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SPECTRAL CHARACTERISTICS OF THE 1960 TSUNAMI AT CRESCENT CITY, CA

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ABSTRACT

Spectral characteristics of sea level fluctuations during the May 1960 Chilean Earthquake tsunami are investigated using digitized strip chart recordings from two docks within Crescent City Harbor. Peaks in sea level spectra at the two docks near 10^{-3} Hz and near 2.1 $x10^{-3}$ Hz correspond to the two lowest frequency harbor modes, occurring above the frequency band most strongly excited by the tsunami. Tidal modulation of harbor spectral structure at very short periods is observed. Theoretical estimates of shelf edge wave resonant modes fall within the frequency band strongly excited by the tsunami, in contrast to modeled edge waves from a seismic event near Cape Mendocino that show no evidence of the reflection necessary for a strong shelf resonance. This suggests that heightened susceptibility of sea level (but not necessarily currents) at Crescent City to tsunami is not due primarily to either harbor or shelf resonances.

Keywords: *Crescent City Harbor, tsunami tidal modulation, marigram digitization, harbor modes*

1. INTRODUCTION

Crescent City, located on the California coast about 460 km north of San Francisco, has suffered greater damage from tsunamis in historic times than any other community on the West Coast of the North America [*Dengler and Magoon* 2006]. Previous studies of individual tsunami events at Crescent City have invoked the importance of source directionality [*Wiegel* 1976; *Hatori* 1993], focusing of wave energy by offshore bathymetry [*Roberts and Chien* 1964], and resonant shelf oscillations [*Wilson and Torum* 1968; *Gonzalez et al.* 1995] to explain high tsunami amplitudes at Crescent City.

The two possible explanations for local amplification considered in this paper are (1) near-resonant oscillations in the Crescent City harbor, and (2) near-resonant oscillations on the shelf adjacent to Crescent City [*Horillo et al.* 2008].

A record of the observations of the 1960 Chilean tsunami at Crescent City was provided by virtually continuous strip chart recordings over 11 May 1960 to 16 June 1960 from pressure gauges in stilling wells at two locations in the harbor [*Kendall et al.* 2008]. *Magoon* [1962] digitized and analyzed a small portion of this record. *Holmes-Dean et al.* [2009] digitized an eleven-day interval 20 May 1960 to 31 May 1960 that captures both the onset and decay at a sampling frequency of one Hz. The data and digitization procedures are documented in *Holmes-Dean et al.* [2009].

The present day harbor configuration and the 1960 locations of the two pressure gauges, at Dutton's Dock and at Citizen's Dock (the present day NOAA tide gauge is very near Citizen's dock), are shown in Figure 1a. The geometry of the harbor was modified in 1972 by carving the 200 x 300 m Small Boat Basin into the northeastern shore of the harbor, northward of Citizen's dock [*Dengler and Uslu* 2011]

2. THE TSUNAMI IN THE TIME DOMAIN

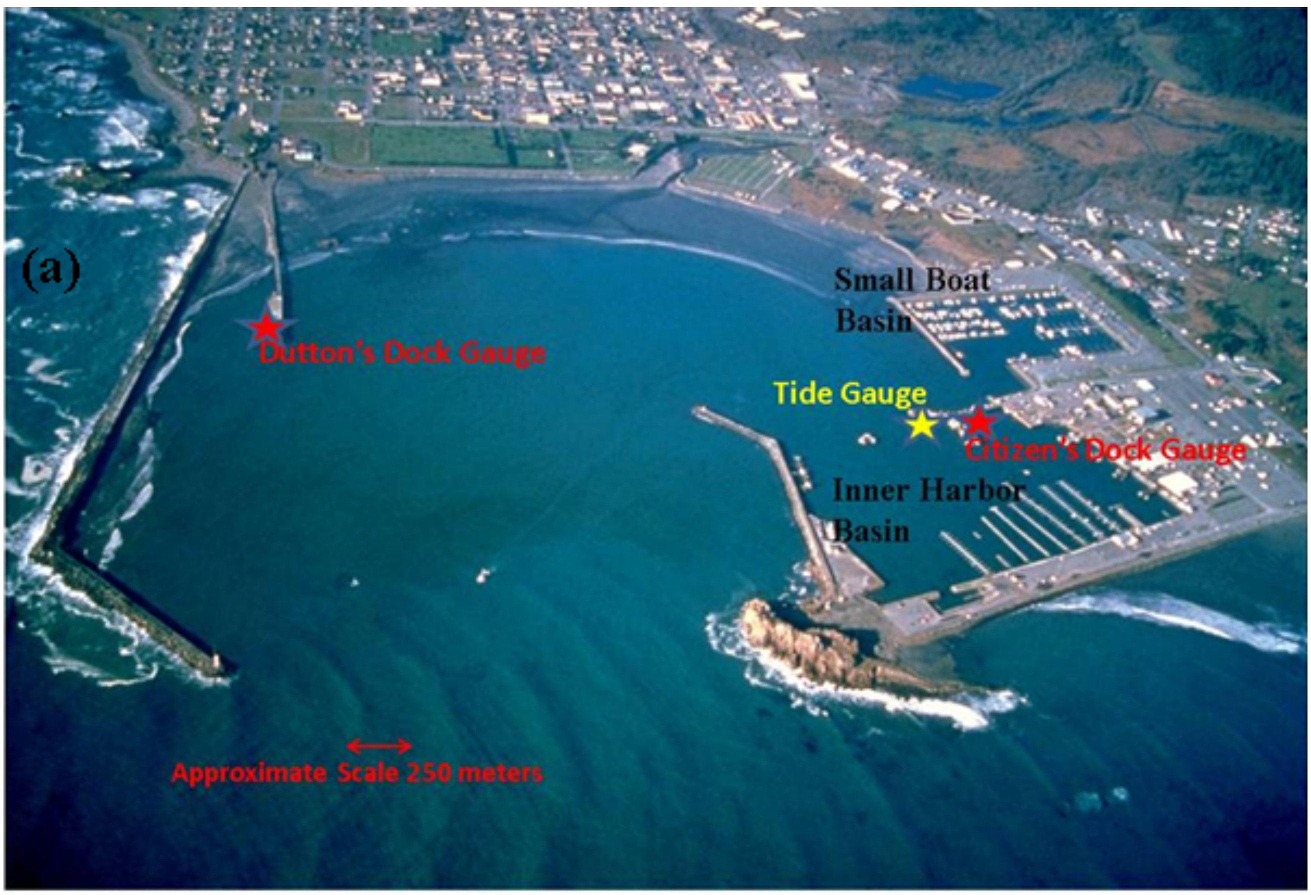
The digitized records of sea level at the two pressure gauges as well as the NOAA predicted tide for Crescent City are displayed in Figure 1b. The records span from two days after the beginning of digitization, encompassing several hours after the onset of the tsunami arrivals at about 0220 PST, 23 May 1960 [*Magoon* 1962].

The two records are not identical. They differ not only at short time scales, but also because of apparent timing errors in either or both of the two records. In some instances, timing error is clearly associated with a shift from one strip chart record to the next (each strip chart record spans about 24 hours). In other instances, the error appears to vary slowly over many hours. The origins of these errors are fully discussed in *Holmes-Dean et al.* [2009]. An attempt to further reduce this error is discussed below.

3. SEA LEVEL SPECTRA

All spectra, S(f), discussed below are estimates of one-sided power spectra with signal variance given by $\int_o^{\infty} S(f)\,df$.

Individual spectra for each of the seven days following the onset of the tsunami are shown at Citizen's dock in Figure 2a and at Dutton's dock in Figure 2b. Also shown are pre-tsunami and post-tsunami spectra (plotted two decades lower than the seven day spectra for easy distinction). Estimates of the frequency and period corresponding to each of the features labeled in Figure 2 are given in Table 1. In subsequent discussion, these features are referenced using the identifying labels given in Table 1.



(Robert Campbell photograph)

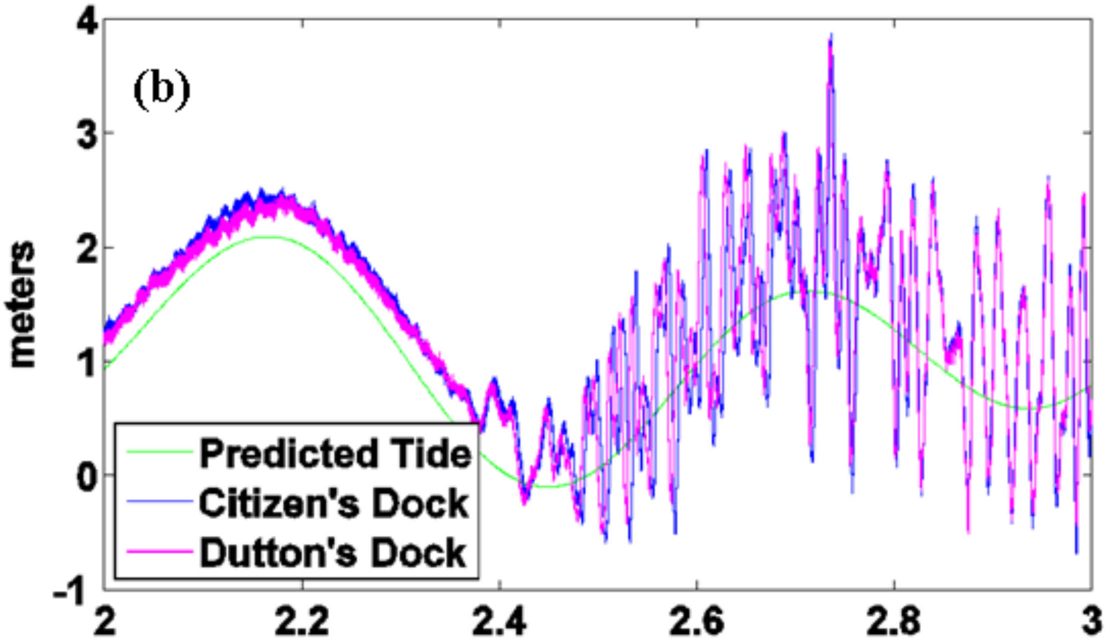


Figure 1. (a) Crescent City Harbor with locations of pressure gauges at Dutton's dock (northwestern corner of the harbor) and at Citizen's dock to the east behind the eastern inner harbor jetty, with the current NOAA Crescent City tsunami tide gauge location (yellow star). Note that the Small Boat Basin in the northeastern corner of the harbor was built in 1972 (*Dengler et al*., 2011). Dutton's Dock has been replaced and realigned since the 1960 Chilean tsunami sea level data were recorded. (b) Predicted tide (green line) and sea level at Dutton's dock and at Citizen's dock as determined hydrostatically from pressure gauge records over a one-day interval spanning the onset of the tsunami arrivals from the Chilean earthquake of May 1960.

The spectra at the two gauges are nearly equal to one another day by day at frequencies below the break frequency, $f_{br} \sim 10^{-3}$ Hz, at which they clearly diverge. At frequencies lower than the break frequency, the pre-tsunami and post-tsunami spectra fall off less steeply than the f^{-2} falloff for open ocean background spectra found by *Filloux et al.* [1991] and *Rabinovich et al.* [2011]. At frequencies immediately above f_{br}, all the spectra begin to decrease significantly more rapidly than the f^{-2} background falloff.

At both docks the spectra become indistinguishable from the pre-tsunami and post-tsunami background at and above a high frequency, f_{hi}, at about 7 $x10^{-3}$ Hz. At Citizen's dock (in the eastern part of the harbor), the fall off from f_{br} is interrupted by sharp spectral peaks (identifiable in each daily spectrum) at $f_{cd1} \sim 2.1$ $x10^{-3}$ Hz, $f_{ci2} \sim 8$ $x10^{-3}$ Hz, and $f_{ci3} \sim 1.8$ $x10^{-2}$ Hz. At Dutton's dock (in the western harbor, directly exposed to the harbor mouth), the fall off from f_{br} is interrupted by the sharp peak at $f_{cd1} \sim 2.1$ $x10^{-3}$ Hz, also visible at Citizen's dock, and by very broad peaks that have no counterparts at Citizen's dock centered near $f_{du2} \sim 5$ $x10^{-3}$ Hz and $f_{du3} \sim 2$ $x10^{-2}$ Hz.

Table 1. Spectral features labeled in Figure 2

Frequency Label	Description	Frequency (Hz)	Period
f_{lo}	rough lower limit of the frequency range excited by the tsunami	$\sim 10^{-4}$	~ 2.8 hours
f_{hi}	rough upper limit of the frequency range excited by the tsunami; frequency at which the spectrum on the first day of the tsunami drops below spectra on subsequent days	$\sim 7 \times 10^{-3}$	~ 2.4 min
f_{br}	frequency at which spectra at both gauges suddenly break from being nearly flat to rapidly falling off	$\sim 10^{-3}$	~ 16.7 min
f_{cd1}	central frequency of lowest frequency sharp peak on all spectra at both gauges	$\sim 2.1 \times 10^{-3}$	~ 7.9 min
f_{ci2}	central frequency of second peak on all Citizen's dock spectra	$\sim 8 \times 10^{-3}$	~ 2.1 min
f_{ci3}	central frequency of third peak on all Citizen's dock spectra	$\sim 1.8 \times 10^{-2}$	~ 56 s
f_{du2}	central frequency of second (very broad) peak on all Dutton's dock spectra	$\sim 5 \times 10^{-3}$	~ 3.3 min
f_{du3}	central frequency of second (very broad) peak on all Dutton's dock spectra	$\sim 2 \times 10^{-2}$	~ 50 s

The range of frequencies clearly excited during the tsunami begins slightly below $f_{lo} \sim 10^{-4}$ Hz (Figure 2). The spectrum on the first day of the tsunami is indistinguishable from that of the next day for frequencies higher than roughly $f_{hi} \sim 7 \times 10^{-3}$ Hz. At first glance it appears that the spectral levels during the tsunami's final day (solid black line) lie below that of the previous days at frequencies as high as 6×10^{-2} Hz (~ 17 s), so that sea level variance up to this frequency might be thought to be associated with tsunami arrivals. But this at least in part reflects the fact that sea level variance at these frequencies is also associated with background processes not related to the tsunami whose intensity varies day by day. Thus, for example, the *least* energetic of all the spectra in Figures 2a and 2b is the spectrum for the seventh day of the tsunami and not, as might have been thought, the post-tsunami spectrum.

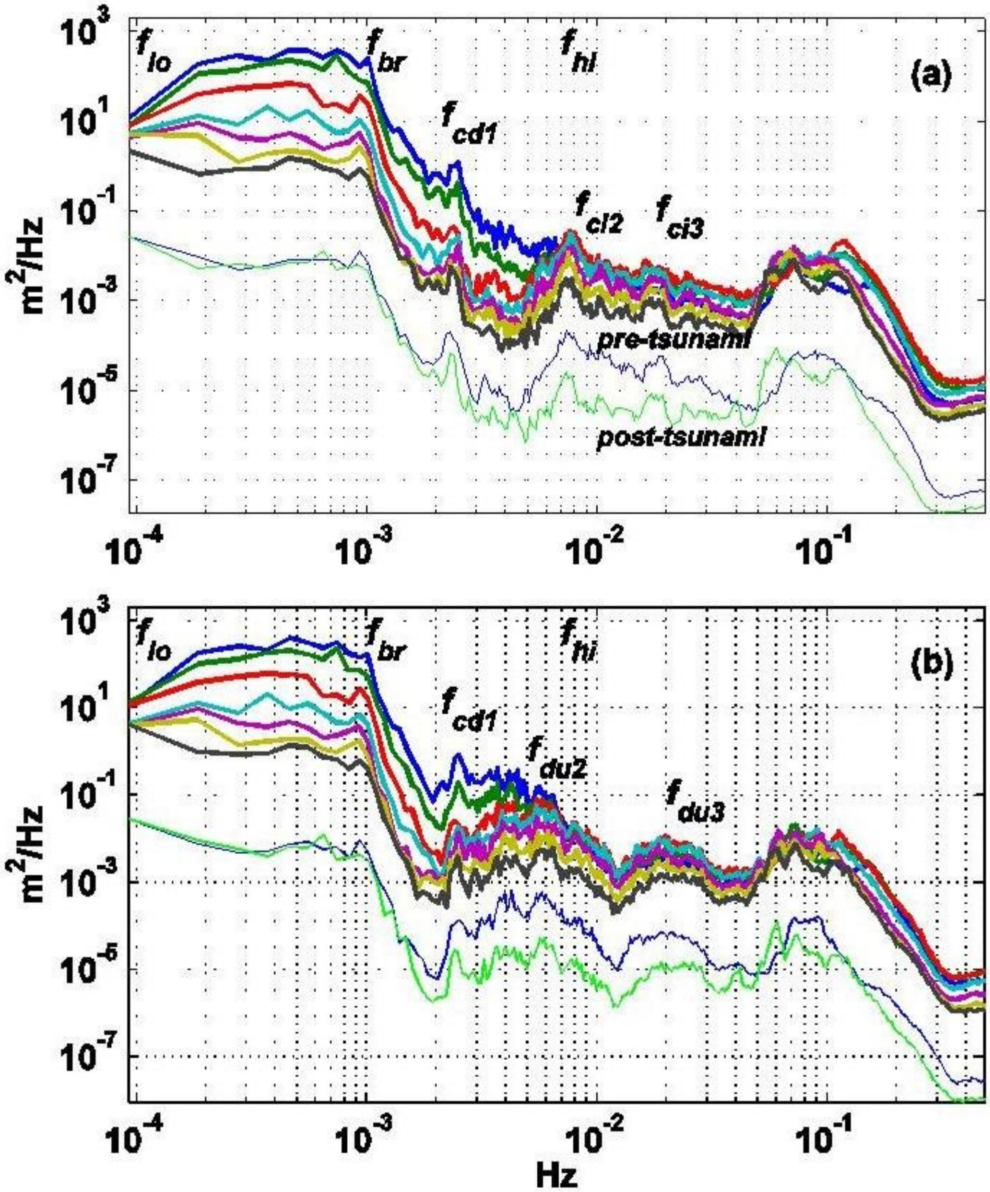


Figure 2. (a) At Citizen's dock: Upper seven curves are sea level spectra (m^2/Hz) for the first seven days of tsunami arrivals (over the lowest decade in frequency, the spectrum for each day is above that for all following days), pre- and post-tsunami spectra (thin blue and green lines, respectively) are displaced downward vertically by two decades for ready visualization. Each spectrum is calculated from two days of de-tided record broken into 50% overlapping Hamming-windowed six-hour segments. Note that (i) the post-tsunami spectrum (thin green line) has *lower* spectral levels than the pre-tsunami spectrum (thin blue line) for frequencies above 10^{-3} Hz, and (ii) the first day tsunami spectral levels (uppermost curve) drop below those for subsequent days at about 7 x10^{-3} Hz (f_{hi}). Labels $f_{lo,}$ f_{br}, apply to specific spectral peaks and characteristics discussed in the text. (b) Same as (a) but for Dutton's dock.

Within the frequency range clearly attributable directly to the tsunami between $f_{lo} \sim 10^{-4}$ Hz and about $f_{hi} \sim 7 \times 10^{-3}$ Hz (Figure 2), the spectra decay monotonically in time at each frequency. However, as shown in Figure 2, for frequencies above about 2×10^{-3} Hz, sea level variance associated with background processes unrelated to the tsunami (e.g. the pre- and post-tsunami spectra) is comparable to tsunami induced changes in spectral levels at the high end of the range of frequencies excited by the tsunami. Thus it is not possible to ascertain whether tsunami spectra at higher frequencies decay in time appreciably faster than tsunami spectra at lower frequencies.

4. HARBOR AND SHELF RESONANCES

Below we compare various of the observed spectral peaks noted above with numerical estimates of resonance frequencies within Crescent City harbor and over the continental shelf adjacent to Crescent City from previous studies.

4.1 Numerically estimated harbor resonances

Horillo et al. [2008] solve a shallow water model of Crescent City harbor sea level variation for the first four (longest period) harbor normal modes with mean depths differing by two meters, corresponding to high tide (MHHW) and low tide (MLLW), obtaining the periods and corresponding natural frequencies given in Table 2. Model sea level has a node at the open mouth of the harbor. From low tide to high tide, the first and second numerical mode frequencies shift towards higher frequencies, in qualitative agreement with what one expects for modes whose natural frequency depends on the shallow water wave speed. But remarkably the reverse occurs for the third and fourth numerical modes; from low tide to high tide their frequencies shift towards lower frequencies. Some evidence of the former behavior is described in the following analysis of the records, but not of the latter.

Table 2. Harbor Mode Numerical Model Results of *Horillo et al.* [2008]

Frequency Label	Description	Period	Frequency (Hz)
	Harbor normal modes at high tide		
$f^{MHHW}(1)$	Mode 1 High Tide	14.45 min	1.15×10^{-3}
$f^{MHHW}(2)$	Mode 2 High Tide	7.68 min	2.17×10^{-3}
$f^{MHHW}(3)$	Mode 3 High Tide	7.28 min	2.29×10^{-3}
$f^{MHHW}(4)$	Mode 4 High Tide	5.68 min	2.93×10^{-3}
	Harbor normal modes at low tide		
$f^{MLLW}(1)$	Mode 1 Low Tide	15.68 min	1.06×10^{-3}
$f^{MLLW}(2)$	Mode 2 Low Tide	9.01 min	1.85×10^{-3}
$f^{MLLW}(3)$	Mode 3 Low Tide	6.38 min	2.61×10^{-3}
$f^{MLLW}(4)$	Mode 4 Low Tide	4.71 min	3.54×10^{-3}

Agreement between these model normal mode frequencies and those of our spectral peaks has to be limited at least because (i) the open mouth condition imposed in the model is not exact, and (ii) the shape of the harbor modeled is different from the harbor shape during the 1960 tsunami. The tidal modulation of the spectra shown in Figure 2 is investigated below.

(i) In the shallow water model of *Horillo et al.* [2008], sea level is forced to have a node at the mouth of the harbor. If the true harbor modes are radiatively coupled to external shelf modes or to the open ocean, these estimates of harbor normal mode frequencies are, by analogy with Rayleigh's correction for an open-ended organ pipe [*Rayleigh* 1904], likely to be somewhat high. The general problem of coupling harbor oscillations to a larger exterior domain has been discussed by *Miles* [1974]. Simple application of his methods to the Crescent City region is beyond the scope of this paper because the exterior domain begins with offshore deepening continental-shelf bottom relief that can potentially support edge waves, well outside Crescent City Harbor.

(ii) The Small Boat Basin shown on Figure 1a was carved into the northeast shore of the harbor in 1972 [*Dengler and Uslu* 2011]. This harbor modification significantly affects any comparison of features of the 1960 spectra with the model results of *Horillo et al.* [2008] because the model sea level variance associated with the second and third modes of *Horillo et al.* [2008, their figure 4] is strongly concentrated in the Small Boat Basin just north of Citizen's dock (Figure 1a) at low tide, (although not at high tide). These model modes may thus not closely resemble the modes of the harbor at the time of the 1960 tsunami.

4.2 Evidence for tidal modulation

Tidal modulation of the period of a harbor seiche at Grindavik Harbor, Iceland, has been reported by *Donn and Wolf* [1972], and *Lee et al. [2012]* have emphasized the importance of allowing for tidal variation in interpreting spectra of sea level variance associated with tsunami. Accordingly, spectra of sea level at Citizen's dock and Dutton's dock were constructed as averages over three-hour intervals centered first at high tide and then at low tide (Figure 3). The spectral peaks at Citizen's dock (f_{cd1}, f_{ci2}, f_{ci3}) and at Dutton's dock (f_{cd1}, f_{du2}, f_{du3}) identified in Figure 2 can be identified in Figure 3, but are not as well resolved as in Figure 2 because of the shorter record length necessitated by analyzing high and low tide segments. The shifts of the first two model normal mode frequencies towards higher frequency from low to high tide is a consequence of increasing gravity wave phase speed with increased water depth, i.e. $f^{MLLW}(1) \sim 1.06 \times 10^{-3}$ Hz to $f^{MHHW}(1) \sim 1.15 \times 10^{-3}$ Hz and $f^{MLLW}(2) \sim 1.85 \times 10^{-3}$ Hz to $f^{MHHW}(2) \sim 2.17 \times 10^{-3}$ Hz, which can correspondingly not be resolved.

Yet the entire spectrum at Dutton's dock (Figure 3b), over the frequency band from roughly 6×10^{-3} Hz (~ 2.8 min) to about 3×10^{-2} Hz (~ 33 s), shifts towards higher frequencies from low tide to high tide with little change in shape. In particular, at Dutton's dock (but not Citizen's), the broad peak labeled f_{du2} shifts about 0.1×10^{-2} Hz towards higher frequency from low to high tide. The lower limit of this range over which the shift can be identified is not well defined, in part because of the shortness of the segments necessitated by stratification of observations between high and low tide. In contrast at Citizen's dock (Figure 3a), there is little if any systematic difference between the spectra at high and low tide.

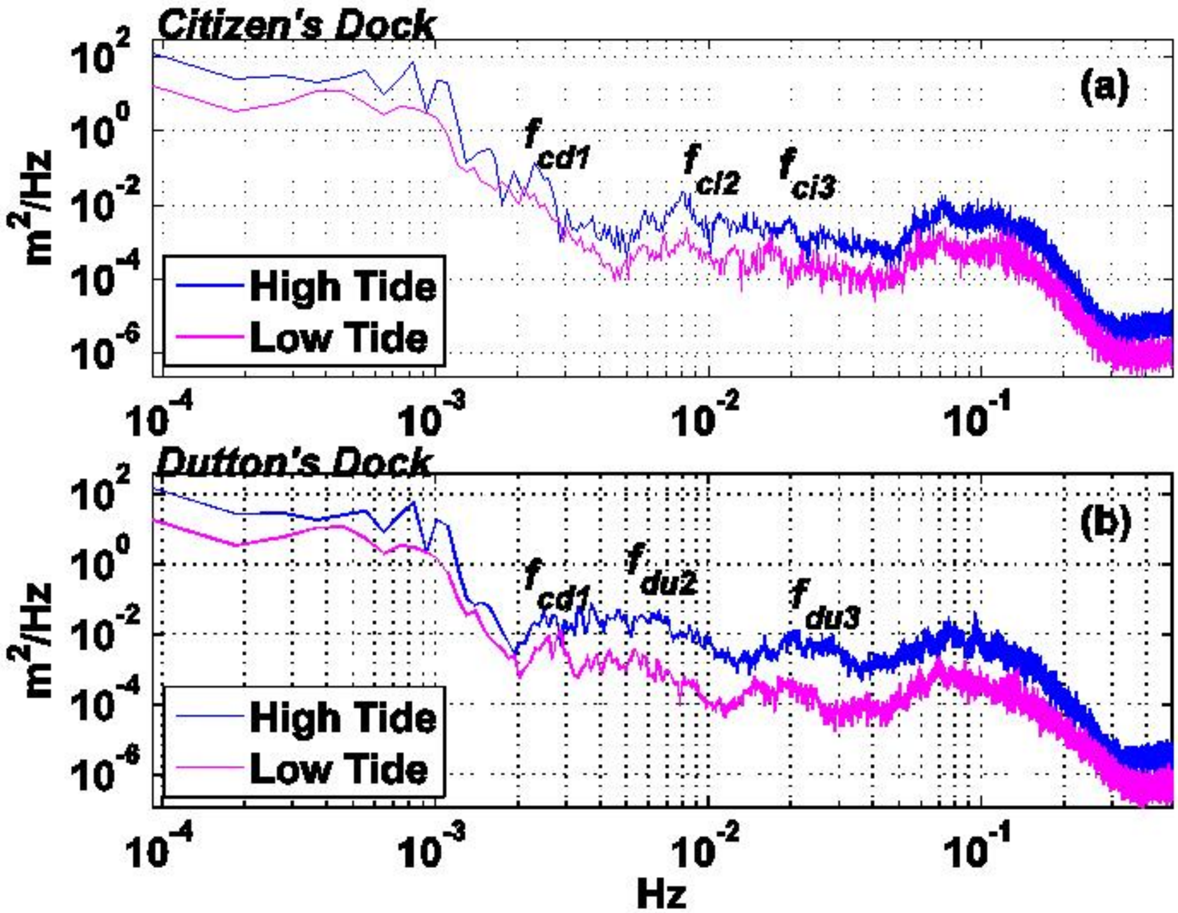


Figure 3. (a) Sea level spectra (m^2/Hz) at Citizen's dock estimated from three-hour segments of de-tided sea level fluctuations centered at high tide and low tide. (b) Sea level spectra (m^2/Hz) at Dutton's dock estimated from three-hour segments of de-tided sea level fluctuations centered at high tide and low tide.

The shift of spectral features towards higher frequencies at high tide (Figure 3b), is in accord with that of the first and second modes of *Horillo et al.* [2008; Table 2] at Dutton's dock (in the western part of the harbor, Figure 1). However, no such systematic spectral shift is seen at Citizen's dock (Figure 3a). We have no certain explanation for this observation. One explanation might be that higher frequency modes are trapped against the western wall of the harbor in a manner analogous to that in which one of the modes in Kahului Harbor, (Maui, Hawaii) found by *Okihiro et al.* [1994, their figures 7, 8, 9] is trapped against one wall of the harbor. This speculation is not in very good accord with the spatial structure of the higher modes displayed by *Horillo et al.* [2008], but, as noted above, they may not be representative of the harbor modes at the time of the 1960 tsunami on account of the subsequent construction of the small boat basin.

4.3 Comparison of sea level spectral features with numerically estimated harbor resonances

Prominent peaks are clearly visible in the spectra at both docks, with higher frequency peaks also showing some correspondence (Figure 2). These peaks are associated with harbor modes that characterize water level variability within Crescent City Harbor.

First Mode. The break in spectral levels (f_{br}, Figure 2) appears to correspond to the first (lowest frequency) of the numerically determined harbor modes of *Horillo et al.* [2008; our Table 2]: $f^{MLLW}(1) \sim 1.06 \times 10^{-3}$ Hz, $f^{MHHW}(1) \sim 1.15 \times 10^{-3}$ Hz, $f_{br} \sim 10^{-3}$ Hz.

Sea level fluctuations near f_{br} are expected to be well correlated between the two stations, with very similar amplitude and zero phase shift (Figure 4). This is in accord with the first mode in the model simulation of *Horillo et al.* [2008] extending across the entire harbor with little change in shape between high and low tide, and having no interior nodal line. The correlation estimation procedure is discussed below, in Section 4.4.

Second Mode. The next lowest frequency feature of the 1960 tsunami spectra (Figure 2, labeled f_{cd1}), appears to correspond to the second (next lowest frequency) of the numerically determined harbor modes of *Horillo et al.* [2008; our Table 2]: $f^{MLLW}(2) \sim 1.85 \times 10^{-3}$ Hz, $f^{MHHW}(2) \sim 2.17 \times 10^{-3}$ Hz, $f_{cd1} \sim 2.1 \times 10^{-3}$ Hz.

Sea level fluctuations near f_{cd1} are detectably correlated between the two stations (Figure 4), in qualitative accord with the fact that the second mode in the model simulation of *Horillo et al.* [2008] extends across the entire harbor. However, the phase lag is about two radians and not zero or π radians as would be expected for the position of the interior node in the second standing modes of *Horillo et al.* [2008] at low and high tide, respectively.

Higher modes. Sharp higher frequency peaks appear in the Citizen's spectra (at $f_{ci2} \sim 8 \times 10^{-3}$ Hz and $f_{ci3} \sim 1.8 \times 10^{-2}$) Hz, with broad higher frequency peaks also appearing in the Dutton's spectra (centered at $f_{du2} \sim 5 \times 10^{-3}$ Hz and $f_{du3} \sim 2 \times 10^{-2}$ Hz). Their frequencies are all somewhat higher than those of the third and fourth modes of *Horillo et al.* [2008; our Table 2]. The two records are not detectably correlated at these frequency peaks (Figure 4), indicating no correspondence with any harbor-wide mode. This lack of correlation may however result from timing errors not being fully removed by the timing-adjustment procedure given in Section 4.4.

The observational picture regarding higher modes is thus incomplete. Since the higher mode frequencies lie above the frequency range within which sea level variation within the harbor is excited by the tsunami, this may have little practical significance for the response of sea level within the harbor to tsunami. However, the same may not be true for the response of currents within the harbor to tsunami.

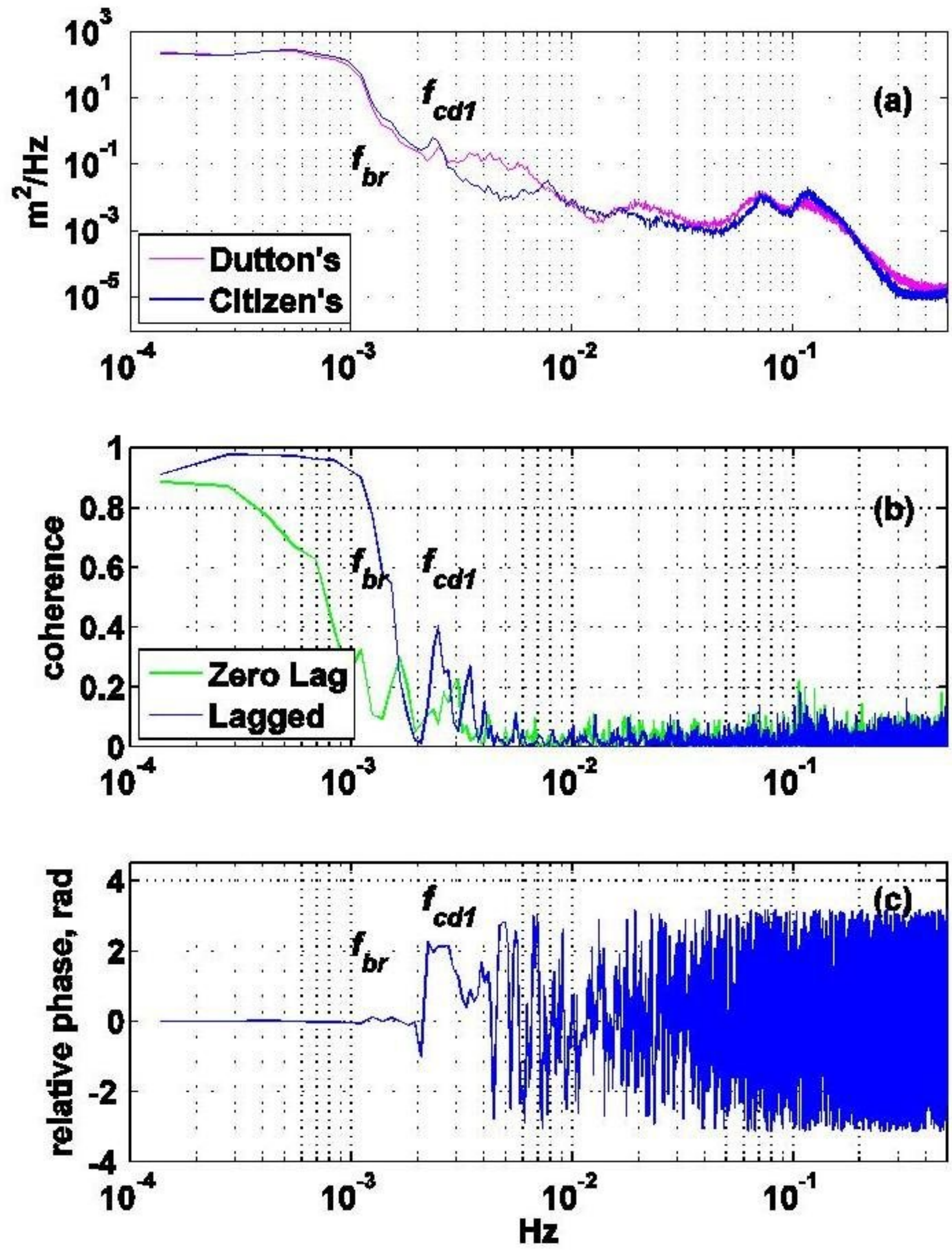


Figure 4. (a) Sea level spectra (m^2/Hz) at Dutton's and Citizen's docks for first three days of tsunami arrivals. Three days are divided into 36 two-hour 50% overlapping Hamming-windowed segments. (b) Coherence between records at Citizen's and Dutton's docks lagged as explained in Section 4.4 (blue line); coherence between the records at Citizen's and Dutton's docks without lag (green line). (c) Relative phase between records at Citizen's and Dutton's docks lagged as explained in Section 4.4.

4.4 Estimation of Correlation within Crescent City Harbor

In order to estimate frequency domain correlations between the two records, the first three days of each de-tided record after the onset of the tsunami (a time when modes are expected to be most strongly energized) were divided into two-hour segments. The frequency correlation (coherence) between Dutton's and Citizens' docks was computed for each segment and then averaged over all segments (Figure 4b). The coherence decreased from near unity to small values over the band spanning 1.4 x10^{-4} Hz (~ 2 hours) to about 10^{-3} Hz (~ 16.7 min), with low coherence at higher frequencies but with very small phase shifts over the entire band. If we assume that at least some of the loss of coherence at higher frequencies results from the timing errors noted above, then a possible remedy is to suppose, on physical grounds, that the lowest resolved frequencies are in fact in phase at the two gauges.

Accordingly, the Dutton's and Citizen's records were band passed so that only the variance at periods between 30 min and 90 min was retained. For each sampling instant, the immediately following two hour segment of the band-passed record at Dutton's dock was shifted relative to the corresponding segment of the band passed record at Citizen's dock by a lag chosen to maximize their time domain correlation. The correlations between corresponding segments of the records before band passing were then recomputed at that lag. The resulting correlation and relative phase are shown in Figure 4.

This procedure has forced nearly unit correlation with zero phase lag at frequencies spanning the band from the lowest resolved frequency 1.4 x10^{-4} Hz (~ 2 h) to f_{br} ~ 10^{-3} Hz (~ 16.7 min). It additionally allows resolution of a sharp peak in coherence (about 0.4) at about 2.1 x10^{-3} Hz, with a nearly constant phase lag. This is the frequency f_{cd1} at which background and tsunami spectra (Figure 2) consistently show a sharp peak. We have thus achieved a modestly enhanced coherence estimate at a frequency that may correspond to that of the second harbor mode of *Horillo et al*. [2008].

4.5 Shelf resonances and edge waves

The modeled harbor modes of *Horillo et al.* [2008] are the most complete in the literature. We have above identified the first two of these modes with features in the sea level spectra. But the spectral region most strongly energized by the tsunami lies at lower frequencies (Figure 2). The pre-tsunami and post-tsunami spectra in this region fall off less steeply than the f^{-2} falloff for open ocean background spectra found by *Filloux et al.* [1991] and *Rabinovich et al.* [2011]. What then determines the spectral shape in this region? Shelf modes (edge waves) standing or propagating along the coast are an obvious possibility.

Horillo et al. [2008] estimated the spatial patterns and periods of standing shallow water normal modes in a domain exterior to the harbor that spans the coast and the shelf between Pt. St. Georges (a few tens of km north of Crescent City along the coast) and Patrick's Point (some 80 km south of Crescent City along the coast). They imposed boundary conditions of no normal flow at the coast and of no sea level variation (a node) at the offshore 200 m isobath, with straight reflecting boundaries extending westward from the coast at Pt. St. Georges and Patrick's Point until the offshore 200 m isobath. These boundary conditions allow no flow of energy out of the domain, and thus make possible resonant modes. *Horillo et al.* [2008] find alongshore standing-wave periods within this domain spanning 67 min (2.5 x10^{-4} Hz) to 18 min (9.3 x10^{-4} Hz). (Higher frequency numerical modes no doubt exist but are not reported). Alongshore standing wave modes 1, 4, 6, 7, 8 and 14 are qualitatively similar to alongshore standing-edge waves having mode zero cross-shore structure (monotonic decay away from a maximum at the coast). Other modes displayed have one or two zero crossings offshore.

A number of these shelf modes have natural frequencies in the frequency range $f_{lo} \sim 10^{-4}$ Hz to about $f_{hi} \sim 7$ x10^{-3} Hz most strongly excited by the tsunami, if they were strongly resonant they could contribute appreciably to sea level response to tsunami within Crescent City Harbor.

For standing edge-mode shelf resonances corresponding to the shelf modes of *Horillo et al.* [2008] to occur, there should be strong reflection of coastally-trapped edge waves at coastal features such as Patrick's Point (about 80 km south of Crescent City) and Pt. St. Georges (about 10 km north of Crescent City). Somewhat surprisingly, such reflection does *not* occur in the shallow water model of *Gonzalez et al.* [1995], who modeled disturbances associated with the seismic event of April, 1992 centered near the coast close to Cape Mendocino (about 150 km south of Crescent City). Their model domain spanned the continental shelf, extending from south of Port San Luis (about 800 km south of Crescent City) to north of Point Orford (about 100 km north of Crescent City). The modeled seismogenic coastal edge waves propagated along the coast past Patrick's Point, Crescent City and Pt. St. Georges without any appreciable amplification or reflection. The modeled sea level fluctuations at North Spit (the tide gauge closest to, and north of the epicenter) were about the same amplitude as those observed at the North Spit tide gauge, but modeled sea level fluctuations at the alongshore location near Crescent City were not enhanced relative to those modeled at Crescent City Harbor, and were only about half those observed at the Crescent City Harbor tide gauge (*Gonzalez et al.* 1995, their figure 4).

The model results of *Gonzalez et al.* [1995] thus argue *against* the importance of resonant standing edge mode shelf contributions to the sea level fluctuations observed at Crescent City harbor during the 1960 tsunami. Yet *Horillo et al.* [2008] also find broad peaks corresponding to some (but not all) of these shelf modes in a nonlinear and highly dissipative shallow water model occupying a somewhat larger region, with harmonic forcing at the western boundary and energetics such that the energy influx through the western boundary is balanced by dissipation and energy outflow through the northern and southern boundaries. In particular (their figure 10), they identify a peak in their forced model response at 21 min period (7.9 x10^{-4} Hz), with a peak at the same period in their estimate of the spectrum of de-tided sea level variation at the Crescent City tide gauge associated with the Kuril Island tsunami of 2006. Our spectra are not directly comparable with their spectrum because we have averaged more heavily in order to increase statistical reliability, but the important point is that the *broad* peaks at 21 min (7.9 x10^{-4} Hz), 36 min (4.6 x10^{-4} Hz), 40 min (4.1 x10^{-4} Hz) and 52 min (3.2 x10^{-4} Hz) in their forced model response span much of the spectral region most strongly energized by the 1960 tsunami (Figure 2), an observation in support of harbor response due to adjacent shelf bathymetry for these frequencies.

Further elucidation of the role of shelf edge-wave resonances in the response of Crescent City harbor to tsunami would require either additional measurements on the shelf as well as within the harbor, and/or much more detailed numerical modeling, both beyond the scope of this paper. These results indicate that the simple resonance of either harbor or adjacent shelf modes will not entirely explain the enhanced response of sea level in Crescent City harbor to tsunami. We note however, with *Dengler and Uslu* [2011], that the higher modes may be much more important for the response of currents in the harbor to tsunami than they are for the response of sea level. Further modeling work is needed to resolve this and other questions.

5. SUMMARY

Analog sea level data recorded at two pressure gauges in the harbor at Crescent City in northern California during the tsunami generated by the May 1960 Chilean earthquake have been digitized at a sampling interval of 1 Hz. The records from 20 May 1960 to 31 May 1960 were analyzed to describe sea level variation associated with that tsunami in Crescent City harbor.

Evidence is found for the excitation of harbor modes resembling the two lowest frequency modeled shallow-water harbor modes of *Horillo et al.* [2008]: an abrupt downward trend in spectral slope at both gauges starting very near the frequency of the grave mode ($\sim 10^{-3}$ Hz), and a distinct peak at both gauges near the frequency of the second mode ($\sim 2.1 \times 10^{-3}$ Hz). Coherence between the two gauges at and below the frequency of the grave mode is high and, after removal of timing errors between the two gauges, is detectable at the frequency of the second mode. These harbor resonant frequencies do not however span the lower decade of the frequency band most strongly excited by the tsunami, $\sim 10^{-4}$ Hz to $\sim 7 \times 10^{-3}$ Hz. This suggests that heightened susceptibility of sea level (but not necessarily currents) at Crescent City Harbor to tsunami is not due primarily to harbor resonances.

Acknowledgements

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SEDIMENTARY EVIDENCE OF PALAEO-TSUNAMI DEPOSITS ALONG THE LOUKKOS ESTUARY (MOROCCAN ATLANTIC COAST)

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ABSTRACT

Analysis of the CARLA-11 core drilled along the lower Loukkos valley near Larache in northern Morocco shows a thin level of shelly sand at 465 to 482 cm depth, whose sedimentological features are those of a high-energy, certainly a tsunami deposit. The level can be subdivided into 3 subunits: Subunit 1 (6 cm) shows a sharp erosive base and comprises basal medium to coarse sands containing numerous marine shell fragments of bivalves, plant fragments and rip-up clasts of organic matter. Subunit 2 (7 cm) is a flame structure consisting of coarse sand containing a layer of organic matter and another one of greyish clay. Subunit 3 (4 cm) is similar to subunit 1 and consists of coarse sands containing numerous complete or broken shells of bivalves, plant fragments and dark organic matter. The deposit is mostly composed of subangular to subrounded quartz grains derived from nearby Miocene sandstones. Benthic and planctonic foraminifera are common within the samples. Magnetic susceptibility measurements show two major lows at ~350 cm, and especially at 477 cm within the high-energy deposit. Subunit 1 can be interpreted as the result of the first wave uprush of a tsunami,

the fine mud level of subunit 2 capping subunit 1 can be interpreted as emplaced during a decantation phase, and subunit 2 probably corresponds to a second wave uprush, Subunit 3 might be interpreted as the result of the backwash (outflow phase). The age of this event can be roughly dated between 5 and 3 ky BP according to recent dating of nearby levels.

Keywords: *Loukkos, Gulf of Cadiz, sedimentology, high-energy events, tsunami*

1 INTRODUCTION

The Gulf of Cadiz is a well-known seismogenic and tsunamigenic zone, to which are related catastrophic events such as the Lisbon earthquake and tsunami on 1st November 1755, one of the strongest earthquakes in human history. Several studies along the coastal areas of Portugal, Spain and Morocco, which are the regions that are most exposed to the tsunami threat, have shown that the 1755 and older events (listed in Baptista and Miranda 2009; Maramai et al. 2014) were recorded along the coasts by either the displacement of large boulders (Scheffers and Kelletat 2005; Whelan and Kelletat 2005; Mhammdi et al. 2008; Medina et al. 2011) or the deposition of generally thin shelly sand levels within the generally finer marsh or lagoonal sediments (Dawson et al. 1995, Luque et al. 2001; Scheffers and Kelletat 2005; Kortekaas and Dawson 2007; Morales et al. 2008, 2011; Font et al. 2010, 2013; Rodriguez-Vidal et al. 2011; Costa et al. 2012; Cuven et al. 2013).

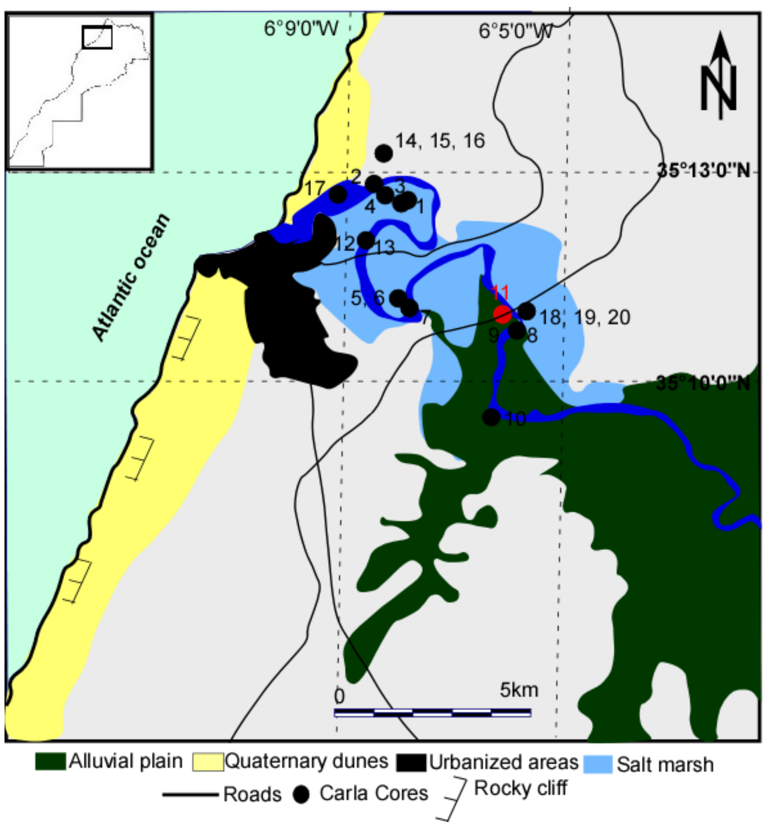


Figure 1. Simplified map of the Oued Loukkos lower valley and estuary, and location of the cores of the CARLA campaign.

As indicated in the previous paragraph, although large boulders related to high-energy events were observed in Morocco, thin sandy levels typical of tsunami deposits (washovers) were only recently described along the Moroccan coast at Oualidia (Mellas 2012). In 2004, a coring campaign (named CARLA) was carried out along the Loukkos estuary in Northwest Morocco (Fig. 1). One of the cores (CARLA-11) showed the presence of a level rich in coarse sands and shell fragments, similar to high-energy deposits (tsunamis, storms), intercalated within low to medium-energy fluvial and lacustrine strata (Fig. 2). This paper exposes the results of the sedimentological, grain size and magnetic susceptibility analyses of the high-energy levels of core CARLA-11 in order to discuss their eventual tsunamic origin.

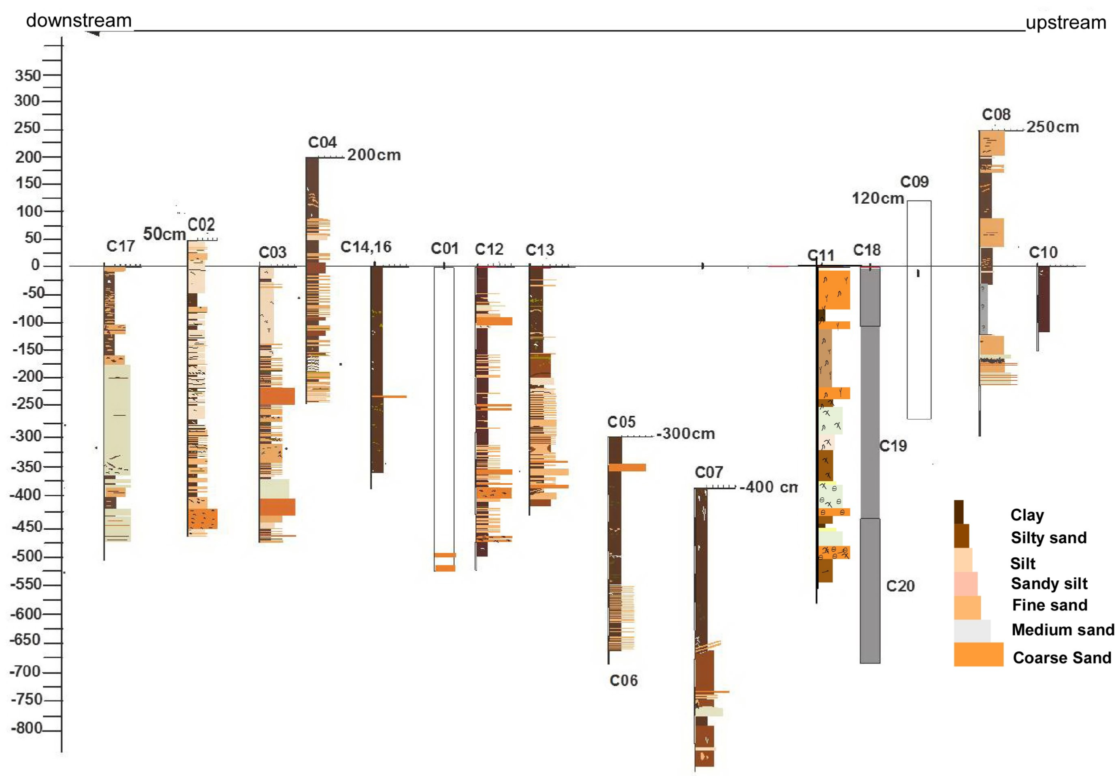


Figure 2. Compilation and correlation of the cores obtained during the CARLA campaign along the Loukkos lower valley. Location in Figure 1.

2 GENERAL SETTING

The CARLA-11 core is situated on the left bank of the lower valley of the Loukkos river (oued) in northwest Morocco (**Fig. 1**; x=35°10.933'N; y=6°07.245'W), the largest river of the region with a watershed of 3,740 km2. Topographically, the lower valley of Oued Loukkos is very flat (10–15 m.a.s.l) with a negligible slope. The valley is even below sea level at 44 km from the river mouth. The main channel depth varies from –2 to –4 m a.s.l. but may reach –15 m a.s.l. (Snoussi 1980).

The climate of the Loukkos basin is of Mediterranean type with an oceanic influence (El Gharbaoui 1981, 1987). The average annual rainfall is 700 mm. The hydrological network of the Loukkos watershed is formed by surface waters of the Loukkos river and its tributaries. The Loukkos drainage is characterized by an irregular inter-annual regime; the low flows are generally zero, except for streams that drain the water from the left bank with an average flow of 500 l/s (El Gharbaoui 1981, 1987).

The mesotidal Loukkos estuary is a tide-dominated system (tide of 3.5 m, semi diurnal with $T \sim 12$ h 20 min), according to the classification of Dalrymple (1992). For the Larache coast, Tejera de León and Duplantier (1981) indicate that the main wind direction is W-WNW with a mean velocity of 5-10 m.s-1, and that the main swell (amplitude >0.5 m) direction is N290° to N305° according to a quoted brief study by LHCF from October 1969 to January 1970. However, swell with maximum energy has a SW direction.

The history of the Loukkos valley started after the Villafranchian (Early Quaternary), represented by mostly continental red deposits overlying Pliocene sandstones and Miocene marine marls (Bouhmadi et al. 1994). Fluvial deposition characterizes the valley during the Quaternary except during the Flandrian (called Mellahian in Morocco) transgression and more recently by the progression of the sandy spit (Trentesaux et al. 2005; Aloussi 2008; Carmona and Ruiz 2009).

3 CORING AND ANALYTICAL METHODS

During the CARLA sampling campaign carried out in 2004, twenty cores were collected along the Loukkos estuary using a Vibrocoring apparatus of Lille University (Fig. 2). The cores were 7.6 cm in diameter and 2–5 m in length (depth). One half of each core was preserved and archived and the other was used for sedimentological analyses. For the present study, we describe one of the most distal cores with respect to the river mouth, which was chosen in order to avoid the interference with deposits related to proximal coastal dynamics. The other cores will be described later in a more detailed paper focused on sedimentology.

Sedimentary facies are described following the classification of Reineck and Wunderlich (1968) based on color, texture, structure, bedding and type and concentration of accessory materials such as plant fragments, organic matter content, mud and peat clasts. Carbonate content was measured using a Bernard calcimeter. Grain size analyses of the <2 mm sediment fraction were performed using a

Coulter Laser LS230 particle sizer at the University of Lille; the distinguished classes were clays (<4 µm), fine silt (4–15 µm), medium silt (15–30 µm), coarse silt (30–63 µm), very fine sand (63–125 µm), fine sand (125– 250 µm), medium sand (250–500 µm) and coarse sand (500–1000 µm) (Table 1). Magnetic susceptibility (MS) was measured each 2–10 cm by using a MFK1 kappabridge (AGICO ent.) at the Laboratory of Rock Magnetism of the Institute Dom Luís, University of Lisbon, Portugal. Before, hand samples were filled into 2•2•2 plastic cubic boxes and MSs were subsequently normalized by the mass of the sample (expressed in m3/kg).

4 STRATIGRAPHY, SEDIMENTARY FACIES AND COMPOSITION

Core CARLA-11 (Fig. 3) is 523 cm long and shows four coarsening-upward sequences, each starting with silts and sandy clays and topped by coarse sands. The three upper sequences are ~1 m thick whereas the lower one is more than 2 m thick. In this article, we only describe the results of the analysis of the upper part of the lowest sequence, which we consider as a probable palaeo-tsunami deposit because of its particular sedimentary characteristics.

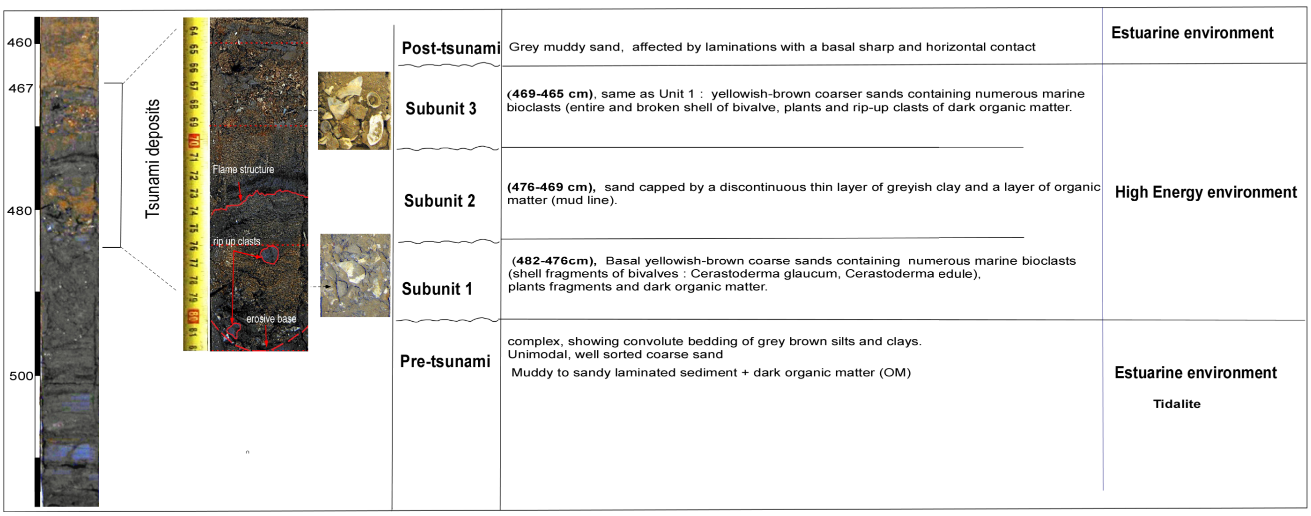


Figure 3. Photograph of the lower section of core CARLA-11 and description of the lithology of the observed subunits of the inferred tsunami deposit.

From the bottom of the core to 482 cm, the deposits correspond to a sandy mud with organic matter, which is sharply overlain by the lower contact of the high-energy marine deposit, which appears from 465 to 482 cm depth as a shelly coarse sand, that can be subvided into 3 subunits (Fig. 3):

1- The basal bed, subunit 1 (482-476 cm) shows an erosional base (Fig. 3) and comprises at its base yellowish-brown medium to coarse sands (median=536.7 µm; Fig. 4) with numerous marine shell fragments of bivalves *Cerastoderma glaucum* and *C. edule*, plant fragments and organic matter-rich rip-up clasts . The sediment is polymodal, poorly sorted (1.987 F) and very fine skewed (0.566 F).

2- Subunit 2 (476–469 cm) is a flame structure consisting of coarse sand (median=690 µm; Fig. 4) containing a layer of organic matter and another one of greyish clay. The deposit is polymodal, poorly sorted (1.496 F) and symmetrical (0.003 F).

3- Subunit 3 (469–465 cm) is similar to subunit 1 and consists of yellowish-brown coarse sands (median=618.7 µm; Fig. 4) containing numerous entire or broken shells of bivalves *Cerastoderma glaucum* and *C. edule*, plant fragments and dark organic matter. The sediment is bimodal, poorly sorted (1.866 F) and almost symmetrical (0.036 F).

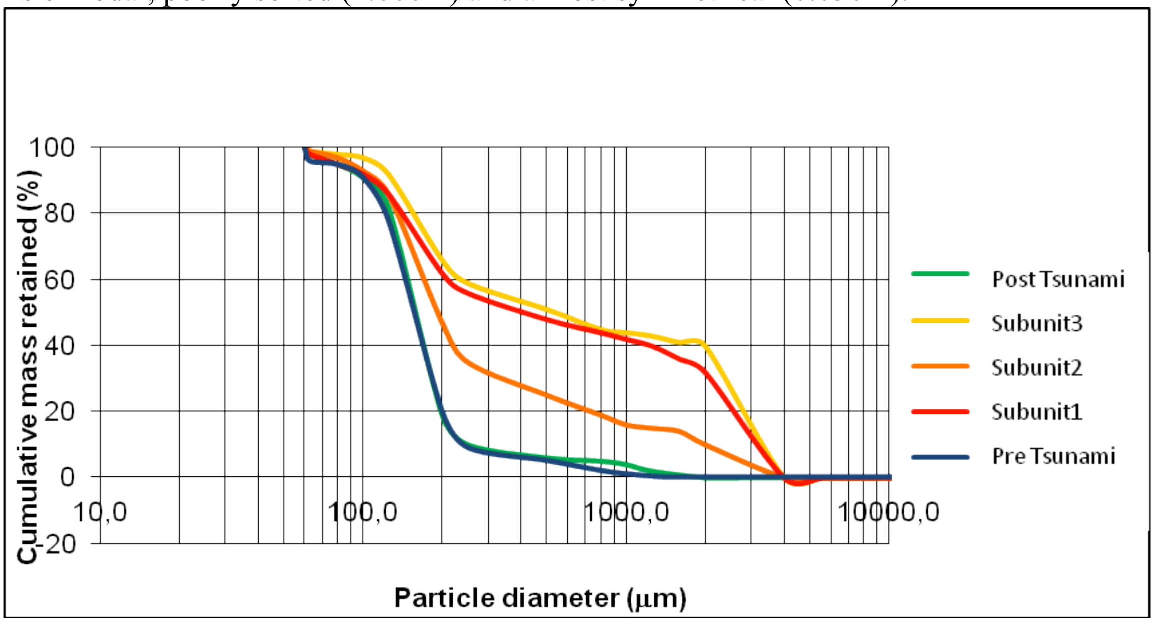
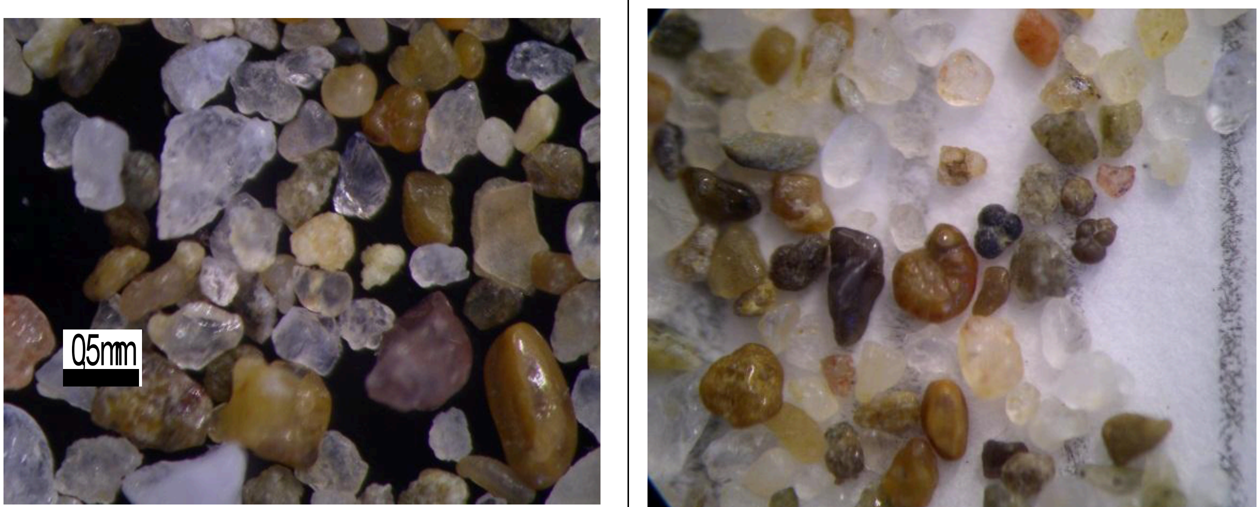


Figure 4. Cumulative frequency curves of the deposits of the subunits in core CARLA-11. Note that the pre- and post-tsunami samples have the same characteristics and that the two layers are "sandwiching" the tsunami sediments.

The upper boundary of the high-energy deposit contains coarse to fine sand to silt, and then forms a fining-upwards sequence which ends at 423 cm. The high-energy deposit is mostly (at 60–90%) composed of subangular to subrounded quartz grains (Fig. 5A) probably derived from beach sands supplied by the Loukkos river from nearby Cenozoic sandstones, together with sub-rounded orthopyroxenes (5–30%), other heavy minerals (10%), and minor amounts of goethite. In addition to the fragments of shells (mainly bivalves), numerous marine bioclasts were identified such as sponge spicules and calcareous rhodophyta (Fig. 5B), which are scattered throughout the bed, but can sometimes form shell levels. Under SEM, we observed fossil foraminifera (mainly planktonic) and more recent – mainly benthic – foraminifera. Observed smoothed and re-mineralized specimens are clearly reworked from the Tertiary strata of the Rif nappes, while those that are more fresh with angular breaks were living and have been transported by the waves from the sea (Fig. 6).



A B

Figure 5. Optical microscope photographs of the shelly deposits of core CARLA-11.
A, quartz grains; B, foraminifera.

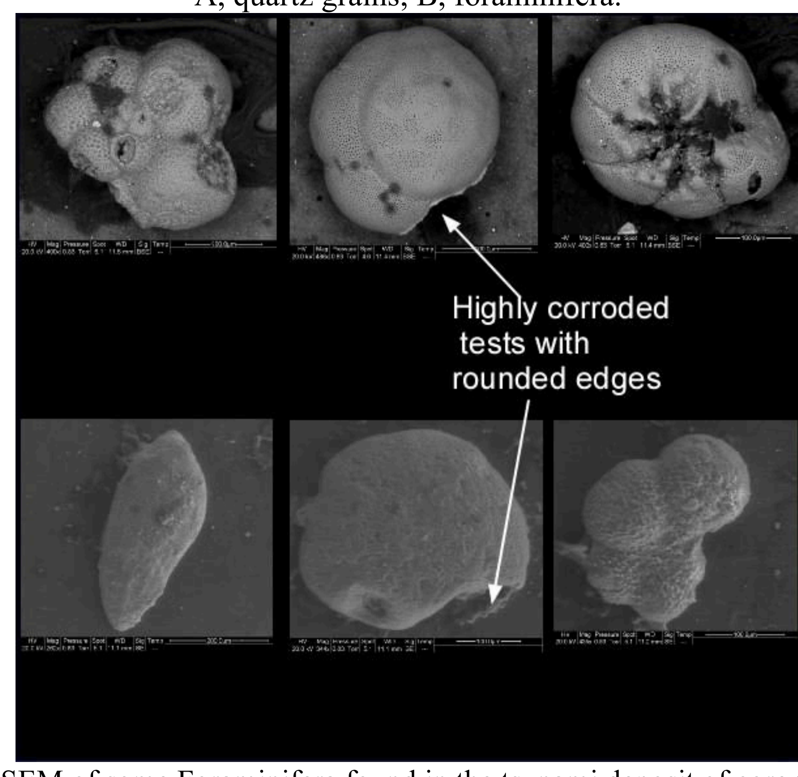


Figure 6. SEM of some Foraminifera found in the tsunami deposit of core CARLA-11.

In order to determine the flow type that transported the high-energy sediment, the samples were plotted in a C–M diagram (Passega 1957). Samples of the high-energy deposit of the Loukkos estuary plot mainly within the N–O and O–P segments (Fig. 7), which suggests that the majority of the grains were transported by rolling, and a small fraction by rolling and suspension under strong hydrodynamic conditions.

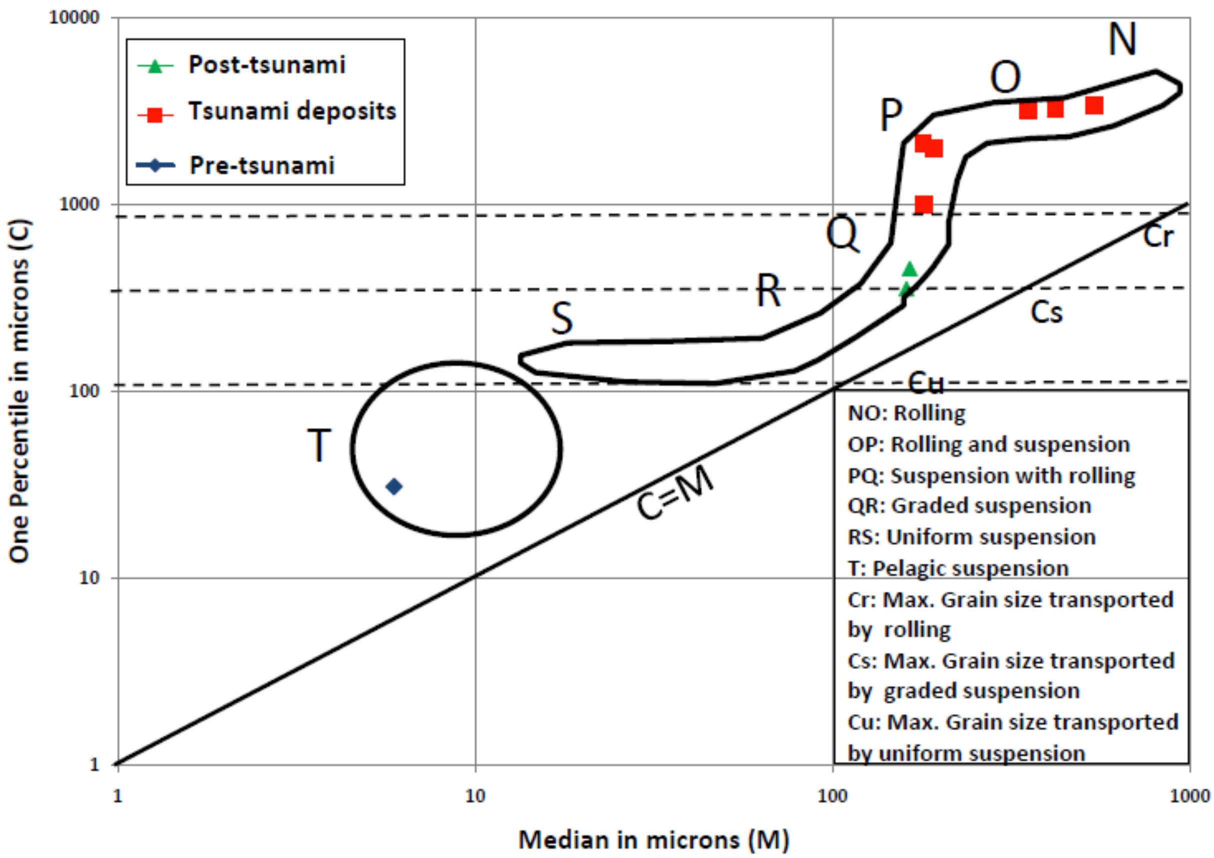


Figure 7. C-M Passega diagram of the samples of the tsunami bed of core CARLA-11.

Magnetic susceptibility measurements show no large differences between the high-energy beds and the upper part of the core, although the latter was not tightly sampled. However, two major lows appear at ~350 cm, and especially at 477 cm within the high-energy deposit (Fig. 8). The latter was sampled tightly and shows a clear vertical variability from one sample to another.

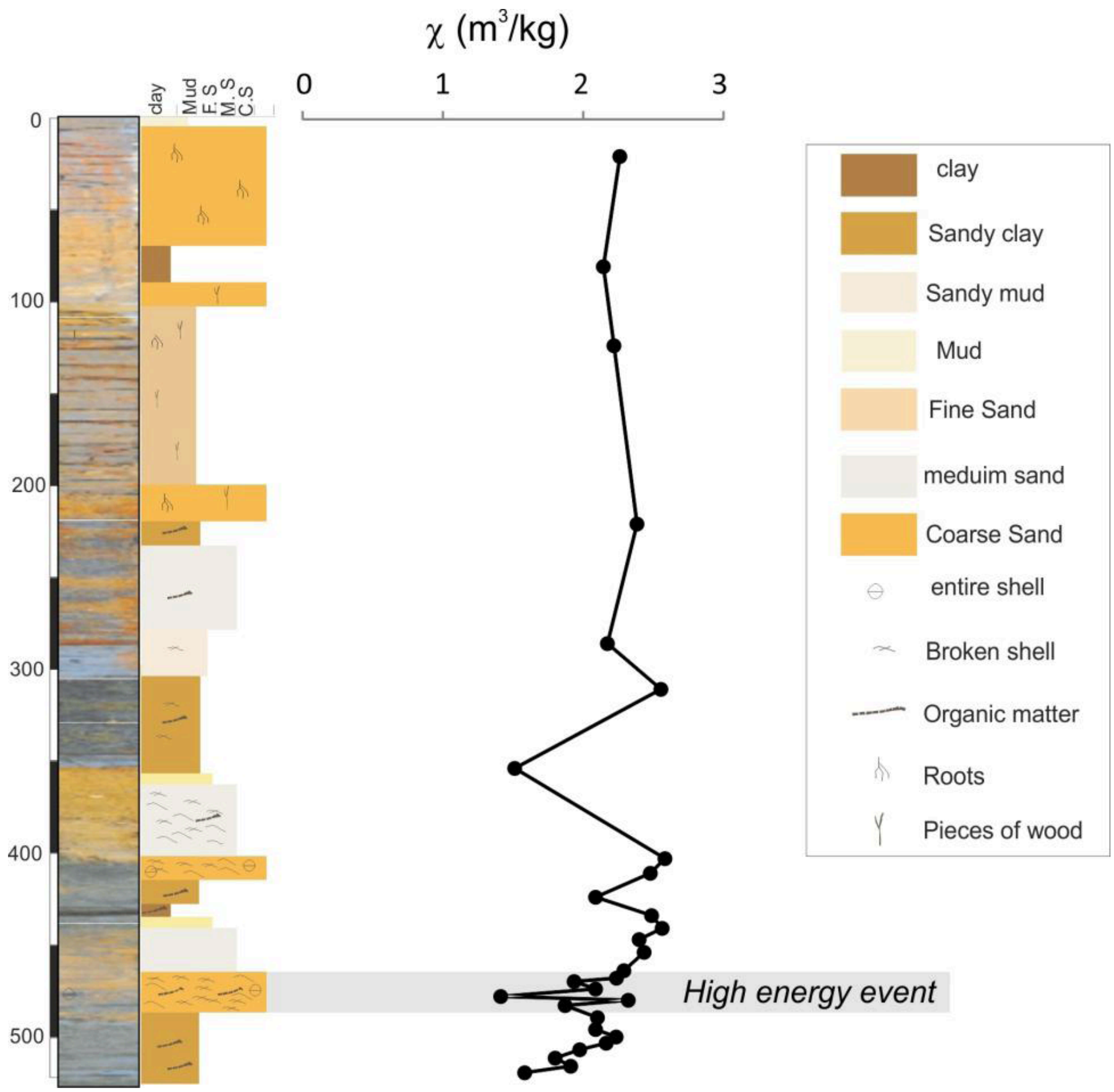


Figure 8. Magnetic susceptibility curve of core CARLA-11.

5 INTERPRETATION

The fact that such a marine shelly level was found within marsh fluvial deposits at a large distance from the river mouth is indicative of a high-energy event, which may correspond to extreme waves generated either by a storm or by a tsunami. In the following, we assess the tsunami scenario because of the very large distance to the river mouth (6 km on map) and because any explanation for the origin of this unit should include a plausible mechanism for depositing large (≤0.5 m diameter), angular, poorly sorted clasts, various sized shell fragments, and sand into the low-energy environment of the marsh estuary.

In the tsunami scenario, the observed sub-units can be interpreted as the following:

• Subunit 1 can be interpreted as the result of the first wave uprush, characterized by a pulse of sand-size sediments mostly composed of sand with bioclasts. The abrupt transition from dark grey clays to coarser deposits is indicative of a change in flow energy. Erosion of the underlying clay is attested by numerous rip-up clasts. Subunit 1 is very poorly sorted and dominated by traction. The fine mud level capping subunit 1 can be interpreted as emplaced during a decantation phase.

• Subunit 2 probably corresponds to a second wave uprush, but its characteristics differ slightly from subunit 1 in terms of composition (few marine bioclasts), texture (inverse grading) and sediment source (organic matter-rich rip-up clasts in the upper part of the subunit).

• Subunit 3 might be interpreted as the result of the backwash (outflow phase). Compared to uprush subunits, it is characterized by abundant small-size marine bioclasts, numerous rip-up clasts and renewed traction.

The tsunami deposit is poorly sorted, with negative skewness indicating that the transport was under high hydrodynamics during a short time (Tuttle et al. 2004). This may be the result of the first tsunami wave and the second less energetic tsunami inundation or the backwash from the first wave that comes from the offshore, erodes the material from the littoral and mixes it with reworked materials before being deposited.

Rip-up clasts (fragments of a cohesive substrate contained within a sedimentary deposit) indicate high-energy flows and also suggest that the material was not reworked for periods of time that are long enough to break apart the material into individual grains.

An assessment of the backflow transport conditions of this mixed material suggests that bedload transport was achieved by supercritical flows, whereas deposition occurred when currents had decelerated enough on the low-gradient lower valley. The marine-brackish to 'chaotic' assemblages comprising marine, brackish and freshwater taxa, and Foraminifera assemblages from mostly large to small benthic taxa, reflect the changes in flow condition during the waves.

6 POSSIBLE AGE

Because radiometric dating from the shells collected in the cores are still being performed, we use the ages determined by Carmona and Ruiz (2009) from nearby sites, which correspond to the Bou Hanani terrace, located to the west of CARLA-11, and Core 5, located at a distance of 4 km south of CARLA-11. The Bou Hanani terrace outcropping shells yielded ages of 4,740 ± 40 Ma to 5,080 ± 40 Ma B.P. which clearly correspond to the Holocene maximum inundation. Core 5 yielded ages of 3,080 ± 50 Ma B.P. at 3.1 m depth and 2,470 ± 40 Ma B.P. at 3.5 m. As the studied level is located at more than 4.5 m depth, the age of the tsunami deposit can be between 5,000 and 3,000 Ma B.P., assuming a steady deposition rate, which is a rough approximation in fluvial settings. This age interval is much older than any recorded event, since the oldest historical tsunami in the Gulf of Cadiz occurred some 2,000 years ago (60 BC according to Baptista and Miranda 2009).

7 DISCUSSION

In recent years, numerous studies have dealt with the geological record of past high-energy events such as storms, hurricanes and tsunamis, using (litho-)stratigraphical, sedimentological, geochemical, magnetic, faunal and radiocarbon datings for this purpose (e.g., Clague et al. 2000; Goff and McFadgen 2002; Radtke et al. 2003; Smith et al. 2004). These studies show that tsunamis and storms may significantly disturb the actual sedimentation regimes of coastal areas, by depositing sands far inland, a feature which constitutes the most common signature of flooding in intermediate to slightly reflective coastal environments. However, despite the increase in the palaeo-tsunami studies during the recent years, especially after the 2004 Indian Ocean event, it still appears problematic to distinguish from geological evidence the tsunami deposits from other coastal flooding events like storms (e.g. Kortekaas and Dawson 2007).

7.1 Distance to the shoreline

The fact that these marine deposits were found far inland (6 km on map, 14 km upstream) is a common case of tsunami deposition. For instance, in the Gulf of Cadiz, tsunami deposits of the 1755 event are located as far as 4 km and 16 km respectively from the Atlantic Ocean at Lagoa de Obidos in Portugal and from Huelva estuary in Spain (Morales et al. 2011; Costa et al. 2012). Tsunami deposits at Seven Mile Creek along the Coquille River estuary are located at 8 km from the shoreline (Witter 1999). At Young's Bay, along the Columbia River, they have been found 10 km upstream (Peterson et al. 1993). Tsunami deposits along the Bone, Niawiakum, and Palix rivers near Willapa Bay, Washington, reach up to 3 km inland (Reinhart and Bourgeois 1987; Reinhart 1991; Atwater and Hemphill-Haley 1997). Along the Niawiakum River, marine diatoms have been found overlying buried soils up to 4 km inland, 1 km beyond the limit of tsunami sediments (Hemphill-Haley 1995).

7.2 General depositional features

Tsunami deposits are typically produced through suspended load transport. There are common characteristic features, which have been described by numerous researchers (e.g. Dawson and Smith 2000; Goff et al. 2001; Tuttle et al. 2004; Morton et al. 2007): (i) Laterally extensive and thickly-bedded sand sheets (often structureless) showing landward thinning; (ii) normal or inverse grading; (iii) presence of marine microfossils and macrofauna. In contrast, storm deposits typically are produced through bedload transport and display extensive planar laminae, foresets, troughs, and climbing ripples with a maximum bed thickness close to shore thinning abruptly landward (Morton et al. 2007).

The typical depositional features comprise (Morton et al. 2007): (i) an erosional base; (ii) coarser sediments than in the overlying and underlying beds; (iii) a fabrics characterized by a remarkably poor internal arrangement; (iv) the presence of exotic sedimentary particles from environments external to those where they are deposited; and (v) abundance of alien marine organisms such as foraminifera, diatoms, and even mollusk shells. In the CARLA-11 section, all these features were encountered, so they attest for their origin from tsunami waves.

7.3 Sediment composition

The composition of tsunami sediments reflects the local coastal environments from which the sediment is derived (Jaffe et al. 2003; Goff et al. 2006; Morton et al. 2007). Several worldwide examples have recently been described for recent tsunamis; for instance, at Playa Jahuay in Peru, following the 21 June 2001 tsunami, the mineralogy of the tsunami deposit was similar to the sand found on the nearby beach and contrasted with the mineralogy of the underlying fluvial sand (Jaffe et al. 2003). Nanayama and Shigeno (2006) found that a bimodal distribution in deposits from the 1993 Hokkaido tsunami indicate both a marine sediment source and a terrestrial source. The deposits of the December 2004 tsunami in Indonesia have been described by Paris et al. (2007) as a poorly sorted sediment.

Heavy minerals, including magnetite, amphibole, ilmenite, garnet, zircon, rutile, monazite, and sillimanite, were present in the tsunami deposits of Java (Razzhigaeva et al. 2006; Bahlburg and Weiss 2007; Fritz et al. 2007; Narayana et al. 2007; Jackson 2008; Jagodziski et al. 2009).

Jagodziski et al. (2009) found a depletion of tourmalines in the tsunami deposit compared to the underlying deposits. Kortekaas and Dawson (2007) have shown that the tsunami deposits near Lisbon contain significant percentages of shells, shell debris and benthic foraminifera in shallow water environments. The altered Foraminifera have been used as a tsunami indicator; it provides information about energy and transport condition. (e.g. Mamo et al. 2009, and references therein; Uchida et al. 2010; Pilarczyk et al. 2011; Pilarczyk and Reinhardt 2012b) through their different taphonomic characters (Pilarczyk et al. 2011).

Measurements show that most of the sediments have a relatively high MS reflecting the magnetized clay content; however, low MS can be clearly observed at the tsunami deposit, which match the shelly sand levels described in the previous section (Font et al., 2010).

In our case, the composition of the CARLA-11 tsunami bed includes all these features. However, it is useless to compare the sands in the core to those of the present-day beach because of the older age of the deposit and the change in marine and fluvial dynamics since that time (~3-4 ky).

7.4 Summary

In Table 1 we list the observed characters among those proposed by Kortekaas and Dawson (2007) to distinguish between tsunami and storm deposits. Most observed features are those of tsunami deposits, but others could not be observed because of the age, the position and the technical conditions of the core, including severe oxidation.

Table 1. Characteristics of the CARLA-11 deposits which may be present in tsunami and storm deposits. P = present; A = absent; ? = unknown or not studied.

Evidence (tsunami/*storm*)	P/A	Comments
Morphological		
Wash-over fans behind breached barriers / *idem*	**?**	Ancient morphology
Stratigraphical		
Thins inland and becomes discontinuous / *thins inland*	**?**	Correlations are difficult
Fines inland / *idem*	**?**	Difficult to observe
Erosional basal contact / *idem*	**P**	
Large inland extent / *Relative smaller inland extent*	**P**	6-14 km
Sedimentological		
Boulders / *Boulder deposition has been reported*	**A**	Found at the beach
One or more fining upward sequences, sometimes homogeneous / *fining upward or homogeneous*	**P**	
Intraclasts from underlying material / *not found*	**P**	
Loading structures at the base / *not found*	**P**	
Bi-directional imbrications / *Unidirectional imbrication*	**?**	It is possible that coring altered structures
Poorly sorted (particle size ranging from mud to boulders) / *relatively better sorted*	**P?**	
Sedimentary structures very seldom found / *sedimentary structures more common*	**P**	It is however possible that coring altered structures
Geochemical		
Increase in geochemical elements indicating marine origin / *No information found, but similar signature is expected because of marine origin*	**?**	No geochemical analyses were performed because of high alteration of core
Palaeontological		
Marine fossils / *idem*	**P**	
Increased diversity (mixture marine and brackish fossils) / *mixture of marine and fresh water fossils*	**?**	
Relative well/poorly preserved fossils / *poorly preserved fossils*	**P**	
Plant fragments / *idem*	**?**	
Shell rich units / *shell fragments*	**P**	
Rafting light material / *not found*	**P**	
Buried plants at base / *idem*	**?**	

8 CONCLUSION

Numerous high-energy thin levels have been identified around the tsunamigenic Gulf of Cadiz in the last decade, and have been associated to tsunami waves, especially those following the Lisbon earthquake of 1st November 1755. These beds are preserved in the estuaries of the Algarve, Portugal and southern Spain. In Morocco, no such high-energy sandy deposits were described although most of the northwest coast of Morocco was strongly affected historical tsunamis, as attested by the existence of supra-littoral boulders in Rabat and Larache coasts (Mhammdi et al. 2008; Medina et al. 2011) whose displacement has been attributed to the tsunami of 1755. The present study is the first report of such fine deposits along the Moroccan coast, although they seem to belong to an early to middle

Holocene event. We expect that similar deposits of more recent age may be better preserved within calm lagoons such as the Moulay Bousselham or El Walidiya lagoons, as they are less exposed to fluvial actions than in estuaries.

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TSUNAMI WARNING SYSTEM IN THE PACIFIC

Brief Historical Review of its Establishment and Institutional Support

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ABSTRACT

The year 2015 marks the 50th anniversary of operations of the International Tsunami Warning System in the Pacific Ocean. The present report describes briefly the establishment of the rudimentary early tsunami warning system in 1948 by the USA after the disastrous tsunami of April 1, 1946, generated by a great earthquake in the Aleutian Islands, struck without warning the Hawaiian Islands and other parts of the Pacific. Also reviewed are the progressive improvements made to the U.S. warning system, following the destructive tsunamis of 1952, 1957, 1960 and 1964, and of the early, support efforts undertaken in the U.S.A., initially by the Hawaii Institute of Geophysics of the University of Hawaii, by the U. S. Coast and Geodetic Survey and by the Honolulu Observatory - later renamed Pacific Tsunami Warning Center (PTWC). Following the 1964 Alaska tsunami, there was increased international cooperation, which resulted in a better understanding of the tsunami phenomenon and the development of a new field of Science of Tsunami Hazards in support of the early U.S. Warning System. Continuous supporting international cooperative efforts after 1965, resulted in the integration of the U.S. early warning system with other early regional tsunami warning systems of other nations to become the International Tsunami Warning System under the auspices of the Intergovernmental Oceanographic Commission (IOC) of UNESCO for the purpose of mitigating the disaster's impact in the Pacific, but later expanded to include other regions. Briefly reviewed in this paper is the subsequent institutional support of the International Tsunami Warning System in the Pacific, by the International Tsunami Information Center (ITIC), the International Tsunami Coordination Group (ICG/ITS), the Alaska Tsunami Warning Center (ATWC), the Joint Tsunami Research Effort (JTRE), NOAA's National Geophysical Center (NGDC), the Pacific Marine Laboratory (PMEL) of NOAA and of the later-established Joint Institute of Marine and Atmospheric Research (JIMAR) and the School of Ocean and Earth Science and Technology (SOEST) of the

University of Hawaii, in close cooperation with scientists at the Pacific Division of the National Weather Service (NWS) of NOAA. Additionally, the present paper reviews briefly the significant supportive roles of the U.S. Geological Survey, of U.S. Universities and of other national and international governmental and of non-governmental institutions. A historical review of the pioneering research efforts in support of the Tsunami Warning System in the Pacific will be provided in a separate paper.

Keywords: *Tsunami research; Science of Tsunami Hazards; Pacific Tsunami Warning System; International cooperation;*

1. INTRODUCTION

Since the beginning of recorded history, tsunamis have been responsible for enormous destruction of coastal communities and great losses of lives. While most of the destructive tsunamis have occurred in the Pacific Ocean, devastating tsunamis have occurred also in the Atlantic and Indian Oceans, as well as in the Mediterranean, Caribbean and other Seas. Tremendous growth and development of coastal areas in most of the developing or developed nations increased their vulnerability to the tsunami hazard over the years. This was the result of population growth and of technological and economic developments that made the use of the coastal zone more necessary than before. This combination of social and economic factors made a number of countries vulnerable to the threat of tsunamis.

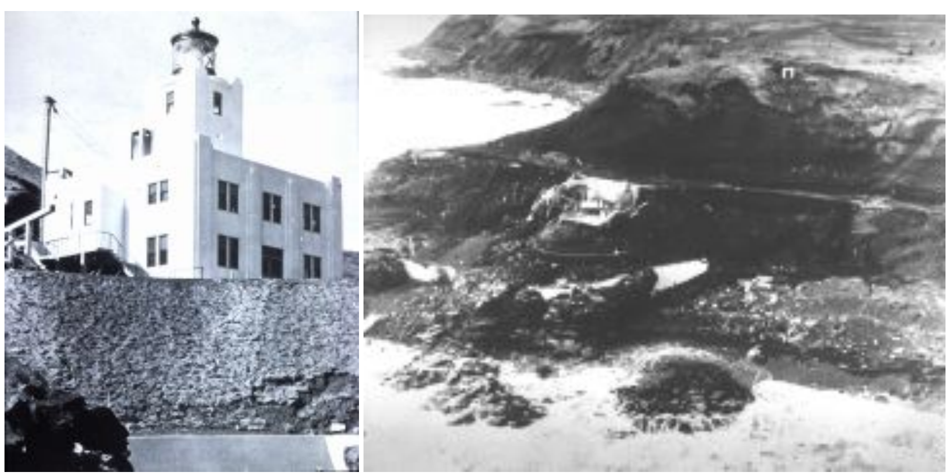

Fig. 1 Damage to the Scotch Cap lighthouse from the Aleutian tsunami of April 1946, Umimak Island, Alaska; before and after (Coast Guard Photos).

After the Aleutian tsunami of April 1, 1946 caused major damage and many casualties, it became obvious that it was necessary for the United States to establish a warning system that could provide timely warnings to threatened populations in Hawaii, Alaska, the Pacific Northwest and in other U.S.

Possessions and Territories in the Pacific. The present paper describes briefly the early U.S. Tsunami Warning System created in 1948, and the subsequent support which begun at the Hawaii Institute of Geophysics of University of Hawaii, but which gradually expanded with the support and cooperation of several U.S. governmental agencies and academic institutions. Additionally reviewed is how the 1960 Great Chilean and the 1964 Great Alaska earthquakes and tsunamis became the catalysts for the establishment of an International Tsunami Warning System for the Pacific, under the auspices of the Intergovernmental Oceanographic Commission (IOC), with support from United States and other Pacific Nations and by the subsequent theoretical and applied research efforts that helped to better understand the tsunami phenomenon and to improve the operations and effectiveness of the Warning System.

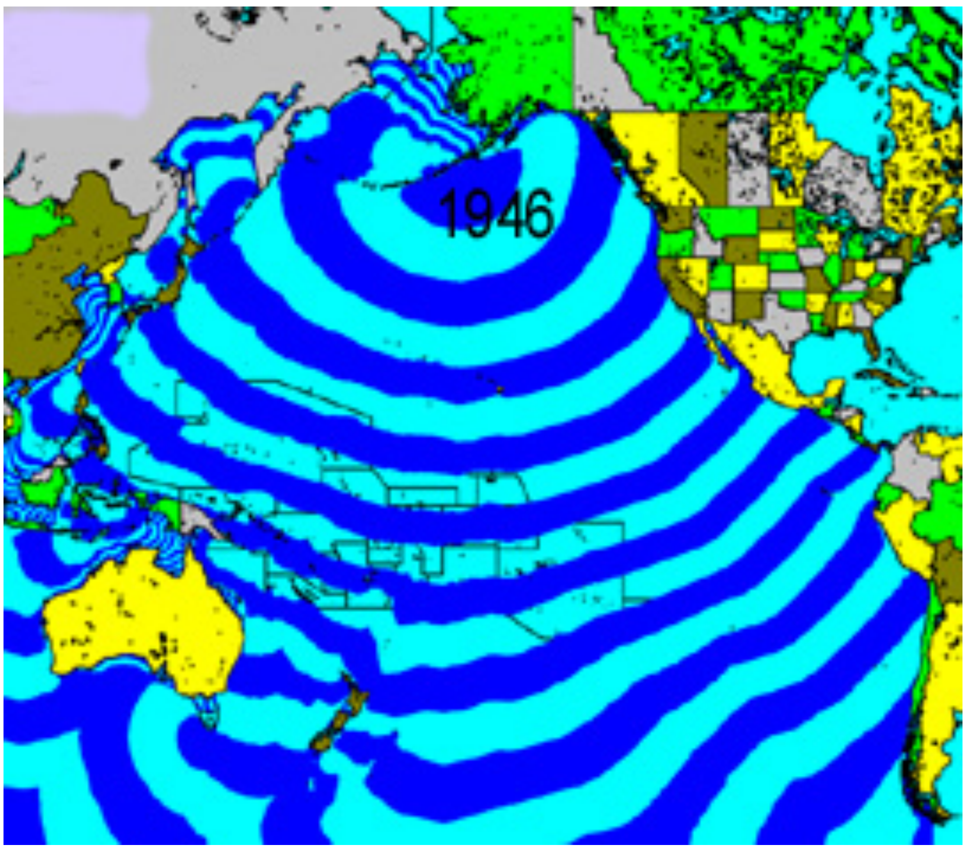

Fig. *2 Travel Time Chart in hours of the 1 April 1946 Tsunami from the Aleutian Islands*

Also, the present paper concentrates mainly on documenting the creation and development of the Pacific Tsunami Warning System in the Pacific. It describes the initial, limited capabilities and limitations and the subsequent institutional support and national and international cooperation which led to a better understanding of the tsunami phenomenon and to improvements of the tsunami warning service over the first twenty-five years of operation but continued uninterrupted for the next 25 years.

As indicated by the bibliography, the present review is based primarily on the author's recollection and on personal and public records available to him. Thus, there may be omissions. A subsequent paper will be devoted to a more thorough review of the early research efforts - concentrating primarily on work initiated and conducted in Hawaii and, to a lesser extent, on research conducted elsewhere in the USA and internationally which - over the years - helped improve the Tsunami Warning System in the Pacific and in other World Oceans and Seas.

1. THE U.S.A. AND OTHER EARLY TSUNAMI WARNING SYSTEMS

1.1 The Early U.S. Seismic Sea Wave Warning System" (SSWWS)

Shortly after the great 1946 disastrous tsunami struck without warning, work begun on developing an early U.S. Tsunami Warning System. However, in 1946 the technology was still inadequate. Photographic methods were being used to record earthquakes, because they were simple, practical and precise, however, this data could not be immediately available to help provide timely earthquake information or tsunami warnings. Thus, some type of visual recording equipment was needed to be used in conjunction with existing seismographs so that the data could be promptly used for tsunami evaluation and warnings. Subsequently, in 1947 and 1948, such new instruments were built and installed at three U.S. seismic observatories. Based on these developments, in August 1948 the U.S. established "The Seismic Sea Wave Warning System" (SSWWS), which became operational in 1949. Although somewhat functional for warning about tsunamis of distant sources, the system could not operate quickly enough to give timely warnings for tsunamis from close sources.

1.1.1 Functions and Seismic and Tidal Stations of the Early U.S. SSWWS

The early SSWWS had to detect and rapidly locate earthquakes in the Pacific region, and if one occurred in an area where tsunami generation was possible, to determine quickly whether indeed one had been generated so that a timely warning could be issued. The SSWWS was based on obtaining data from the three seismological observatories of the U. S. Coast and Geodetic Survey (USCGS) at Sitka, College, Tucson, and Honolulu, and from tide stations at Attu, Adak, Dutch Harbor, Sitka, Palmyra Island, Midway Island, Johnston Atoll, Hilo, and Honolulu. The Honolulu Magnetic Observatory of the USC&GS was renamed as Honolulu Observatory (HO) and was established as the headquarters of this Early Tsunami Warning System. Its function was to supply tsunami watch and warning information to the civil authorities and various military headquarters in the Hawaiian Islands for dissemination to military bases throughout the Pacific and to the islands in the United States Trust Territories of the Pacific. Later, in 1953, the warning information was also given to the civil defense agencies in Alaska, California, Oregon, and Washington. The early functioning of this U.S. Tsunami Warning System and its subsequent improvements to mitigate the tsunami hazard's impact, have been extensively described in the scientific literature over the years (Cox, 1963,1968; Spaeth, 1962; Murphy & Eppley, 1969; Pararas-Carayannis, 1977, 1986).

1.1.2 *Improvements to the Early U.S. SSWWS – Development of a Communication Plan*

Installations at seismic stations were gradually improved by modifying and adding a new electronic amplifier, which included an alarm circuit, so that whenever a major earthquake was recorded, an audible and/or visible alarm was tripped, thus insuring prompt observation of every major earthquake by personnel on stand-by status at each station. For the initial prototype U.S Warning System, a detector was additionally developed for tide gauge stations, which was actuated to ring an alarm by any sudden and unusual sea level change that could have been caused by the wave motion of a tsunami. Also, in order to support this early warning system, a tentative communication plan was prepared utilizing the existing communication of the U.S. Armed Forces and of the Civil Aeronautics Administration (Spaeth, 1962), and a manual on wave reporting procedures was prepared for tide observers at stations participating in the U.S. SSWWS (Spaeth et al, 1966). Communications were carried out by teletype machines, using paper tapes. However, in spite of these improvements, the SSWWS was still confronted with a number of problems that had to be solved.

Fig. 3 Tsunami Travel time chart for Honolulu, Hawaiian Islands.

1.1.3 *Development of a Tsunami Travel Time Chart in support of the U.S. SSWWS*

For the system to function more effectively, it was necessary to develop a methodology for determining accurately the arrival times of the tsunami at various places. Thus, to support this early warning system, a tsunami travel time chart for Honolulu was first prepared. The chart was based on refracting the initial wave of a tsunami hypothetically generated near Honolulu, then using this wave reversely to estimate its travel time back to the approximate earthquake generating source, as established from an epicenter determination. This first tsunami travel time chart was based on a Mercator projection of the Pacific, and a hand-drawn flat earth, shallow-wave approximation of tsunami travel based on refraction and somewhat inadequate data of ocean bathymetry. In spite of these limitations, this first travel time chart provided a relatively good approximation for the Hawaiian Islands, but was of little use for any other threatened coastlines close or far from the origin source of the tsunami – which was much larger than a point source assumed by using only the quake's epicenter. Obviously, for a more effective warning system, better tsunami travel charts were needed for other locations around the Pacific. Later development of tsunami travel time charts for the Pacific – described at a subsequent paper – involved numerical modeling of tsunami travel based on coupling with both spherical and flat-earth approximations and using more reliable ocean bathymentry (Pararas-Carayannis et al., 1968; 1969).

1.2 Capabilities and Limitations of the Early U.S. Seismic Sea Wave Warning System" (SSWWS)

In order to function even more effectively in issuing tsunami warnings, this early tsunami warning system **(**SSWWS) needed rapid data handling and communications. However, because of time delays in collecting and processing seismic and tidal data, and because of delays in communications, the warnings that were initially issued by the Honolulu Observatory could not protect coastal areas against local tsunamis in the first hour after generation. National regional warning systems had been established in some other Pacific areas, but these also had serious limitations in assessing both seismic and tidal data in a short window of time.

The regional systems generally had data from a number of seismic and tide stations telemetered to a central headquarters. Nearby earthquakes were located, usually in 15 minutes or less, and a warning based primarily on short wave period seismic recordings, was subsequently released to the population of the threatened coastal area. Since the warnings were issued on the basis of seismic data alone, watches or even warnings were occasionally issued when tsunamis had not been generated – which the public perceived as "false warnings". However, since these warnings were issued only to restricted areas and confirmation of the existence or nonexistence of a tsunami was rapidly determined, the dislocations of populations were minimized. To limit the number of agencies to be contacted, the warnings were generally issued to only one agency in each country, territory, or administrative area.

1.3 Other Early Regional Tsunami Warning Systems

After the 1960 Chilean tsunami, other countries in the Pacific, such as Japan, USSR (Russian Federation) and Chile, had established rudimentary national warning systems, with the responsibility of warning primarily their own civil defense authorities and protecting their own national interests. Also, these systems had the same limited data collection capabilities, the same limited communications within their own national jurisdictions, and the limited capability of warning dissemination to the public.

Fig. 4 The railroad yard at Seward, Alaska after the 1964 tsunami struck

1.3.1 Establishment of a Local Tsunami Warning System for the Hawaiian Islands

Shortly after the establishment of JTRE at the Hawaii Institute of Geophysics, efforts were made to set up an early experimental local Tsunami Warning System for the Hawaiian Islands. Martin Vitousek and Bill Adams, in cooperation with the Hawaii Volcano Observatory and the Hawaii Civil Defense Agency, established data telemetry of sea level from existing tide gauges in the Hawaiian Islands. In addition, two new pressure sensors were positioned along the south and west coasts of the island of Hawaii. A third unit consisting of a bottom–mounted pressure sensor and an acoustic transponder was placed below a buoy at about 100 km north of the Hawaiian Islands. This was the predecessor to the DART ocean buoy systems presently in use around the world's oceans for the detection of tsunamis.

2. ESTABLISHMENT OF THE INTERNATIONAL TSUNAMI WARNING SYSTEM IN THE PACIFIC

As stated, the great Chilean earthquake and tsunami of May 22, 1960 and the destruction it caused in Hawaii, Japan and elsewhere in the Pacific, made it obvious that there was an urgent need for nations of the Pacific to cooperate in establishing an effective, International Tsunami Warning System that could share data and communications for warning purposes.

2.1 International Cooperation

When the great Alaskan earthquake of 1964 generated the devastating tsunami that affected a good part of the Pacific, additional attention was focused for immediate action on a Tsunami Warning System. Thus in 1965, at an international meeting held in Honolulu, Hawaii, the United Nations Educational, Scientific, and Cultural Organization's (UNESCO), Intergovernmental Oceanographic Commission (IOC) accepted the offer made by the United States to expand its existing Tsunami Warning Center in Honolulu to become the headquarters of the Tsunami Warning System in the Pacific. At the same time IOC accepted the offers of other member states to integrate their existing facilities and communications into this system. The stated purpose for the establishment of the system was to protect life and property in the Pacific by using a more extensive international network of seismic and tidal stations, as well as existing and enhanced communications, so as to ensure that the warning information was prompt, accurate and available to all. To further ensure proper functioning and coordination of this Pacific Tsunami Warning System, an agreement was reached to establish an International Tsunami Information Center (ITIC) and an International Coordination Group given the acronym ICG/ITSU.

Fig. 5 Photo of the 1964 tsunami damage at Port Alberni, British Columbia, Canada

2.1.1 The International Tsunami Information Center (ITIC)

According to the 1965 agreement, the International Tsunami Information Center (ITIC) was established and given the general mandate of helping to mitigate the effects of tsunamis throughout the Pacific by supporting member states of the ICG/ITSU in developing and improving preparedness for tsunamis; by monitoring and seeking to improve the Tsunami Warning System for the Pacific; by gathering and disseminating knowledge on tsunamis; by fostering tsunami research; and by bringing to non-member states a knowledge of the Tsunami Warning System and of ITIC, and information on how Pacific nations could become participants in the International Tsunami Warning System through IOC/ITSU. The United States agreed to host ITIC in Honolulu and to subsidize most of its operating expenses. The contributions of ITIC to this mandate and functions over the years are discussed in subsequent sections of the present report.

2.1.2 The International Coordination Group for the Pacific Tsunami Warning System (ICG/ITSU)

The International Coordination Group (ICG/ITSU) also established by the 1965 agreement, was designated to be a subsidiary body of IOC. It begun convening biennially since 1968 in a member state to coordinate and review the activities of the International Tsunami Warning System (ITWS). These ITSU Sessions provided an opportunity for the Member States to report on any aspect of tsunami preparedness undertaken in the 2-year intercessional period, on programmes of education, on technological improvements and action on recommendations and on resolutions from the previous sessions. During these sessions, new levels of cooperation were continuously explored, priorities and budgets were established and formal recommendations of the Group were submitted to the IOC General Assembly for action and funding. Thus the ICG/ITSU group helped build the needed international cooperation in dealing with mutually shared problems. Its recommendations provided guidelines and direction for the improvement and expansion of the Pacific Tsunami Warning System by agreement, rather than through unilateral decisions. In addition to the Pacific Tsunami Warning System, ICG/ITSU recognized in several of its sessions the need for the development of regional tsunami warning systems in areas where tsunami warnings could not be provided by the existing system. The work of the ITSU Group continues in the same way to the present time. The International Tsunami Warning System and the benefits of this international coordination are described in the early literature and later on the Internet (Pararas-Carayannis, G. 1977, 1986) and in subsequent sections of this overview.

2.1.3 International Tsunami Warning System in the Pacific

Based on the same 1965 international agreement, the existing U.S. Warning System was integrated with the Systems of Japan, USSR, Chile, and of other regional centers, and expanded to become the International Tsunami Warning System for the Pacific (ITWSP). Initial membership was small and restricted to the few Pacific countries, which had participated, in the initial meeting in Honolulu. However, subsequent development and plans for the international system included the addition of new seismic and tide stations, as well as new visible recording seismic systems and electronic recording tide gauges to many participating stations in the Pacific. Also, under a U.S. Environmental Science Services

Administration (ESSA) contract, the previously described experimental tsunami warning system in Hawaii was installed by the University of Hawaii, in an effort to provide earlier warnings to residents of Hawaii for locally generated tsunamis. Subsequently, a research study was also conducted to determine the effectiveness of a newly established regional Alaska Warning System (Murphy & Eppley, 1969).

As stated, the objectives of the Pacific Tsunami Warning System were to detect and locate major earthquakes in the Pacific region as soon as possible, to determine whether they have generated tsunamis, and to provide timely and effective information and warnings to the population of the Pacific in order to minimize the hazards to life and property. These responsibilities increased in subsequent years to include other geographical areas. In the next 20 years after the establishment of the Pacific Tsunami Warning System, the membership increased greatly as more and more IOC member states decided on the need for tsunami protection. Eventually, the following twenty-eight nations became participating members of ITSU. The member states were: Australia, Canada, Chile, China, Colombia, Cook Islands, Costa Rica, Democratic People's Republic of Korea, Ecuador, Fiji, France, Guatemala, Indonesia, Japan, Mexico, New Zealand, Nicaragua, Peru, Philippines, Republic of Korea, Singapore, Thailand, Federation of Russia, United States of America (USA) and Western Samoa. Also, several nonmember states and territories maintained stations for the initial ITWS. The System initially made use of 69 seismic stations, 65 tide stations and 101 dissemination points scattered throughout the Pacific Basin under the varying control of the member states of ITSU.

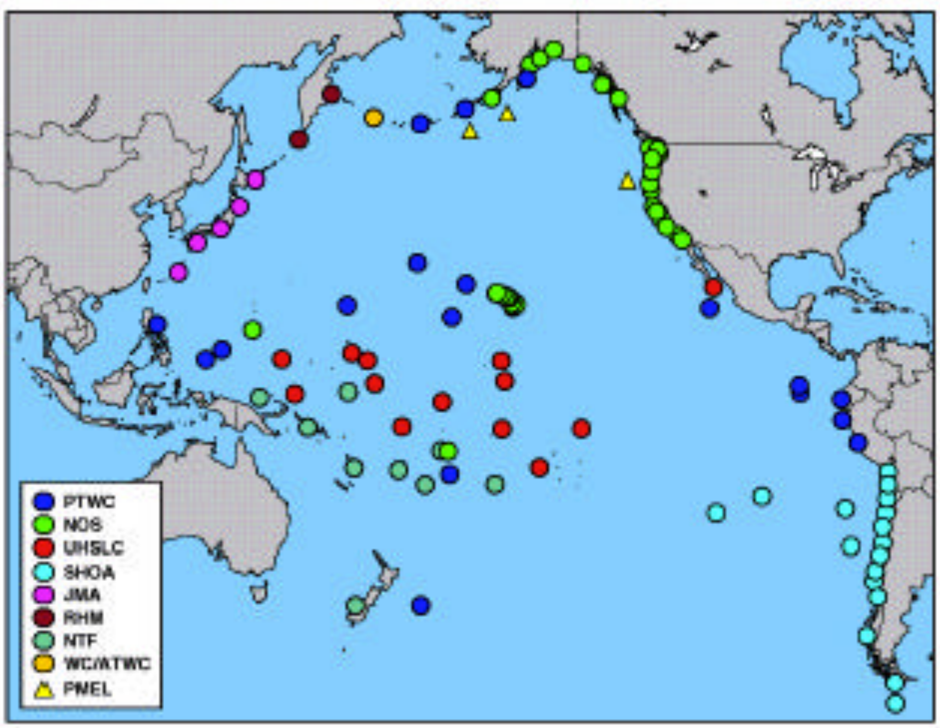

Fig. 6 Tsunami Warning System Sea Level Gauges

The Honolulu Observatory at Ewa Beach near Honolulu was again renamed as the Pacific Tsunami Warning Center (PTWC) and continued to be operated first by the U.S. Coast and Geodetic Survey and later by the U.S. National Weather Service, Pacific Region. In subsequent years, the membership of the Pacific Tsunami Warning System increased, as well as the number of seismic and coastal tide gauge stations. In later years deep ocean stations and platforms were included in the network.

2.1.4 Programs of Tsunami Preparedness and Education

A program of tsunami preparedness and education was initially developed by the International Tsunami Information Center ITIC and IOC - as recommended by ICG/ITSU - and in close cooperation and Civil Defense authorities of IOC member states, for the purpose of alerting coastal populations, industries, to respond to tsunami warnings. The responsibility of coordinating public educational programs for each participating country was also assigned to ITIC, which worked closely with government agencies, private institutions and Civil Defense authorities, in developing sound coastal management policies which included zoning and planning for coastal areas, as well as standard operating procedures in case of an actual event.

Dissemination agencies in each member country had the continuing responsibility for educating the public concerning the dangers of tsunamis and for developing safety measures that must be taken to avoid loss of life and to reduce property damage. These agencies were encouraged to develop emergency plans for all threatened localities, clearly delineating areas of possible tsunami inundation. Thus, evacuation routes were designated, safe areas were marked and the amount of advance warning to insure evacuation from danger areas was determined. All these activities resulted from close international cooperation promulgated through the efforts of IOC, ITIC and ICG/ITSU.

2.1.5 The Success of the International Tsunami Warning System in the Pacific

Through the above-described efforts, the Tsunami Warning System in the Pacific became an example of how a natural disaster’s impact can be mitigated through international cooperation, concerted research and the sharing of knowledge and information. The Tsunami Warning System in the Pacific became one of the first and the most successful international programs ever undertaken, involving a multitude of nations with the direct responsibility of mitigating the effects of tsunamis, the saving of lives and the preservation of property. It became an effective operational program with a direct humanitarian objective - the protection of human lives bordering the Pacific Ocean and subsequently of other coastal areas in the Atlantic and Indian Oceans, and in the Caribbean and Mediterranean Seas. The success of the system was made possible by the generous contributions and participation of the Community of Nations, by IOC's involvement and leadership, and by the active and effective coordination of ITIC and of the International Coordination Group.

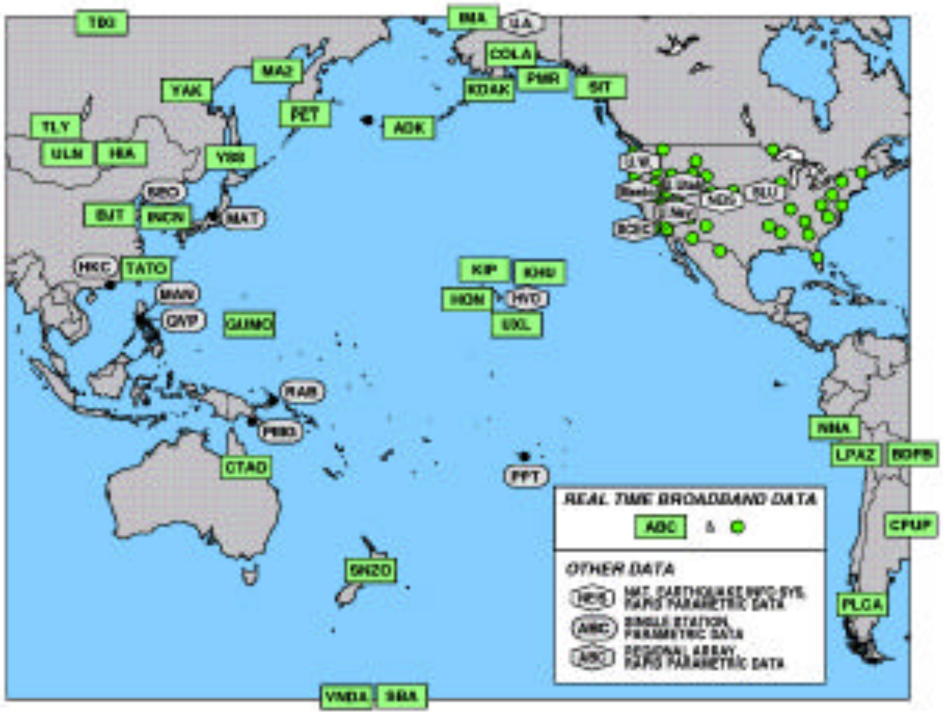

Fig. 7 Sea-level (or tidal) data provided by ITSU member nations, by NOAA's National Ocean Service, by the ATWC, by GLOSS and by university monitoring networks.

3. INSTITUTIONS INVOLVED IN RESEARCH AND PROGRAMS IN SUPPORT OF THE PACIFIC TSUNAMI WARNING SYSTEM

The following is a brief summary of principal institutions and government agencies supporting the early tsunami warning system and later the International Tsunami Warning System in the Pacific.

3.1 Hawaii Institute of Geophysics (HIG) of the University of Hawaii

Pioneering tsunami research in the U.S. begun at the University of Hawaii following the devastating 1946 tsunami that struck without warning the Hawaiian Islands and caused many deaths and extensive destruction. Francis Shepard from the Scripps Institution of Oceanography and Gordon Mcdonald and Doak Cox from the University of Hawaii participated in the initial survey of this tsunami in the Hawaiian Islands and wrote an extensive report on its impact. Additionally, Pacific-wide tsunamis that struck the Hawaiian Islands in 1952, 1957 and 1960, were also investigated by the U.S. Army Corps of Engineers, the U.S. Coast and Geodetic Survey and University of Hawaii scientists, who documented wave height distribution and impact, mainly in the Hawaiian Islands.

As mentioned, the disastrous 1946 tsunami and the subsequent tsunamis that struck the Hawaiian Islands in 1952 and in 1957, emphasized the need to begin a research program at the University of Hawaii to help evaluate the local risk and to support the early tsunami warning system that was established in 1948. Thus, following the devastating May 22, 1960 tsunami from Chile, the State of Hawaii provided funds for a program of tsunami investigations at the University. Doak Cox, then employed at the Sugar Planters Research Facility transferred to the University to assist with such a program. He was joined by Martin Vitousek, Rockne Johnson, Gordon Groves and other scientists who had participated in the International Geophysical Year. Doak Cox hired graduate students to assist in this effort.

In 1964, the construction of the Hawaii Institute of Geophysics (HIG) building was completed at the University of Hawaii campus in Manoa Valley. Dr. George Woollard arrived from the University of Wisconsin to assume the HIG Directorship. He brought with him geophysicists, graduate students and the contracts he had with the Office of Naval Research (ONR) and Office of Naval Intelligence (ONI) to continue investigations of the MOHOLE project. "MOHOLE" was the effort to drill through the earth's crust to the mantle in order to determine its consistency and possibly the earth's and our solar system's evolution. Finding the thinnest part of the earth's crust to drill the MOHOLE became one of the major research projects at HIG. The Geology, Oceanography and Geophysics Departments came under the umbrella of HIG at that time. The University's newly established Computing Center occupied a wing of the 3rd floor of the new HIG building. A fishing boat from Alaska, the "Neptune", was purchased and equipped to conduct the offshore seismic surveys for a MOHOLE drilling site and other oceanographic investigations. Graduate students in Oceanography, Geology and Geophysics begun to participate in these surveys and study tsunamis as well.

The following people at the University of Hawaii and JTRE participated in early tsunami research and in support of the Tsunami Warning System in the early 1960's and thereafter in JIMAR in the 1970s and 1980s. The listing may not be complete but in the 1960s included: Gordon McDonald, Doak Cox, Martin Vitousek, Rockne Johnson, Roger Norris, John Northrop, George Woollard, Ralph Moberly, Augustine Furumoto, Harold Loomis, Bill Adams, Loren Kronke, Alexander Malahoff, Don Hussong, Fred Duennebier, Floyd McCoy, Gary Stice, Frisbee Campbell, George Pararas-Carayannis, Daniel Walker, Tom Sokolowski, Stephen Langford, James Larsen and Jean Foytik.

3.2 The United States Coast and Geodetic Survey (USC&GS)

As indicated previously, the United States Coast and Geodetic Survey (USC&GS) (1878-1970), was the federal agency that organized in 1948 the Early U. S. Seismic Sea Wave Warning System (SSWWS) and designated its Honolulu Magnetic Observatory to be the headquarters in evaluating seismic and tidal data and issuing tsunami advisories, watches and warning information to the civil authorities and various military headquarters in the Hawaiian Islands for dissemination to military bases throughout the Pacific and to the islands in the United States Trust Territories of the Pacific. Also, and as previously mentioned, in 1953 tsunami warning information was given to the civil defense agencies of California, Oregon, and Washington. USC&GS scientists that participated in early tsunami research at the Survey's headquarters, included Robert Eppley, Mark Spaeth, Leonard Murphy and Saul Berkman. Later, Robert Eppley was transferred to Hawaii, then to the Tsunami Warning Center in Alaska.

3.3 Establishment of the Joint Tsunami Research Effort (JTRE) at the University of Hawaii - Integration with the HIG Research Projects

The 1965 agreement between the University of Hawaii and the U.S. Coast and Geodetic Survey (USC&GS) included the formation of the Joint Tsunami Research Effort (JTRE). The tsunami research team at that time included professors, researchers and graduate students who were already working at HIG or other University of Hawaii departments. Some of them had dual appointments and could only work on a part time basis. Additional funding was provided by the State of Hawaii and by the USC&GS to continue the on-going tsunami research at HIG and to support the cooperative effort by bringing in new people.

The following additional scientists participated in tsunami research at the University of Hawaii and JTRE in the early 1960's and thereafter in JIMAR in the 1970s and 1980's - in support of the Tsunami Warning System. The listing may not be complete but included: Rudolph Preisendorfer, Gaylord Miller, Gordon Groves, Lester Spielvogel, Jim Larsen, George Curtis, Bob Harvey, Eddie Bernard, James Sasser, George Sutton, Charles Helsley, Dennis Moore, Gerard Fryer, Barbara Keating, Walt Dudley, Chip McCreery, Stephen Langford. Scientists from the Engineering Department of the University joined the group (Cheung, Michelle Teng, Brandis and N. Saxena among others).

Bill Adams, a professor of seismology at HIG, served as the initial Director of JTRE, then Gaylord Miller - an oceanographer who had worked with Walter Munk at the Scripps Institution of Oceanography on long period wave research. Subsequently, Doak Cox assumed the Directorship of the Environmental Center at the University but continued to be active with JTRE. In 1967, George Pararas-Carayannis went to work for the newly formed International Tsunami Information Center (ITIC), but continued his close cooperation with the JTRE Group – working with Doak Cox on the historical tsunami databases and with Gaylord Miller on numerical modeling for the preparation of tsunami travel time charts for the Tsunami Warning System.

Several of the HIG and JTRE scientists listed above had participated to the First Meeting of the International Coordinating Group of the Tsunami Warning System in the Pacific (ITSU) at the East West Center in 1968 and had provided significant input. Over the years, and as described in subsequent sections of this report, JTRE played a significant role in many improvements of the Tsunami Warning System. Subsequent government reorganizations brought JTRE under the joint auspices of the University of Hawaii and the newly established U.S. Environmental Services Science Administration (ESSA), then, in the 1970s, the Pacific Marine Environmental Laboratory, ERL, NOAA (ESSA reorganized under this new name) provided funding through the University's Research Corporation to support newly appointed scientists and additional graduate students.

During the 1970s Gaylord Miller, George Curtis, Harold Loomis, and Lester Spielvogel continued to carry out tsunami research at the University of Hawaii with such support. Charles Mader was with the U.S. Los Alamos Laboratory, but was an active participant in the U.S. tsunami program. There was no other significant tsunami research being carried out anywhere in the U.S. at the time, although scientists like George Carrier at Harvard were primarily involved in theoretical studies of wave theory.

3.4 Environmental Science Services Administration (ESSA, 1965-1970)

In 1965, there were several organizational changes when the Environmental Science Services Administration (ESSA) was created as part of a reorganization of the United States Department of Commerce and given the additional mission of overseeing weather and climate operations. In January 1966, ESSA changed the Weather Bureau's name to National Weather Service (NWS) and the National Data Center was renamed as the Environmental Data Service (EDS). Furthermore, the USCGS Commissioned Corps were separated from the Survey to become the Environmental Science Services Administration Corps (or "ESSA Corps").

3.5 The International Tsunami Information Center (ITIC)

As previously described the International Tsunami Information Center was established in 1965 in Honolulu by international agreement to support and improve the Tsunami Warning System for the Pacific by gathering and disseminating knowledge on tsunamis and by fostering tsunami research. Beginning in 1967, Commander Robert Munson, the Pacific Region Director of USC&GS was the first appointed director of ITIC, assisted by oceanographer George Pararas-Carayannnis. After the reorganization of the USC&GS to the Environmental Sciences Services Administration (ESSA), then to NOAA, Gaylord Miller and Robert Eppley served as Directors. In 1974, George Pararas-Carayannis was appointed Director until 1993, when Dennis Sigrist begun serving. Subsequent directors were Michael Blackford and Chip McCreery. Laura Kong is the present Director.

Syd Wigen of Canada was the first Associate Director of ITIC appointed in 1976 to 1978. Norman Ridgway from New Zealand was the next Associate Director. Both were funded by their governments and moved to Hawaii with their families for the duration of their terms. Subsequent Associate Director was Salvador Farreras who served from April 1995 through April 1996 at CICESE in Ensenada, Mexico. At the 6th Session of ICG/ITSU meeting in Lima, Peru, the Chilean delegation made the offer of having Dr. R. Nunez of the Navy Hydrographic Office in Valparaiso to serve as Associate Director of ITIC and his term begun in 1998. However, neither Farreras or Nunez moved to Hawaii.

The numerous contributions of ITIC to the success of the International Tsunami Warning System are too many to describe in this report, but can be documented by reading the ITIC reports to the biannual ICG/ITSU meetings. Also, a detailed report of ITIC activities was presented as part of a press kit describing UNESCO activities at the May 1994 World Conference on Natural Disaster Reduction, in Yokohama, Japan (Pararas-Carayannis, 1994). The contributions of ITIC to the operations of the Tsunami Warning System and to tsunami research begun 50 years ago and continue to the present time. The following sections describe briefly and give examples of some of the ITIC contributions that helped improve the Tsunami Warning System.

3.5.1 Five-Year Master Plan for the Development of a Regional Tsunami Warning System in the Southwest Pacific (Experts Missions and Project Formulation)

Efforts in establishing a Regional Tsunami Warning System in South America and the Southwest

Pacific began in 1979. The first mission by the Director of ITIC (George Pararas-Carayannis at the time) in South America resulted in the drafting of a proposal which was submitted for funding to UNDP through UNESCO in October 1980. Since no response was reccived, the project document was redrafted and resubmitted to UNDP, through the IOC Secretariat and UNESCO. The project was not funded. It was recognizcd that strong support was needed by concerned Member States and that national counterpart contributions were essential if funds were to be made available by UNDP for improvements of the Tsunami Warning System in the Pacific and for regional networks.

At its Eighth Session in 1982, ICG/lTSU had further recommended, through Resolution ITSU-νIII.4 that the highest priority be given to the installation of national and/or regional tsunami warning systems to the nations concerned. Following this recommendation, IOC organized ín1984 an experts mission to the Southwest Pacific region (Philippines, Thailand, Indonesia, Solomon Islands, New Hebrides, and Papua New Guinea), and drafted a project proposal, which was well supported by the Group. At its Ninth Session in 1984, the Coordination Group recognized that national programs would become an integral part of a regional warning system and also that technology, educational programmes, and warning procedures would need to be further developed by Member States. Following the 1984 experts mission to the region, another project proposal was drafted, which was well accepted by the ITSU Group and was submitted in the same year to UNDP and considered as a pipeline project. However, following the endorsement of the project at the Fourth Cycle, Mid-Term Review of the UNDP Programme at a meeting in Jakarta, in March 1989, UNDP headquarters in New York, requested that a survey of the needs of the region be made again leading to project formulation.

Thus, a mission of experts was organized which included George Pararas-Carayannis (Mission Leader), Ron Richmond (Australia) and Kazuhiro Kitazawa of IOC (Mission Secretary). In May 1989 this mission visited the countries concerned and reviewed the national networks of tide stations and seismic observatories to determine appropriate ways and means to strengthen existing networks. Of special concern to the mission was the complex seismicity of the Southwest Pacific Region and in particular the existence of seismic gaps and the potential of future destructive tsunamigenic earthquakes. The mission established short and long period objectives, training and public education needs, and needed equipment and installations for national and regional tsunami warning systems. Specifically the ITIC-led mission identified seismic gaps in Fiji, Samoa, New Hebrides, Vanuatu, and Solomon Islands. Lower Sunda Islands, Java and Sumatra. Subsequently a report was prepared, a master plan for the region and a funding proposal was drafted for submission by IOC to UNDP (Pararas-Carayannis, 1989). The report called special attention to Sumatra and designated the need for seismic and tidal stations at Nias Island, Simuele Island, Padang and Aceh. The same concern for potential tsunamis was emphasized for Java, the Lesser Sunda Islands, Papua New Guinea, Solomon Islands and Vanuatu. Based on the ITIC mission's report and concerns, the IOC submitted a finalized proposal to UNDP to fund a regional warning system in the Southwest Pacific. Although the project went into the UNDP pipeline for funding, officials in countries of the region decided there was no immediate danger and that the money could be used for other projects. Unfortunately, this was a bad judgment as destructive tsunamis occurred later, exactly along the seismic gaps that had been identified by the ITIC-led mission (in Papua- New Guinea, Vanuatu, Lesser Sunda Islands, Sumatra, Java, Fiji, Samoa).

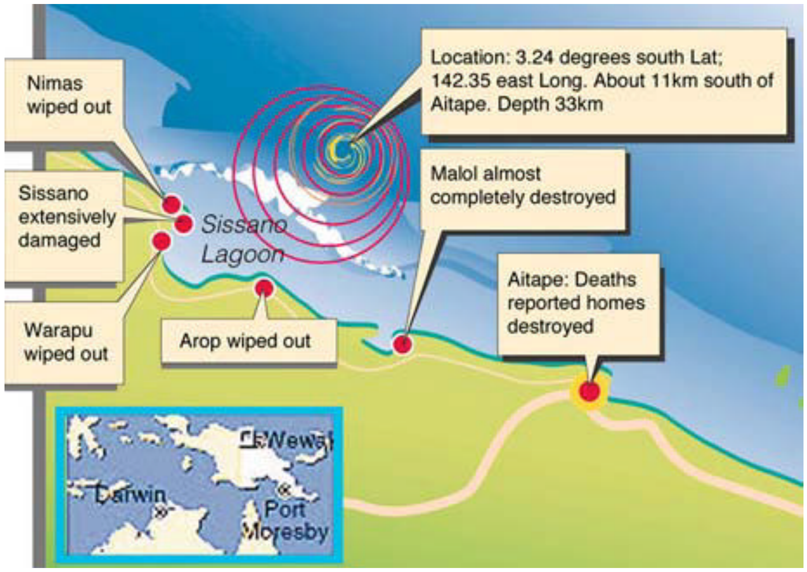

Fig. 8 Papua-New Guinea Tsunami of 17 July 1998. At least 2,182 people died and another 1,000 were injured. More than 10,000 people were left homeless (graphic from http://drgeorgepc.com).

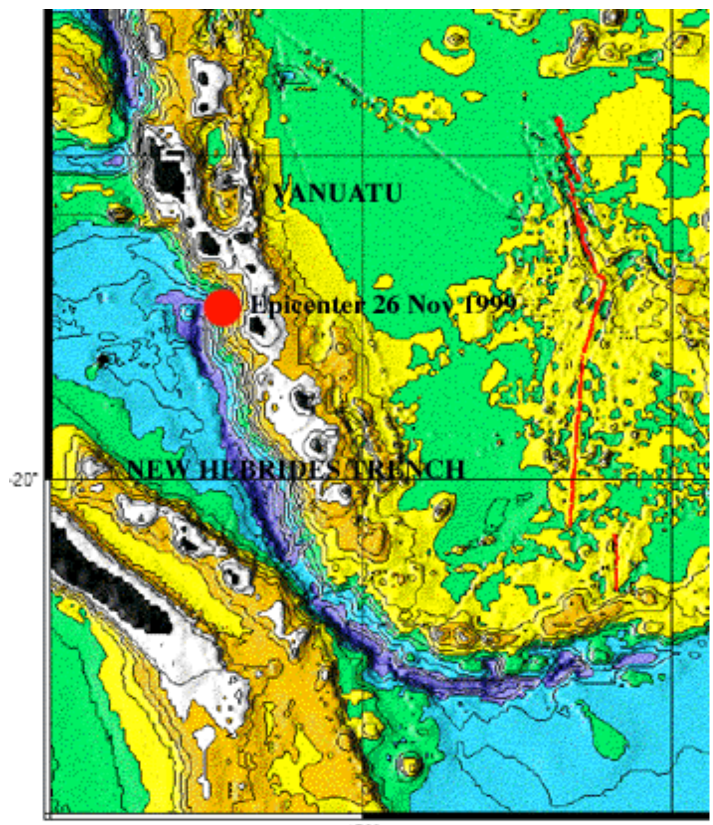

Fig. 9 Vanuatu - 26 November 1999 Tsunami. Thousands of people were left homeless and lost virtually everything in the disaster (graphic from http://drgeorgepc.com).

Fig. 10 Destruction of Banda Aceh from the 26 December 2004 Tsunami

3.5.2 Post Tsunami Surveys

George Pararas-Carayannis, as Director of ITIC, and with help from Associate Directors Syd Wigen (Canada) and Norman Ridgeway (New Zealand) continued to conduct post-tsunami surveys following destructive events in Hawaii, Indonesia, Philippines, Peru, Colombia and Mexico. Also, ITIC continued to develop an extensive historical tsunami database, and to coordinate matters related to the Pacific Tsunami Warning System with guidance from IOC and the ICG/ITSU.

3.5.3 Visiting Scientists Training Programs at ITIC and PTWC

A visiting scientists training program was established at ITIC with financial help from the U.S. National Weather Service of NOAA and from the IOC. Also, workshops were conducted by ITIC in South America with support of UN Organizations such as UNESCO, IOC, UNDP and UNDRO.

3.5.4 ITIC Preparation of Educational Materials in Support of Public Education and Awareness and of the Tsunami Warning System

The ICG/ITSU Group also looked at tsunami education and identified three groups of interest regarding tsunami education programs to improve preparedness: the scientific community, the coordinators and operators of the TWS in all Member States, and the general public. It was determined that the general public education program was the weakest of the three and was in need of immediate attention.

It was obvious that the best way of mitigating the tsunami hazard was with a program of public education and awareness. It was recognized that because of the infrequency of tsunamis, the public must be constantly reminded of the potential hazard. Public informational activities needed to be sponsored by governmental authorities on a regular and continuous basis to assure awareness and public response when a tsunami warning is issued. Thus, development of appropriate educational materials, such as brochures, pamphlets, children's books and audiovisual materials were necessary to implement a program of tsunami disaster mitigation. Such educational materials needed to be developed with national and international support. The preparation of such educational materials was again tasked to ITIC with the recommendation that ITSU member states should also work on educational materials by translating in their own language existing educational materials, particularly for use at schools.

ITIC was a main contributor to the 1975 first edition of "The Great Waves". The work begun in 1974. George Pararas-Carayannis at ITIC, Bob Eppley and Marc Spaeth contributed to the final writing. Glenn Flittner and Bert Thompson coordinated the effort at the Silver Springs NWS headquarters and arranged for the original printing and distribution. All original photos for the Great Waves were from ITIC and HIG files. The post 1975 editions of the "Great Waves" were slightly modified based on the 1975 edition but with enhanced graphics and illustrations. Also, the preparation of additional tsunami travel time charts was assigned to ITIC. George Pararas-Carayannis of ITIC, in with Gaylord Miller at JTRE prepared such charts for the tsunami warning system.

3.5.4 Preparation of Wave Reporting Procedures for Tide Observers in the Tsunami Warning System, Manuals and Guides

Additionally, based on recommendations of the IOC/ITSU Group, ITIC was tasked to compile a standardized guide on how tide observers participating in the Tsunami Warning System should report their recordings or observations to the local tsunami-warning center and to the Pacific Tsunami Warning Center for proper evaluation. In 1975 such a guide prepared by ITIC, was subsequently published by IOC (Intergovernmental Oceanographic Commission (of UNESCO), 1975).

3.5.5 Compilations of Tsunami Glossaries

Also, at the 10th session of the ICG/ITSU group in Sidney, Canada in 1985 a recommendation was made for ITIC to compile a Glossary of multidisciplinary terms, acronyms, mathematical concepts and physical principles that were or could be directly of indirectly applicable to tsunami research work at that particular time or in the future. A preliminary draft of such a Glossary - which included primary and secondary terms - was completed by ITIC. The Glossary received a thorough review by a designated ICG/ITSU committee, which also suggested what terms to use as primary and as secondary. The document in final form was presented at the 1989 ITSU XII meeting and at the IOC Workshop on the Technical Aspects of Tsunami Warning Systems, Tsunami Analysis, Preparedness, Observation and Instrumentation in Novosibirsk (Pararas-Carayannis G., 1989c), and at the 1991 IUGG Tsunami Symposium at the University of Vienna, in Austria (Pararas-Carayannis, 1991). The approved glossary was published in final form and distributed in 1991 by the Intergovernmental Oceanographic Commission as Technical Series #37 (IOC, 1991; Pararas-Carayannis, 1991c). Ten years later in 2001, a second, much shorter version of only primary terms was published by IOC as a separate report. Finally, in 2013, IOC published an illustrated version of a Tsunami Glossary, as UNESCO Technical Series Report #85.

3.5.6 Tsunami Survey Methodology

Similarly, based on recommendations by the IOC/ITSU Group, ITIC and people at JIMAR (Loomis, 1981; Curtis, 1982) prepared guidelines for the conduct of tsunami surveys, which were subsequently incorporated in 1998 into the IOC manuals and guides #37 (Intergovernmental Oceanographic Commission (of UNESCO), 1998).

3.6 ICG/ITSU – Brief History of the Early Years (1965-1979)

As previously discussed, the tsunamigenic earthquakes of 1946, 1952, 1957 brought about the formation of the U.S. Tsunami Warning System. The Chile earthquake on May 22, 1960 generated an even more devastating destructive, Pacific-wide tsunami. Subsequently, the great Alaskan earthquake of March 28, 1964 in Prince William Sound and the Gulf of Alaska generated another devastating tsunami that affected a good part of the Pacific – thus focusing additional attention to the need for an International Pacific Tsunami Warning System and prompting a large number of countries and territories to wish to join with the U.S. Pacific TWS, initially by contributing data and information.

Pursuant to Resolution III-8 of the Third Session of the Intergovernmental Oceanographic Commission (IOC) in June 1964, a Working Group was designated to meet in order to "discuss international aspects of a Tsunami Warning System for the Pacific with a view towards securing the best possible international cooperation". As previously stated, such a meeting Sponsored by the IOC was held in Honolulu on April 27-30, 1965. At this meeting, the convening Working Group accepted the offer made by the United States to expand its existing Tsunami Warning Center in Honolulu to become the headquarters of an International Pacific Tsunami Warning System and at the same time accepted the offers of other IOC member countries to integrate their existing facilities and communications into this System. At that time the United States had the most advanced Tsunami Warning System in the Pacific. Also, Japan had a local warning system tied in with that of the United States, and Russia (then USSR) had a local warning system for the Kamchatka Peninsula and the Kurile Islands. The integration of these and other local systems into one Tsunami Warning System for the Pacific was the major business of the 1965 meeting. Also, such a unified system had been proposed in a resolution adopted by the UNESCO Intergovernmental Conference on Seismology and Earthquake Engineering in 1964 and was additionally supported by a similar resolution adopted by the International Union of Geodesy and Geophysics (IUGG).

As already stated, the Working Group's 1965 meeting in Honolulu established the International Tsunami Information Center (ITIC) and accepted the offer of the United States to support such a center. Also established was the International Coordination Group for the Tsunami Warning System (ICG/ITSU) as a subsidiary body of IOC to:

(i) effect liaison among the participating countries at the technical level, particularly with regard to communications,
(ii) ensure exchange of information on developments of observing methods and of techniques of tsunami forecasting,
(iii) effect liaison and coordination with the Intergovernmental Oceanographic Commission, World Meteorological Organization, and the International Union of Geodesy and Geophysics – particularly with its Tsunami Committee, and
(iv) provide essential secretarial service for the International Tsunami Information Service and for the International Tsunami Warning System.

The specific activities and recommendations of each IOC/TSU session, as well as the actions taken to implement them during the intercessional periods, are well documented at the websites of the Intergovernmental Oceanographic Commission (IOC) and of the International Tsunami Information Center - which include national reports of ITSU member countries and of ITIC progress reports submitted at each session by attending directors of ITIC (i.e. Pararas-Carayannis, 1976, 1976b, 1977, 1978, 1979, 1980, 1982, 1984, 1985a, 1986, 1987, 1989a,b,c, 1991; Pararas-Carayannis & Bernard, 1979). The following are only very brief summaries of the IOC/ITSU early sessions during and of reported progress of Group. The reader is referred to the aforementioned websites for a more detailed history of the early sessions and of sessions subsequent to 1982 (http://itic.ioc-unesco.org) the following are brief summaries of the ICG/ITSU Sessions in different member states from 1968 to 1992. The reader is referred to the ITIC and UNESCO/IOC websites for additional summaries of subsequent sessions.

3.6.1 IOC/ITSU-I – International Co-ordination Group for the Tsunami Warning System in the Pacific, First Session, Honolulu, Hawaii, USA, March 25-28, 1968

The IOC accepted the Working Group's 1965 recommendations, and the first meeting of (ICG/ITSU) was held in Honolulu on March 25-28, 1968. At that time the ICG had six member states included in the PTWS but only representatives of five of the member states were in attendance. The USA, Japan and the USSR – the countries that had existing regional tsunami warning systems – as well as Canada and Chile. The sixth member of the group, the United Kingdom, did not send representatives. Mr. John M. Klaasse (USA) was elected as Chair of the ICG/ITSU and Dr. George L. Pickard (Canada) was elected as Vice-Chair. As previously stated, the International Tsunami Information Center (ITIC) had been established prior to this first ICG/ITSU meeting and its main role was to serve as a focal point to provide liaison to Member States within the ITSU Group. As stated, the International Tsunami Information Center (ITIC) had been established prior to this first ICG/ITSU meeting and Cdr. Robert Munson, the Pacific Field Regional Director of the U.S. Coast and Geodetic Survey, was the first Director of the ITIC. The ITIC's role was to serve as a focal point and to provide liaison to Member States within the ITSU Group.

The purpose of this initial meeting was to discuss international aspects of the Tsunami Warning System and to report on current research regarding tsunamis. UNESCO/IOC was represented at the meeting, and the WMO, the IUGG and France also attended as observers. Subsequently since this initial meeting, both the WMO and IUGG became closely associated with the ICG/ITSU. The WMO had a similar mandate in collecting and analyzing meteorological data and disseminating forecasts and warnings to member states. Also, the IUGG has a mandate to research geological hazards including earthquakes and tsunamis. A set of 12 tsunami travel time charts was prepared for the TWS by researchers at the University of Hawaii. In time, this set of charts would expand to include 82 stations throughout the Pacific.

For more information see go to: http://itic.ioc-unesco.org/images/docs/SR_I_Honolulu_1968.pdf

3.6.2 IOC/ITSU-II – International Co-ordination Group for the Tsunami Warning System in the Pacific, Second Session, Vancouver, Canada, 12-14 May, 1970

The second meeting of ICG/ITSU was held from 12-14 May 1970 in Vancouver, Canada, in accordance with the 1965 recommendation for the Group to meet roughly every two years. At this second ICG/ITSU meeting, it was agreed that tsunami wave heights would be reported in centimeters and that the tidal stations in member states would report the time, tendency and height of the first rise or fall of the tsunami wave. It was also decided to conduct a communication test between the warning centers in Honolulu, Tokyo and Khabarovsk, and thereafter to carry out communication tests at least every three months.

The first communications test was held on September 16, 1970. The message was routed from Honolulu to Tokyo and then to Khabarovsk. An acknowledgement was then sent back along the same route. This first communication test took 70 minutes to complete – a very slow process by today's standards, but it was a considerable achievement at a time before computers, the internet and satellite communications. At subsequent meetings of the ICG/ITSU, the emphasis was on reporting the progress made by individual Member States and on making recommendations for improvements in coverage, instrumentation and communications.

It was recognized at this ITSU session that the network of tide gauges and seismic stations was slowly growing and during 1970, in response to an invitation from the IOC, Taiwan, Ecuador, France, New Zealand and the Philippines also joined as member-states of the ICG. The ITIC was further tasked with collecting and archiving analogue and digitized copies of all tsunami records obtained by Member States, as the Center was also designated as the World Data Center A – Tsunami. One of the ITIC functions as World Data Center A – Tsunami was to compile an Atlas of Tsunami Marigrams. When the World Data Center A- Tsunami was transferred to the U.S. National Geophysical Data Center in Colorado, the ITIC data files on tsunami marigrams and all unpublished compiled tsunami historical data for the Atlas were transferred to NGDC.

For more information see go to: http://itic.ioc-unesco.org/images/docs/SR_II_Vancouver_1970.pdf

3.6.3 IOC/ITSU-III – International Co-ordination Group for the Tsunami Warning System in the Pacific, Third Session, Tokyo, Japan, 8-12 May, 1972

The third meeting of the Group was held in Tokyo, Japan in 8-12, May 1972. Professor Pickard (Canada) acted as Chairman. Welcoming speeches were made by Dr. K. Takahashi, Director-General of the Japan Meteorological Agency, and Dr. K. Nishida, Director-General of the Japan National Committee for Unesco. Both underlined the importance of the work of the ICG/ITSU Group. On behalf of IOC, Mr. Tolkachev acted as rapporteur. Peru and Thailand joined the TWS in the Pacific. Delegates from Canada, Chile, Japan, Peru, United States, Philippines and the Union of Soviet Socialist Republics (USSR) presented reviews of national activities. The effectiveness of communication tests were discussed as well as progress made in tsunami research and in the installation of additional seismic and tidal gauge instrumentation in support of the TWS in the Pacific. The ITIC Director (Dr. Gaylord Miller at the time) reported on visiting scientists at PTWC, ITIC and JTRE and recommended continuation of a visiting scientist program. The IOC representative brought to the attention of the group the IOC resolution VII-28 on the “Tsunami Warning System” and emphasized the need for the preparation of educational materials to improve public tsunami preparedness in member countries.

For moreinformation go to: http://itic.ioc-unesco.org/images/docs/SR_II_Vancouver_1970.pdf

3.6.4 IOC/ITSU-IV/3 - International Co-ordination Group for the Tsunami Warning System in the Pacific, Fourth Session, New Zealand, 4-7 February 1974

The fourth session of ICG/ITSU was held in Wellington, New Zealand in 4-7 February 1974. By this time both Peru and Thailand had become members, and Fiji and Mexico attended as observers. However, only seven Member States attended the fourth meeting. There were Tsunami Warning System participants who were not yet ICG members, and there were some members who were not active participants, both ongoing challenges for the ICG officers and ITIC.

The Group continued to identify locations where additional tide stations and seismic stations were required and worked to secure the instruments required for these stations. The ITIC was a strong central focus of the Tsunami Warning System during this formative period. As previously agreed, ITIC provided technical advice, published a Newsletter, collected tsunami data and helped coordinate many of the TWS activities. At the recommendation of the Group, and the approval of the IOC, the position of ITIC Associate Director was created. This position was to be filled and funded by a

country other than the USA and was intended to make the ITIC more international. It was not until 1975 though that Mr. Sydney Wigen (Canada) became the first Associate Director, followed by Mr. Norman Ridgeway (New Zealand) in 1978. Chile has provided the Associate Director continuously since 1998.

For more information go to: http://itic.ioc-unesco.org/images/docs/SR_IV_Wellington_1974.pdf

3.6.5 IOC/ITSU-V/3 - International Co-ordination Group for the Tsunami Warning System in the Pacific, Fifth Session, Lima/Callao, Peru, 23-27 February 1976

The fifth meeting of the Group was held in Lima, Peru on 23-27 February 1976. Representatives from Canada, Chile, Ecuador France, Peru, Philippines, USA and USSR were present. China, Guatemala, Japan, Korea, New Zealand, Singapore and Thailand were not represented. Mexico sent an observer. The state of implementation of IOC resolutions and recommendations was discussed and representatives of Member States presented their national reports. The ITIC Director (George Pararas-Carayannis) reported on developments at the Center, on tsunami investigations during 1974-1976 and made recommendations for improvements of wave reporting procedures, in communications and on the use of geosynchronous satellites. Also, it was reported that the 8th Edition of the Communication Plan - a comprehensive document of 206 pages - had been released in September 1975.

The Group considered resolutions from other bodies relating to tsunamis, as from the Tsunami Committee of IUGG, from the UN General Assembly, from the United Nations Conference on Trade and Development (UNCTAD) and the Unesco Intergovernmental Conference on the Assessment and Mitigation of Earthquake Risk. The discussion centered on the further expansion of the Tsunami Warning System, improvements. Representatives of Colombia, Ecuador, Peru and Chile – with assistance from ITIC - informed of their decision to submit a proposal to UNDP for support of a regional project for establishment of the national warning systems.

Also, discussed was a pilot project on study of the damage caused by tsunamis on the western coast of South America, and on educational material to raise public awareness of the danger of tsunamis. The Group formulated 13 recommendations, which were adopted at the end of the session, together with the Summary Report (in English). On the last day of the meeting, the Group elected a new Chairman, Mr. G.C. Dohler, from Canada, in succession to Dr. S. Suyehiro (Japan). Leutenant C. Vargas Faucheux (Peru) was elected Vice-Chairman. The Secretary was invited to negotiate with the Government of the Philippines on the possibility of holding the next ITSU meeting in Manila, in early 1978.

For more information go to: http://itic.ioc-unesco.org/images/docs/SR_V_Lima_1976.pdf

3.6.6 IOC/ITSU-VI/3 - International Co-ordination Group for the Tsunami Warning System in the Pacific, Sixth Session, Manila, Philippines, 20-25 February 1978

At the sixth meeting of the Group held in February 1978 at Manila, Philippines 15 Member States attended and 11 Member State reports were submitted. Indonesia and Fiji attended the meeting as observers and soon after became Member States. At this meeting, Canada and the USA were asked to investigate the use of satellites in the TWS and to prepare a report for publication in the ITIC

Newsletter by January 1, 1979. Also at the sixth meeting, the ITIC was provided with a number of guidelines for the operation of the Center. These actions covered reports, communication plans, training and educational plans, cataloging the emergency evacuation plans of Member States, and creating a guide for post-tsunami surveys. An ongoing topic of discussion for both the ICG/ITSU and IOC was the ITIC and its functions. A new mandate and functions for the ITIC were approved by the IOC General Assembly in the fall of 1977.

The ITIC was also tasked to work with the PTWC to prepare a report defining the system of TWS water level gauges needed by the TWS to verify the existence of a tsunami within one hour after the time of generation. A review of PTWC earthquake logs for the period 1969-1978 showed that stations being queried, or available to be queried, could meet this one-hour criteria only 57% of the time. In some regions of the Pacific the percentage of TWS stations meeting the criteria was much less. This was not surprising, given the fact that water level instrumentation (much of it analog), communication networks, and semi-automated processes were not available up to that time.

For more information go to: http://itic.ioc-unesco.org/images/docs/SR_VI_Manila_1978.pdf

3.6.7 IOC/ITSU-VII/3 - International Co-ordination Group for the Tsunami Warning System in the Pacific, Seventh Session, Vina del Mar, Chile, 3-7 March 1980

The seventh session of the ICG/ITSU Group was held in Vina del Mar, Chile, from 3-7 March 1980. Representatives from Canada, Chile, Ecuador, Fiji, France, Indonesia, Peru and USA attended the session and presented national reports. WMO was also represented. The Director of ITIC presented a detailed report outlining the activities of the Center over the last two years and commented on the work of the previous Associate Directors, Mr. Wigen and Mr. Ridgway and that the lack of an Associate Director since June 1979 had an adverse effect.

By Resolution 1 at this session the ICG/ITSU Group decided to establish an ITSU Task Team on a Study of Tsunami Watch and Warning Procedures, and by Resolution 2, a Task Team on Regional Tsunami Warning Centrex. Recommendation 1 asked Member States to continue to make an effort to second an Associate Director to ITIC; Recommendation 2 asked the extra budgetary funding to improve the network; Recommendation 3 referred to tsunami research; Recommendation 4 asked Member States to strengthen their efforts to elaborate, improve and implement educational programmes; Recommendation 5 contained a proposed programme and budget for 1984/85, and

Recommendation 6 asked for post-tsunami surveys.

For more information go to: http://itic.ioc-unesco.org/images/docs/SR_VII_Chile_1980.pdf

3.6.8 ITSU-VIII/3 - International Co-ordination Group for the Tsunami Warning System in the Pacific, Eighth Session, Suva, Fiji, 13-17 April 1982

The 8th Session of the ICG/ITSU Group was held in Suva, Fiji on 13-17 April 1982. Minister Mr. Waqanivavalagi of Fiji extended a warm welcome and best wishes to the participants and further stated that the Session will give the opportunity to monitor, report on, co-ordinate, establish and plan improvements to tsunami warning systems. Mr. H. Plummer, Head of the Fiji Delegation, also gave a welcoming speech to participants. Representatives of member states presented the national reports. The Director of ITIC reported on the activities of the Center for the 1980-1982 period and noted the

highlights of the report, in particular, Tsunami Warning System on-going automation, new reporting stations, on the visiting scientist training program, on completed training exercises and workshop and on the preparation of a number of publications completed during the intercessional period.

For more information go to: http://itic.iocunesco.org/images/docs/ITSU_Summary_Report/itsuviii.pdf

3.6.9 ITSU- IX/3 – International Co-rdination Group for the Tsunami Warning System in the Pacific, Ninth Session, Honolulu, Hawaii, USA, 13-17 March 1984

The Ninth Session of the IOC International Coordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU) was opened by the Chairman, Mr. Gerry Dohler, on 13 March 1984. The session was attended by Mrs. Eileen Anderson, Mayor of Honolulu, Dr. Fujio Matsuda, President, University of Hawaii, Dr. Victor Hao Li, President, East-West Center, and the Assistant Secretary IOC, Dr. I. Oliounine and Mr. Richard H. Hagemeyer, Head of the U.S. Delegation - all of whom made introductory welcome comments and made reference to the importance of the objectives of the Session in establishing additional guidelines that would help improve tha Tsunami Warning System in the Pacific in reducing the the loss of life and property. The Director of ITIC, Dr. George Pararas-Carayannis, introduced a status report (DOC.IOC/ITSU-IX/7) on the activities of the Center during 1982-1983, mentioning the close cooperation with PTWC on communications tests, automation, regionalization of tsunami watch and warning messages, computer software development, communication problems of the TWS. contingency planning, and the monotoringof research for the purpose of finding wasy of improving the TWS. Additionally, his report provided a thorough review of on-going automation in the TWS with on-line processing of seismic data at PTWC, on tide gauge instrumentation. on satellite telemetry, on the destructive tsunami from the 26 May 1983 earthquake in the Sea of Japan, and on the "Tsunami Reports" series, the ITIC Newsletter, on materials, manuals and brochures made available to ITSU member states, and on providing IOC with guidelines for the selection of experts for the ITIC Visiting Scientists Program, as well as a program of their training. Finally the ITIC report provided information on the findings of the 18th General Assembly of the International Union of Geodesy and Geophysics.

Following this report, the Group was presented with national reports of countries participating in the TWS, on their on-going researcb and on measures taken for improvements. The Group agreed on the modification of the U.S. Communication Plan to formulate an International Communication Plan. Finally, the IOC representative proposed that a workshop be held at the 1985 meeting in Sidney, B.C., Canada and that ITIC should to draft a plan for such a workshop. At the end of the Session a number of recommendations were drafted and adopted and it was agreed to hold the Tenth Session in Sideny, B.C., Canada.

For more information go to: http://itic.ioc-unesco.org/images/docs/SR_IX_Honolulu_1984.pdf

3.6.10 ITSU-X/3 – International Co-rdination Group for the Tsunami Warning System in the Pacific, Tenth Session, Sidney, B.C., Canada, 1-3 August 1985.

The Tenth Session of the International Co-ordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU) was convened at the Institute of Ocean Sciences in Sidney, B.C., Canada on Wednesday 1 August 1985. It was chaired by Mr. Norman Ridgway of New Zealand, who also thanked the Canadian authorities for hosting the three-adat Workshop on the Technical Aspects of Tsunami Analyses, Prediction and Communications and commented on its findings and reccomendations. Dr. Cedric Mann, the Director General of the Institute welcomed the ITSU Group.

There were subsequent discussions on the interaction and coordination between ITIC and PTWC related to the automation efforts, improvements of communications, on data collection from three additional tide stations (La Libertad, Ecuador, Baltrais, Rabaul and New Britain), on the collection of data by ITIC and its coordination to assist the Tunami Hazard Reduction Utilizing Systems Technology (THRUST) pilot study and its implementation in Chile. The Director of ITIC, Dr. George Pararas-Carayannis reported that all Resolutions resulting from ITSU-IX had been completed. The resolutions involved: assisting an expert to develop a Master Plan for International Tsunami Warning Operations; determining member requirements for the production of additional travel time charts; determining changes to the existing Communications Plan; seeking funding ro the day to day operations of ITIC and providing a priority list of requirements to support ITIC activities using audio-visula materials, library updates, run-up surveys and printing. The Secretary IOC invited Mr. G. Dohler to present as Consultant to the Group the draft of the Master Plan for subsequent review and comments.

The IOC representative outlined progress made in finalizing the project proposal entitled " Regional Tsunami Warning System in South-east Asia", based in the findings and recommendations of the experts mission to the Phillipines, Papua-New Guinea and Indonesia – which were included for a proposal for submission to members states and UNDP's Fourth Cycle Programme for Asia and the Pacific. There was further reporting to the Group by Mr. Norman Ridgeway and Mr. G. Dohler on their respective missions to Colombia and Ecuador to investigate the existing tsunami warning systems.

For more information go to: http://itic.ioc-unesco.org/images/docs/SR_X_Sidney_1985.pdf

3.6.11 ITSU-XI/3 – International Co-rdination Group for the Tsunami Warning System in the Pacific Eleventh Session, Beijing, People's Republic of China, 8-12 September 1987.

The Director of ITIC, Dr. George Pararas-Carayannis chaired the Eleventh Session begioning on 8 September 1987 at the National Research Center on Marine Environment Forecasts (NRCMEF), thanking the Government of the People's Republic of China and particularly the Director-General of the State Oceanic Administration (SOA) and the Director of NRCMEF for hosting the Meeting and for their continuous support to the Tsunami Warning System. In his welcoming address, he emphasized that the intersessional period from August 1985 to September 1987 has been remarkable in terms of activities for the improvement of the Tsunami Warning System and which will result in further improvements. He then called on the Deputy Director-General of SOA, Mr. Yang Wenhe to address the Session, who extended a warm welcome to Member States of the ICG/ITSU and participants of the Session. He referred to the importance of tsunami studies and the mitigation for China and gave some examples of the loss of life and heavy destruction caused by tsunamis in his country.

After reporting on Intersessional activities and listening to National Reports, the Group reviewed the Master Plan for the International Tsunami Warning System in the Pacific, the status of Tsunami Travel-Time charts, of a Glossary of Tsunami Releted terms, of the Data baseline, of the Communication Plan and of the Guide on Wave Reporting Procedures – topics of resolutons and Recommendations of the Tenth Session. Additionally the Group reviewed: 1) the operational requiremcnts of th TWS; 2) the on-going cooperation with the IUGG Tsunami Commission and other international bodies involved in Tsunami Mitigation and Research; 3) the training and assistance in Tsunami Preparedness; 4) the mandate and functioning of ITIC; 5) Plans for the future. Subsequently the Group made recommendations for additional travel time charts, for the establishement of regional tsunmi warning centers in South East Asia, amended the Mandate of ITIC to coordinate matters with the Secretary of IOC on all policy issues, stated program priorities for 1988-1989, elected a Chairman and Vice-Chairman, adopted the Summary report and decided on the date and place of the next session to be held in Novosibirk, USSR in 1989.

For more information go to: http://itic.ioc-unesco.org/images/docs/SR_XI_Beijing_1987.pdf

3.6.12 ITSU-XII/3 – International Co-rdination Group for the Tsunami Warning System in the Pacific, Twelfth Session, Novosibirsk, USSR, 7-10 August 1989

The Chairman of the International Co-ordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU), Mr. R. H. Hagemeyer, opened the Twelfth Session on 7 August 1989, at the Computing Center of the Siberian Branch of the USSR Academy of Sciences, Novosibirsk (USSR). Dr. A. P. Metalnikov, head of the USSR delegation and Deputy Chairman of the State Committee for Hydrometeorology, welcomed the participants on behalf of Academician A.S.Aledseev, Director of the Computing Cetner of the Siberian Branch of the USSR Academy of Sciences. Dr. Tolkachev of IOC also welcomed the Group and introduced the Agenda which was adopted.

Subsequently, there was extensive discussion of intersessional activities followed by National Reports by Australia, Canada, Chile, China, Fiji, Guatemala, Hong Kong, Japan, Mexico, New

Zealand, United States of America, Republic of Korea and USSR. Dr. George Pararas-Carayannis, Director of ITIC, presented the Center's report on activities such as: 1) Tsunami investigations; 2) TWS Automation; 3) Regional Warning Systems; 4) New reporting stations; 5) Liaison activities; 6) ITSU membership; 7) Training and workshops; 8) Tsunami Travel Time Charts; 9) Visiting scientists' program; 10) Educational materials; 11) Jistorical tsunami database; and 12) ITIC sponsorship of scientific symposia and conferences. Dr. George Pararas-Carayannis and Dr. K. Kitazawa discussed the need for development of a regional Tsunami Warning System in the Southwest Pacific and the mission underataken in May 1989 to the Philippines, Indonesia, Vanuatu, Solomon Islands, Thailand and Papua-New Guinea, supported by UNDP in New York. The Director of ITIC reported of the Five Year Master Plan which was provided to the IOC for submission to UNDP for funding the development of a regional TWS. All these items were discussed extensively and commented on by the Group.

There was subsequent discussion of the Tsunami Travel Time Charts, the Glossary of tsunami terms, the database format, the communication plan, the tsunami brochure and of cooperation with international bodies. The Director of ITIC reported on particiapation in the Third International Conference on Natural and Man-Made hazards, which was sponsored by ITIC and the Tsunami Society in San Diego (Scripps Institution of Oceanography) amd in Ensenada, Mexico (at CICESE) and the establishement of a Society on Natural Hazards (incorporated in Hawaii).

For more information go to: http://itic.ioc-unesco.org/images/docs/SR_XII_Novosibirsk_1989.pdf

3.6.13 ITSU-XIII/3 – International Co-rdination Group for the Tsunami Warning System in the Pacific, Thirteenth Session, Ensenada, Baja California, Mexico, 10-13 September 1991

The Chairman, Mr. R. Hagemeyer, opened the Thirteenth Session of the IOC International Co-ordination Group for the Tsunami Warning System in the Pacific on 10 September 1991 at the Centro de Investigacion Cientifica y Educacion Superior (CICESE) facility in Ensenada, Mexico. He proposed mechanisms and procedures for making the Tsunami Warning System in the Pacific more effective. Dr. Mario Martinez Garcia, Director), and Dr. I. Oliounine, Senior Assistant Secretary IOC, welcomed the participants - the latter calling on the Group to make decisions which may establish a workable strategy to guide the IOC's own direct activities in the tsunami warning system. The Group reviewed the intersessional activities and discussed the starus of implementation of resolutions and recommendations of the 12th Session of the ICG/ITSU. Specifically discussed were th contributions of ICG/ITSU to IDNDR, the Tsunami Inundation Modelling Exchange Project (TIME), the Tsunami Public Education and Awareness Programme, the usage of personal computers fpr Tsunami travel time calculations, the extension of these-level networks in the Pacific by using data collection platform technology, the promotion of International Pacific-wide cooperation in seismology and tsunami preparedness, the implemantation of the provision of the ITSU Master Plan, support of ITIC, the training, education and mutual assistance, and proceeded with election of Cheiarman and Vice-Chairman of the ICG/ITSU, and the Programme Budget for 1992-1993.

For more information see go to: http://itic.ioc-unesco.org/images/docs/SR_XIII_Baja_1991.pdf

3.7 National Oceanic and Atmospheric Administration (NOAA)

In October 1970, the USC&GS underwent several more organizational changes and became part of the National Oceanic and Atmospheric Administration (NOAA) of the United States Department of Commerce. There was additional reorganization and the ESSA Corps became the NOAA Commissioned Corps ("NOAA Corps"), the operation of ships was transferred to the new NOAA fleet, the geodetic responsibilities were placed under the new National Geodetic Survey. The duties for hydrographic surveys came under the jurisdiction of NOAA's new Office of Coast Survey. However, regardless of the organizational changes, personnel involved with the Tsunami Warning Program, continued to work under the new jurisdictions on operations, management and tsunami research projects related to improvements of the International Tsunami Warning System and by participating in joint work with JTRE/JIMAR, PTWC, ITIC, the University of Hawaii and with other governmental organizations and academic institutions.

3.8 Pacific Tsunami Warning Center (PTWC)

As previously mentioned, the early U.S. Tsunami Warning System was established in 1948 in response to the 1 April 1946 tsunami from the Aleutian Islands. However, the official tsunami warning capability in the U.S.A. began in 1949 when the Honolulu Geomagnetic Observatory at Ewa Beach was renamed as the Tsunami Warning Center and designated as headquarters of the newly established U.S. Tsunami Warning System. PTWC issued tsunami warnings to Alaska until 1967, when the West Coast & Alaska Tsunami Warning Center (WCATWC) was established, in response to the 1964 Alaskan earthquake and tsunami.

In 1968, following the first meeting of the Intergovernmental Coordination Group for the Pacific Tsunami Warning System, the Hawaii facility became the operational headquarters for the Pacific Tsunami Warning System and was renamed as the Pacific Tsunami Warning Center (PTWC). Following the 1975 Kalapana earthquake and tsunami on Hawai‘i's Big Island, PTWC began issuing also official tsunami warnings to the state of Hawai‘i for local earthquakes.

In 1982, when WCATWC’s area of responsibility was enlarged to include issuing tsunami warnings to California, Oregon, Washington and British Columbia for potential tsunamigenic earthquakes occurring in their coastal areas, PTWC continued to issue tsunami warnings to these areas for Pacific-wide tsunamigenic sources until 1996, when that responsibility was also given to the WCATWC. On 1 December 2001, PTWC was re-dedicated as the "Richard H. Hagemeyer Pacific Tsunami Warning Center", in honor of the former U.S. Tsunami Program Manager and National Weather Service Pacific Region Director.

Fig. 11 Scientists at work at the Pacific Tsunami Warning Center.

Finally, in the aftermath of the 2004 Indian Ocean tsunami, PTWC took on additional areas of responsibility in 2005, including the Indian Ocean, South China Sea, Caribbean Sea, and Puerto Rico & U.S. Virgin Islands. To compensate for the added responsibility, PTWC's staff size increased from 8 to 15. However, in June 2007 the area of responsibility for issuing local tsunami warnings to Puerto Rico and the U.S. Virgin Islands passed to NTWC.

3.9 Alaska Tsunami Warning Center (ATWC)

In response to the 27 March 1964 great Alaska earthquake and with funding allocated in 1965 by the U.S. Congress, the U.S. Coast and Geodetic Survey (USC&GS) completed in 1967 the construction of Palmer Observatory, in Alaska for the purpose of providing timely and effective tsunami warnings and earthquake information in the state. A second observatory was also constructed at the U.S. Naval Station on Adak Island in the Andreanof Islands in the Central Aleutians. In the summer of 1967, both facilities were instrumented and functional and the Palmer Observatory became the operational headquarters of the Alaska Regional Tsunami Warning System (ARTWS) - which also included the Adak and Sitka seismic observatories. Because of the great geographical extent of Alaska and the Aleutian Islands, the responsibility for issuing tsunami warnings for Adak and Sitka were limited to events occurring within a radius of 300 miles of their location. In subsequent years the Palmer Observatory assumed full responsibility for providing tsunami-warning services for the entire state of Alaska and by the early 1990s both the Sitka and Adak Observatories were closed, but the seismic instrumentation is still maintained.

Subsequent organizational changes in 1973 transferred the Palmer Observatory to the National Weather Services Alaska Region and its name was changed to Alaska Tsunami Warning Center (ATWC). Further changes in 1982, extended the ATWC area of responsibility (AOR) to include the issuance of warnings to California, Oregon, Washington and British Columbia for potential tsunamigenic earthquakes in their coastal areas. The responsibility of ATWC was further expanded in 1996 to include all Pacific-wide potential tsunamigenic sources that could affect California, Oregon, Washington, British Columbia and Alaska coasts and - as stated previously - the name was changed to the West Coast/Alaska Tsunami Warning Center (WCATWC) to reflect the new responsibilities. The facility was further improved in 2003 and a new Tsunami Warning Center building was constructed to house upgraded power and communications equipment and offices for the expanded staff. Finally, following the disastrous Indian Ocean tsunami, in late 2004 the NTWC expanded its range of responsibility to the U.S. Atlantic and Gulf of Mexico coasts, Puerto Rico, the Virgin Islands, and the Atlantic coast of Canada. More recently in October 2013, the West Coast and Alaska Tsunami Warning Center became the National Tsunami Warning Center (NTWC). As will be explained in a subsequent section, scientists at NTWC, cooperating with researchers at University of Alaska and several other institutions, conducted important applied and theoretical research on tsunami scattering and coastal wave amplification.

3.10 NOAA's National Geophysical Data Center (NGDC) - World Data Center A – Tsunami

As previously stated, the 1965 international meeting resulted in the formation of the Pacific Tsunami Warning System and of the International Tsunami Information Center – the latter also designated as the World Data Center A – Tsunami. With this added responsibility, ITIC begun collecting historical data on tsunamis, compiling an Atlas of Tsunami Marigrams and event reports (Pararas-Carayannis, 1967, 1968). When the World Data Center A-Tsunami was subsequently transferred from ITIC to the National Geophysical Data Center (NGDC) in Boulder, Colorado, all the historical tsunami data, photograph files, tsunami reports and tsunami marigrams - in both analog and digitized form - were transferred to the new World Data Center A-Tsunami. Subsequently, there was close cooperation with Jim Lander and John Calebaugh and others in the documentation of historic tsunamis and of tsunami marigrams. Some of the earlier historical tsunami catalogs published as HIG reports, were updated, revised and published as WDC-A reports (Cox et al., 1976; Pararas-Carayannis, & Calebaugh, 1977). The role of NGDC expanded further over the years to provide products, and services for a variety of geophysical data, including Earth observations from space. NGDC has been active in many programs offering scientists around the world access to global databases through international exchange. Its contributions have been outstanding.

3.11 Joint Institute for Marine and Atmospheric Research (JIMAR) at the University of Hawaii integration with the Joint Tsunami Research Effort (JTRE) and with other Cooperative Institute Joint Research Programs in the USA

The Joint Institute for Marine and Atmospheric Research (JIMAR) was created in 1977 under the joint sponsorship of NOAA's Office of Oceanic and Atmospheric (OAR) and the University of Hawaii as an oceanic, atmospheric, and geophysical research institute. The earlier cooperative association of NOAA's predecessor agencies with the University of Hawaii known as Joint Tsunami Research Effort (JTRE) - which had a very active tsunami research program - were integrated into JIMAR.

With the passing of Gaylord Miller and the recruitment of Charles Helsley as the second Director of HIG at the University of Hawaii, a series of discussions about the future of JTRE, took place. Since it had been years since a Pacific-wide tsunami had occurred, a proposal had been made to close JTRE down. This coincided with a move by NOAA to expand their Cooperative Institute Programs. The Boulder CI (CIRES) had already been established in 1967. Thus NOAA developed new CIs at Seattle (JISAO), at Miami (CIMAS) and at Norman (CIMMS). In Hawaii, JIMAR was created and a Memorandum of Understanding (MOU) was signed in September 1977. JIMAR base tsunami funds came from the Pacific Marine Laboratory (PMEL) and EPOCS (Equatorial Pacific Ocean Climate Study). Thus, the JTRE staff was then incorporated within JIMAR and the new CI had the following three initial research themes:

1. tsunamis and other long-period ocean waves,

2. equatorial oceanography (reflecting the new JIMAR Director, Dennis Moore's interests)

3. climate.

Gradually the tsunami effort in Hawaii shrank. The NOAA support for the staff decreased and individuals moved to other UH departments (e.g., Loomis), or away from the UH program (Spielvogel). By the late 1970's, the University tsunami program was down to George Curtis (who later retired but became Associate Professor of the Hilo campus of the University) and Charles Mader who continued to participate from the U.S. Los Alamos Laboratory. Subsequently, JIMAR supported a small tsunami effort, with Gerard Fryer, Vindell Hsu and Barbara Keating and with small support for graduate students (jointly with Sea Grant). During the 1980s, University of Hawaii alumni Walt Dudley joined the University of Hawaii at Hilo and wrote an account of Tsunami Inundations on Hawaii and established the Tsunami Museum.

In the 1990s Dan Walker, Chip McCreery, Gerard Fryer, Vindell Hsu and Barbara Keating (all in HIG), and Cheung, Michelle Teng, Brandis (in Engineering) continued the tsunami research program in Hawaii, but funding was inadequate. No major Pacific-wide tsunami had occurred and thus interest in financing tsunami research was dwindling.

Subsequently Gerard Fryer and Vindell Hsu moved from the University of Hawaii to the Pacific Tsunami Warning Center at Ewa Beach. Much of the subsequent work formerly done via JIMAR was continued either at the Pacific Disaster Center or at the University of Hawaii's Department of Engineering (through the U.S. National Tsunami Mitigation Project).

3.12 The Pacific Marine Laboratory of NOAA (PMEL) – Tsunami Research Program

NOAA's Pacific Marine Environmental Laboratory (PMEL) was established in the 1970s as a federal laboratory with the responsibility of making critical observations and conducting research in order to advance knowledge of the global ocean and its interactions with the earth, atmosphere, ecosystems and climate. PMEL's mission was and continues to be: a) the observation, analysis and prediction of oceanic and atmospheric phenomena; b) the development and deployment of innovative technologies; c) the identification and understanding of ocean-related issues of major consequence, and d) informing society with well-documented, high quality science. Since its establishment, key research areas at PMEL included ocean acidification, tsunami detection and forecasting, hydrothermal vent systems, fisheries oceanography and long term climate monitoring and analysis. PMEL's functions increased over the years and now it is a federal laboratory made up of more than 200 scientists, engineers, administrative and IT professionals. PMEL is located in Seattle, Washington with a satellite campus in Newport, Oregon. Major contributions of PMEL to tsunami research in support of the International Tsunami Warning System, include improvements in measurement technology, optimal tsunami monitoring networks, improved models for increased speed and accuracy of operational tsunami and warnings and improved methods for predicting tsunami impacts on coastal communities and infrastructure.

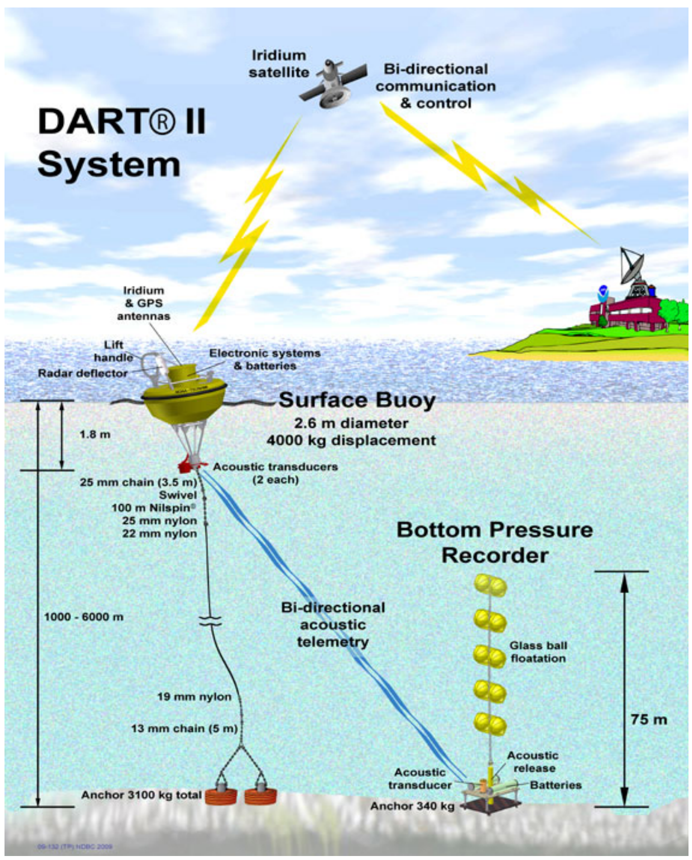

Fig. 12 DART Deep Water Gauge

Tsunami Forecasting – In summary, PMEL played an important role over the years in providing emergency managers and other officials with operational tools for more accurate tsunami forecasts as guidance for rapid, critical decisions in which lives and property are at stake. The more timely and precise the warnings are, the more effective actions can local emergency managers take and the more lives and property can be saved. One of the major contributions of PMEL was and still is the development of the DART platforms for real-time tsunami monitoring systems, positioned at strategic locations throughout the oceans for the purpose of tsunami forecasting.

3.13 The School of Ocean and Earth Science and Technology (SOEST) at the University of Hawaii

There were further changes at the University of Hawaii, which affected the on-going U.S. tsunami research program over the years. In 1988, the School of Ocean and Earth Science and Technology (SOEST) was established at the University of Hawaii's Manoa Campus in Honolulu and JIMAR became part of SOEST. The new School "SOEST" comprised of four academic departments (Geology and Geophysics, Oceanography, Meteorology and Ocean and Resources Engineering) and numerous research institutes, centers and programs. Researchers at SOEST became engaged in Ocean, Earth, and Space science and addressed issues of societal importance, including coastal and natural hazards, natural energy and climate change. A few of the remaining tsunami researchers at the University of Hawaii continued to work on tsunami research projects in close cooperation with PTWC, ITIC and PMEL in Seattle.

3.14 Tsunami Society – Tsunami Society International

In 1982, William Adams, Augustine Furumoto and George Pararas-Carayannis organized and incorporated "The Tsunami Society" in Hawaii, as a professional Society and as a focal organization promoting research and supporting efforts to increase and disseminate knowledge about tsunamis and their hazards. Since the early 1960s the organizers were associated with the initial HIG tsunami research program at the University of Hawaii, with JTRE and with ITIC, and recognized the need for a professional society and a journal devoted exclusively to tsunami hazards. Since its establishment to the present day, the Tsunami Society has continued to promote the awareness and mitigation of tsunami hazards by sponsorship workshops, meetings and symposia, and by the dissemination of knowledge about tsunamis to scientists, officials, the media and the public through the uninterrupted publication of its journal known as "Science of Tsunami Hazards", a home page on the Internet, training exercises, symposiums and other venues. Thus the Society has provided over the years a focus for discussion and interactions among its members, government agencies and the public. The primary objective for the last four decades has always been to mitigate the adverse impact of tsunamis on humanity and to support Tsunami Warning Systems.

Also, in recent years - and because of its expanded role - the organization was renamed "Tsunami Society International" (TSI), to further encourage collaborative, multidisciplinary research related to the tsunami hazards for the purpose of promoting education, training, public awareness and implementation of early warning systems that can save lives around the world and safeguard property. More specifically - and particularly after the tragic (2004) Tsunami Disaster in the Indian Ocean - TSI continued to promote the concept that tsunamis have a common adverse impact that transcends national boundaries and interests and, therefore, encourages regional and international cooperation for research, education and preparedness.

Additionally, TSI: a) promotes the setting up of facilities required for the undertaking of research on tsunamis, based on a holistic approach that combines theoretical and applied sciences and mathematics, as well as social sciences, to the understanding of the tsunami phenomenon; b) promotes the mitigation of the adverse impact of tsunamis on humanity through the implementation and establishment of effective, early warning systems and through programs of education and preparedness; c) co-operates with other international scientific organizations, governments, foundations, industries, academic institutions and other professional groups concerned with the hazards of tsunamis; d) acts as a focal point in assisting coordination between research institutions and universities around the world promoting programs of theoretical and applied tsunami research; e) supports the organization of training programs, symposiums, workshops, seminars and other meetings to study topics of interest related to tsunami studies and preparedness; f) conducts international Tsunami Symposiums; and g) Assists governmental and private organizations with the establishment of appropriate liaison mechanisms.

TSI makes all of its publications available readily to the international scientific community and to the general public by maintaining an OPEN ACESS journal (SCIENCE OF TSUNAMI HAZARDS) and by distributing it free of charge, globally. Finally, to assure high quality standards of publication, all papers submitted to the Science of Tsunami Hazards Journal receive a thorough "peer-review" by an Editorial Board and other senior scholars with specific multidisciplinary expertise. The archived published papers in the Society's journal include a wealth of data, research results and references on tsunamis that does not exist anywhere else.

3.14.1 Tsunami Society's Support of the Tsunami Warning Systems through Dissemination of knowledge, Promotion of Awareness and Mitigation of Tsunami Hazards

In 1981, William (Bill) Adams, Augustine (Gus) Furumoto and George Pararas-Carayannis founded the “Tsunami Society” as a professional scientific organization which was incorporated and registered under an eleemosynary status in the State of Hawaii. The Society begun publishing the International Journal "SCIENCE OF TSUNAMI HAZARDS" (STH) – with papers of ongoing tsunami research of the 1980s and 1990s - thus playing a key role in documenting earlier tsunami research projects in the U.S. and internationally. Bill Adams served as the first president of the Society and other scientists at the University of Hawaii, PTWC and ITIC served as officers. As editor of the journal for several years, Charles Mader organized and archived at the Library of the U.S. Los Alamos National Laboratory, all earlier issues pertaining to published papers on tsunami research in the USA and internationally. In later years, Barbara Keating served as President of Tsunami Society, George Pararas-Carayannis as Vice-President, Gerard Fryer as Secretary and Vindell Hsu as Treasurer. In the late 90s and in the new millennium, with help from the State of Hawaii, the University of Hawaii and the elected officers, the Society organized and held three Symposiums at the East-West Center in Honolulu.

In 2008, when Barbara Keating retired from the University of Hawaii, George Pararas-Carayannis became President of Tsunami Society and also succeeded Charles Mader as Editor of the STH journal. In subsequent years, as global membership increased, the now renamed “Tsunami Society International” (TSI) organized three more successful symposiums in 2010 in Toronto, Canada, in 2012 in Ispra, Italy and in 2014 in Costa Rica and held workshops in China, Ukraine, Malta, Ecuador, Hong Kong, Thailand, Saudi Arabia and Italy.

As of 2015, the TSI’s STH journal, is in its 34th year of continuous and uninterrupted publication since 1982, and remains the only journal devoted exclusively to multidisciplinary papers on tsunami hazards. STH has been certified as an OPEN ACCESS Journal included now in the prestigious international academic journal database DOAJ, which is maintained by the University of Lund in Sweden with the support of the European Union. The journal “is also preserved and archived at the National Library, The Hague, Netherlands and at the U.S. Library of Congress, in Washington D.C., USA. As already mentioned, older issues of STH have been archived at the US Los Alamos Laboratory Library but can also be downloaded from a the Society’s website http://tsunamisociety.org

In addition to the DOAJ database, STH is also included in the EBSCO, ELSEVIER and SPRINGER publishing databases, which give the journal additional global exposure and readership in 90% of the academic institutions worldwide, including nation-wide access to databases in more than 70 countries. Furthermore, TSI participates with DOAJ, the University of Lund in Sweden, the European Library at the Hague and European research libraries to help digitize all past STH articles, so they can be searchable online with the submission of metadata and thus increase, even more, the visibility and usage of past and recent articles included in the Journal.

Finally, with the help of its journal and the organization of Symposiums, TSI provides also a focus for discussion and interactions among its members, government agencies and the public – throughout the world. STH is peer-reviewed and the only journal in the world dealing exclusively with tsunami-related research - combining high qualitative and quantitative standards of content, as well as international diversity of authorship and citations. Thus, STH is well regarded for its uniqueness and depth of coverage and enjoys worldwide popularity. Published on a regular basis, the STH journal is the most appropriate resource for worldwide readership of scientific papers on tsunami hazards and for anyone working on tsunami-related research projects. Through the above-described efforts, the STH has established a very good and long track record and is indexed by the most reputable indexing service of Thomson/Reuters. As of 2013, the journal’s SJR (a measure of a journal impact) was medium (0.29), which is higher than some other reputable journals in the similar field of disasters in the world.

3.15 U. S. Army - Coastal Engineering Research Center (CERC)

The U.S. Army Coastal Engineering Research Center (CERC) was established in 1963 in Washington D.C. to replace the Beach Erosion Board and to handle its Corps of Engineers research mission. Since Its establishment in 1963, CERC has conducted research on shore protection through extensive studies of waves, storm surges, tsunamis, currents, water levels and ocean bathymetry. A part of this work involved engineering works for the protection from storm surges and tsunamis, so the Center got involved as well with the tsunami and storm safety of nuclear power plants and other critical facilities along the coast. Scientists from CERC (i.e. Harris Stewart and Orville Magoon) worked closely in the past with HIG and JTRE researchers. George Pararas-Carayannis, before returning to ITIC in 1974, worked as oceanographer for the U.S, Army Corps of Engineers New York District and subsequently at CERC in Washington DC, where he participated in a task force reporting to the President's Council on Environmental Quality (CEQ) on nuclear power plant safety (Pararas-Carayannis, 1973). Also, under contracts with the U.S. Nuclear Regulatory Agency, he worked on numerical modeling and on other studies related to the safety of nuclear power plants in California and in Florida (Pararas-Carayannis, 1975). Finally, as member of the American Nuclear Society he contributed to the writing of the proposed American National Standard - Aquatic Ecological Survey Guidelines, for the sitting, design, construction and operation of thermal power plants (Pararas-Carayannis G., 1979).

In 1983 CERC moved from Washington D.C. to the Waterways Experiment Station (WES) in Vicksburg, Mississippi. There was also close cooperation of researchers at the University of Hawaii and at ITIC with the U.S. Army Waterways Experiment Station scientists (Robert Whalin and others) to extend historical tsunami investigations in the Islands of Samoa.

3.16 U.S. Atomic Energy Commission (AEC) – Nuclear Regulatory Agency (NRC).

The Atomic Energy Act of 1946 dealt with nuclear regulation in the U.S.A. and assigned the responsibility for regulation to the U.S. Atomic Energy Commission (AEC). In 1954 the U.S. Congress passed the Atomic Energy Act for the purpose of regulating the development of commercial nuclear power and directed the AEC to establish regulatory programs, which ensured public health and safety from the hazards of nuclear power. The AEC's regulatory programs had come under strong attack, so the US Congress decided to abolish the agency and passed "The Energy Reorganization Act of 1974", which created the Nuclear Regulatory Commission (NRC). As the number of plants being built and the size of those plants rapidly increased during the late 1960s and early 1970s, reactor safety became a hotly disputed and enormously complex public policy issue. Proper sitting of nuclear power plants needed extensive assessment of all hazards, including earthquakes hurricane surges and tsunamis. NRC worked closely with ITIC, CERC and other organizations, to assess the potential hazards at each nuclear station site.

3.17 U. S. Geological Survey (USGS)

The United States Geological Survey (USGS) is a scientific bureau within the U.S. Department of Interior with major science disciplines, concerning biology, geography and hydrology. USGS scientists study extensively the U.S. landscape, the country's natural resources and global natural hazards such as earthquakes and tsunamis. The USGS headquarters are in Reston Virginia with major branches near Lakewood, Colorado, at the Denver Federal Center and at Menlo Park in California. Over the years the bureau has added additional responsibilities to its operations, including an Earthquake Hazards Program administered by the National Earthquake Information Center (NEIC) at the Golden, Colorado School of

Mines. NEIC monitors globally earthquake epicenters and magnitudes and has worked closely with ITIC and the tsunami warning centers in exchanging or supplying additional data in support of the Tsunami Warning System. The USGS also runs or supports several regional monitoring networks in the United States under its program of Advanced National Seismic System (ANSS). USGS informs authorities, emergency responders, the media and the public - both domestic and worldwide - about significant earthquakes and maintains archives of earthquake data for scientific and engineering research. USGS operates also several volcanic observatories – including one in Hawaii – and as of 2005, it has been working on establishing a National Volcano Early Warning System to improve the instrumentation monitoring the 169 volcanoes in U.S. territory and by establishing methods for measuring the relative threats posed at each site.

Throughout the years, USGS scientists cooperated closely with counterparts at the University of Hawaii, JTRE, PTWC, ATWC, ITIC, JIMAR and SOEST among others, in investigations of major earthquakes and landslides which generated tsunamis in 1958 in Lituya Bay, Alaska, in Chile in 1960, in Alaska in 1964, and in many other regions around the world.

3.18 Miscellaneous U.S. Government, Academic Institutions and Private Firms

Cooperating tsunami researchers at government and academic institutions in the U.S.A. included among others, Charles Mader at the U.S. Los Alamos Laboratory, George Carrier at Harvard University, Francis Shepard, Walter Munk, Frank Snodgrass and Bill Van Dorn at Scripps Institution of Oceanography, William Berninghausen of the US Navy Hydrographic Office, Frank Press and Robert Wiegel at U.C. Berkeley. There was also close cooperation with scientists at Tetra-Tech and Bechtel Corporation. There was also close cooperation with tsunami research scientists in Japan, USSR and other countries.

In support of the Tsunami Warning System, Frank Snodgrass at the Scripps Institution of Oceanography, developed a precision tide gauge which used vibrating wire pressure transducers which could provide sea level measurements to the nearest one-tenth millimeter (Snodgrass, 1972) – a sensitivity which improved similar to the deep sea vibroton instrumentation which had been developed almost a decade earlier by Martin Vitousek at HIG/JTRE at the University of Hawaii and used for a local tsunami warning system in Hawaii. These developments eventually were used for the deep-ocean DART gauges.

3.19 International Agencies and Academic Institutions

Many other visiting scientists or graduate students from Japan, China and other countries got also involved in tsunami-related projects at HIG. Prominent scientists from as far away as Alaska, other U.S. States and countries in Europe, Asia, Australia, Oceania and Central and South America, joined in this effort. Visiting international scientists cooperating with researchers in Hawaii in the 1960s and in the 1970s included among others: Kumizi Iida (Japan), Motoyasu Miyata (China), Tad Murty (Canada), Sergey Soloviev (Russia), Syd Wigen (Canada), Slava Gusiakov (Russia), Norman Ridgeway (New Zealand), Jaques Talandier (France) and many others. Under the sponsorship of ICG/ITSU with support from member nations and from the Intergovernmental Oceanographic Commission, training programs were initiated and conducted by ITIC and PTWC for visiting scientists, in support of the International Tsunami Warning System and of regional tsunami warning systems and on tsunami preparedness.

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