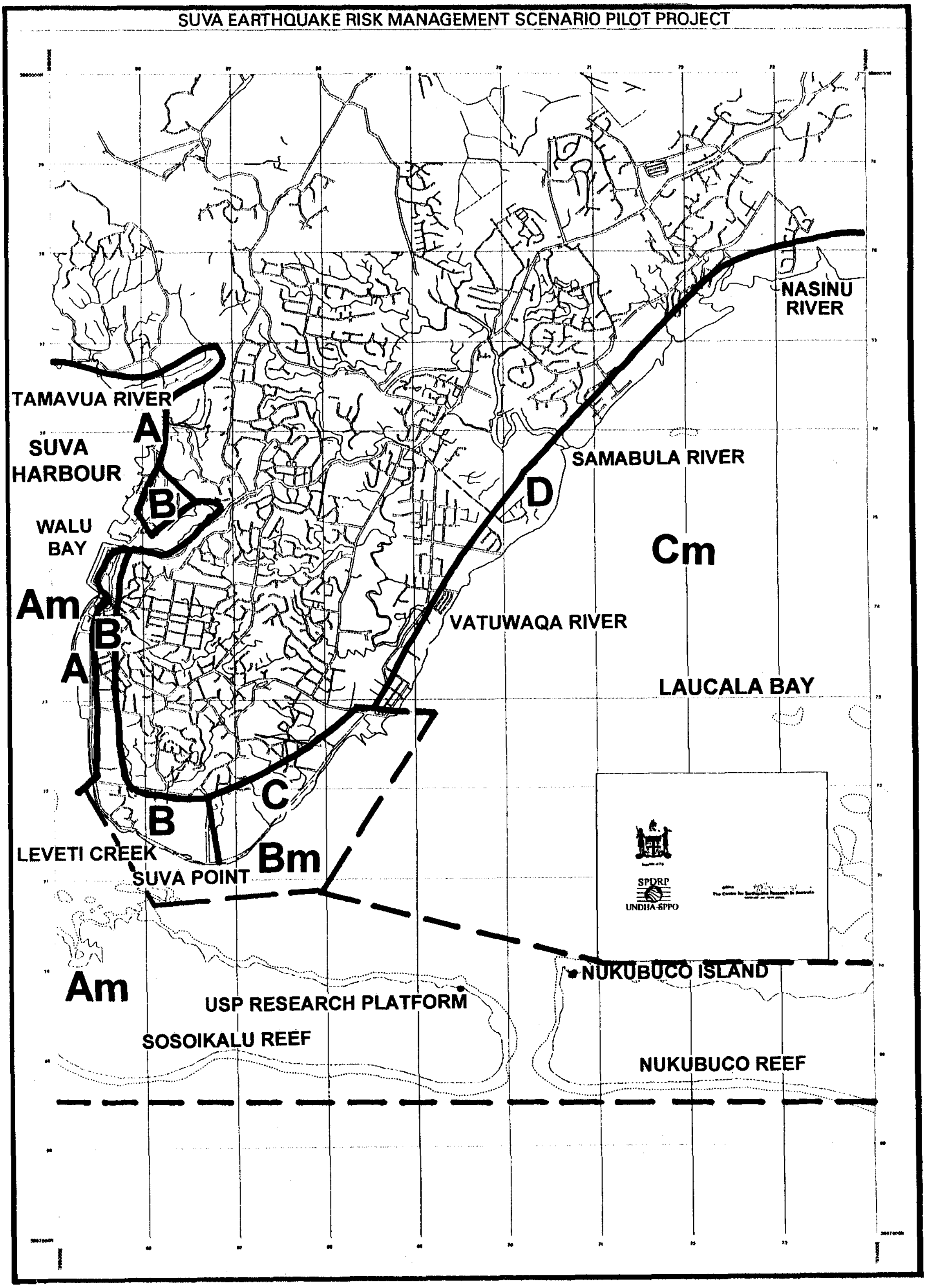

Figure 7: Tsunami Risk Map for the City of Suva (Per SERMP; CERA, 1997a)

TABLE 3 : TSUNAMI RISK ZONATION FOR SERMP SCENARIO TSUNAMI IN TERMS OF VULNERABILITY LEVELS (COMMENTARY FOR FIGURE 7)

TSUNAMI RISK ZONATION ELEMENT	SERMP TSUNAMI RISK ZONE			
	A	B	C	D
ON LAND				
HAZARD (Figure 61)				
ZONE	HI	MED	MED	LO
RUN-UP HEIGHT - AVERAGE	>3m	1-3m	1-3m	0-1m
VULNERABILITY LEVEL (Based on Table 30)	VERY HIGH	HIGH	MEDIUM	LOW
CONTROLS TO DAMAGE				
HYDROLOGICAL - WAVE ACTION	YES	YES	POSSIBLE	NO
- FLOODING	YES	YES	MINOR	MINOR
GEOLOGICAL - CONSEQUENCES	YES	YES	NO	NO
BUILT ENVIRONMENT - POTENTIAL DAMAGE				
CRITICAL FACILITIES	YES	YES	YES	YES
PORT FACILITIES	SEVERE	NO	MINOR	NO
INDUSTRIAL	SEVERE	NO	NO	NO
COMMERCIAL	SEVERE	YES	SMALL	NO
RESIDENTIAL	YES	YES	YES	YES
INFRASTRUCTURE	SEVERE	SMALL	SMALL	SMALL
FISHERIES	YES	NO	NO	NO
POLLUTION	YES	NO	NO	NO
SHIPPING	YES	NO	NO	NO
NATURAL ENVIRONMENT - POTENTIAL DAMAGE				
COASTLINE	YES	YES	SMALL	MINOR
WATERWAYS	YES	YES	NO	MINOR
SWAMPS	YES	YES	NO	YES
DEBRIS DEPOSITION	YES	YES	NO	NO
HUMAN ENVIRONMENT				
POPULATION DENSITY	HIGH	HIGH	MEDIUM	LOW
SCHOOLS	YES	YES	YES	YES
VILLAGES, SETTLEMENTS	YES	NO	YES	YES
SOCIO-ECONOMIC - BUSINESS	YES	YES	SMALL	NO
- RESIDENTIAL	YES	YES	YES	SMALL
- RECREATIONAL	YES	YES	YES	SMALL
SUBURBS OF THE CITY OF SUVA	KOROVOU WALU BAY SUVA CENTRAL THE DOMAIN	WALU BAY SUVA CENTRAL THE DOMAIN NASESE VEIUTO	MUANIKAU LAUCALA BAY MUANIVATU	VATUWAQA LAUCALA BAY KINOYA

TSUNAMI RISK ZONATION ELEMENT	SERMP TSUNAMI RISK ZONE		
	Am	*Bm*	*Cm*
ON WATER			
HAZARD (Figure 61)			
ZONE	HI	MED	LO
WAVE HEIGHTS	>2m	1-2m	<1m
VULNERABILITY LEVEL (Based on Table 30)	VERY HIGH	LOW	LOW
NATURAL ENVIRONMENT - POTENTIAL DAMAGE			
REEFS - WAVE OVERTOPPING	YES	NO	-
- CRACKING	YES	NO	-
- CORAL DAMAGE	YES	NO	-
SEA BOTTOM	YES	NO	NO
ISLANDS	YES	-	-
SEICHE - EXPOSED SEA BOTTOM THEN WATER INRUSH	YES	POSSIBLE	NO
SHIPPING			
CARGO	YES	NO	NO
TOURIST	YES	NO	NO
INTER-ISLAND	YES	NO	NO
NAVY	YES	NO	YES
MARINAS	YES	NO	NO
FISHING	YES	YES	YES
RECREATIONAL	YES	YES	YES
BUILT ENVIRONMENT - POTENTIAL DAMAGE			
SHIPPING CHANNELS	YES	POSSIBLE	NO
NAVIGATIONAL AIDS	SEVERE	POSSIBLE	MINOR
WHARF FACILITIES	SEVERE	POSSIBLE	NO
HUMAN FACTORS			
DROWINGS	YES	POSSIBLE	POSSIBLE
INJURIES - ON SHIPS	YES	POSSIBLE	NO
COLLECTING FISH OFF SEA BOTTOM	YES	NO	NO
SIGHTSEEING	YES	POSSIBLE	NO
GEOGRAPHICAL LOCATIONS	SUVA HARBOUR REEFS ISLANDS	OFF SUVA POINT NORTH TO VATUWAQA RIVER	LAUCALA BAY

Note is made of the following, with specific reference to a potential tsunami disaster :

1. BUILDING CODE - potential damage due to wave action and flooding
2. LAND-USE PLANNING - consider areas prone to wave action (shore facilities) and flooding
4. DISASTER PLANNING - specific land areas along foreshores and the marine environment
6. TRAINING - necessary aspects relevant to marine situations
7. RESCUE AND RESPONSE - marine situations related to shipping (cargo, tourist, inter-island), fishing community, recreational boating, and the local population attempting to collect fish from the exposed seabed of Suva Harbour
10. EXERCISES - as detailed in "SUVEQ 97", effects of a tsunami are intimately related to the causal earthquake.

TSUNAMI WARNINGS

The concept of tsunami warnings for Fiji has been discussed for more than 40 years, primarily as a result of the disastrous 1953 Suva earthquake and associated tsunami. For earthquake generated tsunamis from around the Pacific Basin – that is for "distant" tsunamis – a warning system is in place through the Pacific Tsunami Warning Center (PTWC) in Hawaii. During this Decade, more emphasis has been placed on the nature of such warnings (Prasad, 1992) and dissemination of awareness and preparedness information to the community, through pamphlets (MRD, 1991), fliers and posters. Most written information has been published in the three languages of English, Fijian and Hindi.

SERMP reviewed this available information and considered the "local" tsunamis relative to the City of Suva. A provisional tsunami warning approach, in terms of tsunami travel times for both the far-field (per PTWC Hawaii) and near-field (Everingham, 1987; Prasad, 1992; CERA, 1997a) is given in Table 4.

TABLE 4 TSUNAMI WARNINGS FOR THE CITY OF SUVA (PROVISIONAL)

TSUNAMI CATEGORY	TSUNAMI GENERATION			TSUNAMI WARNING (Prasad, 1992)
	TSUNAMIGENIC EARTHQUAKE EPICENTRE DISTANCE (km)	LOCATION	TSUNAMI TRAVEL TIME	
LOCAL	5 – 25	SUVA (1) NAVUA	FEW MINUTES	**NONE**
	50 – 300	KADAVU TAVEUNI	10-30 MIN	
REGIONAL	UP TO 1500	VANUATU TONGA SAMOA	UP TO 3 HOURS	**LIMITED**
DISTANT	>1500	PACIFIC BASIN (2)	> 3 HOURS	**AMPLE**

(1) 1953 SEP 14 Suva : tsunami travel-time to Suva about 5 minutes
(2) 1960 MAY 22 Chile : tsunami travel-time to Suva about 13 hours

"SUVEQ 97" – SIMULATED EARTHQUAKE AND TSUNAMI EXERCISE

One of the significant objectives within SERMP was to demonstrate, in a most practical manner, the results of this PILOT PROJECT as they apply to emergency management strategies and procedures. This was achieved through the conducting of a simulated earthquake / tsunami exercise called **"SUVEQ 97"** (CERA, 1997b.). The aim was to exercise operational arrangements within NDMO for earthquake and associated tsunami in the Suva area. Its objectives were to test overall emergency management of the national disaster operations room personnel, including multi-agency coordination and liaison and organisational communications, to educate and raise the level of awareness of response agencies and to increase their preparedness. **"SUVEQ 97"** was conducted as a practically based, multi-agency, decision-making exercise and consisted of three parts :

1. WALKTHROUGH SESSION - an information planning and training session for all participants, conducted on Tuesday afternoon, 5 August 1997
2. TABLETOP EXERCISE - a real-time hypothetical earthquake and tsunami scenario for Day One of such a potential disaster, conducted on Wednesday, 27 August 1997
3. WALU BAY FIELD EXERCISE - a real-time detailed simulation for such a potential disaster impacting on the major industrial suburbs of Walu Bay and Korovou, which included several actual simulated incidents, conducted on Thursday morning, 28 August 1997.

The exercise was conducted in terms of the requirements of the Fijian authorities with the "serials" based on the real experiences of the 1953 tsunami and other damaging incidents taken from recent overseas occurrences. Many lessons were learnt, including the practical response to a devastating tsunami, and much information was gained to improve emergency management strategies and capabilities of the responsible Fijian agencies towards tsunami mitigation measures.

RECOMMENDATIONS FROM SERMP – "THE WAY FORWARD"

For a developing island nation such as Fiji, the implementation of mitigation measures for possible future earthquake and tsunami disasters is paramount in ensuring sustainable development. This is no more apparent when considering the City of Suva - the national capital, hub of commerce and economics and location of foreign diplomatic missions, both for Fiji and the neighbouring Pacific Island Countries.

To this end, it was mandatory that SERMP should provide some basis for continuing mitigation strategies by Fiji. A series of 90 Recommendations were prepared, with those specifically relating to tsunami mitigation including :

Scientific endeavours – extend tsunami research in modelling studies for innundation levels, wave heights and travel-time charts, hydrographic studies for harbours and near-shore waters, and seismological studies in potential tsunamigenic sources and source mechanisms

Vulnerability inventories – underetake more detailed inventories of the built environment of coastal regions, with some emphasis on native villages; special emphasis to be placed on potential damage due to flooding, water damage, water-borne debris, pollution, public health hazards, pollution

Continue upgrading of tsunami risk assessments

Training of emergency services personnel – conduct targeted training programs (theory and practice) to improve management and response

Community education programs – a vital element in preparing the public for an impending disaster and thereby be able to reduce potential losses and implement Government policy

Continue to upgrade the tsunami warning system for Fiji

Extend the SERMP-type project to other cities and coastal communities (particularly rural and remote villages) which are considered to have a potential tsunami threat.

FIJI TSUNAMI WARNING SYSTEM

A Government Working Committee has recently been considering tsunami warnings for the Republic of Fiji. A Draft Document "THE FIJI TSUNAMI WARNING SYSTEM AND RESPONSE ARRANGEMENTS" has been prepared. The premise of this regional activity is given in the Preface of this Document :

> "The Fiji Tsunami Warning System and Response Arrangements lists an arrangement of how the tsunami warning will be disseminated to people of Fiji for the primary purpose of saving the lives in an event of tsunami "attack". It also describes how the response agencies will operate at a time of tsunami disaster. Until this arrangement Fiji did not have a structured tsunami warning system and any warnings given out would have not been effective. It was given urgency after a tsunami killed more than 2000 people in Papua New Guinea. Some of the major tsunamis have caused wide spread damage throughout the Pacific. One such occasion was after the 1916 Chilean earthquake, which left memories of disaster in the minds of people from most of the Pacific Rim Nations, especially Hawaii, Japan and Philippines."

A comprehensive set of issues have been considered, which include : scientific information on tsunamis, tsunami watch and warning elements, relationship with other disaster plans, declaration of tsunami disaster, government policy, community response, roles of key agencies, emergency procedures, roles of NGO's, mitigation measures (awareness and preparedness), damage assessments. A close operational association is maintained with the PTWC in Hawaii.

It has been specifically noted that **EXTREME CAUTION** must be exercised in planning purposes, community education and in implementing tsunami warnings.

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See 2000 Journal Issue for Desired Style (page 3-14 for example)

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The International Tsunami Information Center maintains a web site with current information of interest to the Tsunami community. The web site has the following URL:

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The West Coast and Alaska Tsunami Warning Center maintains a web site with tsunami information. The web site has the following URL:

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A beautiful web site about Tsunamis is being published by **Tsunami Society** member, Dr. George Pararas-Carayannis. His tsunami web site has the following URL:

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A web site about The National Tsunami Hazard Mitigation Program is maintained by **PMEL**. The web site has the following URL:

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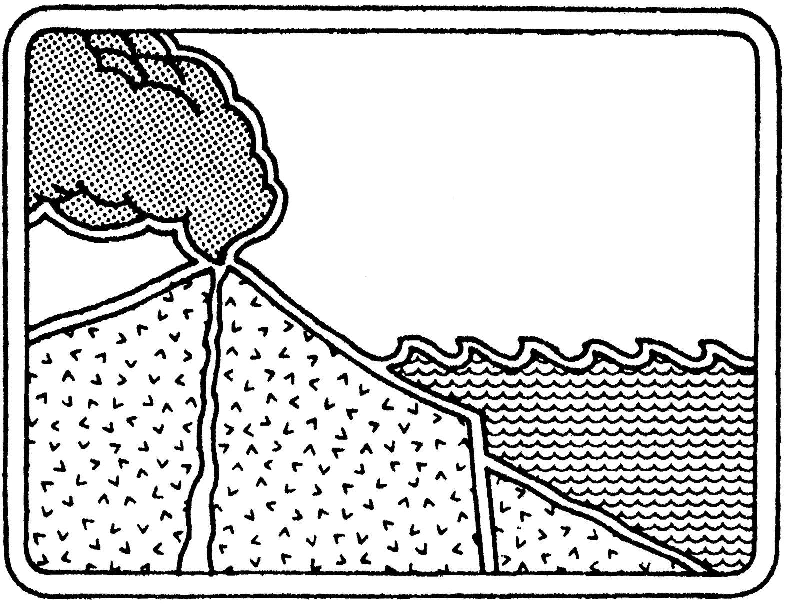

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