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QUANTITATIVE STUDIES ABOUT TSUNAMI GENERATION AND PROPAGATION WAVES BY A STOCHASTIC SUBMARINE SLUMP AND LANDSLIDE SOURCE MODEL

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ABSTRACT

Tsunami generation and propagation due to a vertical time-dependent extent of a stochastic submarine slump and landslide model for different values of Froude number and noise intensity are investigated. The critical parameters controlling the oscillations and the amplitude of the free surface elevation are through the Froude number and the noise intensity induced by the stochastic submarine slump and landslide source model. Quantitative information about the tsunami generation and propagation waves will be provided by estimating the evolution of the displaced water volume, the potential, kinetic and total energy of the resulting waves and the averaged tsunami velocity components at different Froude numbers. The inclusion of the random noise of the submarine slump and landslide deformation provided an additional and a noticeable contribution to the quantitative characteristics of the free surface elevation.

Keywords: Tsunami waves, tsunami energy, velocity flow rate, water displacement, submarine slump and landslide, stochastic process.

1. INTRODUCTION

Tsunami waves generated by submarine landslides may be triggered by earthquakes, by volcanic eruptions, by storm waves, or may be initiated by gravitational loading and instability, and are particularly devastating in the near-field region, producing locally extremely large amplitude waves and run-up for coastal communities (Jiang, L. and LeBlond, 1992, 1994).

Submarine landslides might be locally much stronger and ravaging than the earthquake-induced waves producing major potential hazard, offering little time for warning due to their proximity to shore. Any type of geophysical mass flow events which encompasses a wide range of ground movement such as debris flows, debris avalanches, rock and soil falls can create submarine landslides which generate tsunamis (Yavari-Ramshe and Ataie-Ashtiani, 2016). Catastrophic tsunami events due to submarine landslides such as the Flores Island 1992(Imamura et al., 1995; Bardet et al., 2003), Storegga Slide (Harbitz 1992; Bondevik et al. 2005), Papua New.Guinea 1998 (Synolakis et al., 2002, Tappin et al., 2008), the tsunami in Izmit Bay (Turkey) of 17 August 1999 (Watts et al., 2005), the tsunami in Fatu Hiva, Marquesas islands, French Polynesia, of 13 September 1999 (Okal et al., 2002), the Stromboli tsunami of 30 December 2002 (Tinti et al., 2006), the possible landslide tsunami of 7 May 2007 in the Black Sea (Ranguelov et al., 2008), and the largest known tsunami event in Lituya Bay, Alaska of 9 July 1958 (Fritz et al., 2009), caused widespread damage and loss of life and hence have significantly increased an interest in studying landslide generated tsunamis.

A sudden upward or downward motion of a portion of the ocean floor will displace a large amount of water and generate a tsunami. A tsunami source of energy can be described by the water displacement event. It has been long known that large landslides can displace significant volumes of water and thus cause locally large tsunami waves. Fritz et al. (2003) discussed the landslide impact induced water displacement volume and concluded that the maximum crater volume, which corresponds to the water displacement volume, exceeded the landslide volume by up to an order of magnitude. Ruff (2003) stated that for landslides, the best way for measuring the displaced water volume is through the total material volume, or total distance traveled, or some combination of these two parameters. Satake and Tanioka (2003) computed the displaced water volume from different source models and compared with the displaced water volume at 1998 Papua New Guinea earthquake. They concluded that the far-field tsunami amplitudes are proportional to the displaced water volume at the source, while the near-field tsunami surface elevations are determined by the potential energy of the displaced water. Hassan et al. (2010) studied the maximum tsunami amplitudes for different lengths and widths of a submarine slump and slide source model and concluded that the amplification of the waveforms depends on the volume of the displaced water by the moving submarine landslide which became an important factor in the modeling of the tsunami generation.

Ocean bottoms are indeed far from being flat and smooth. The presence of fluctuations in the sources of tsunamis can cause unexpectedly strong fluctuations in the wave height of tsunamis, with maxima several times higher than the average wave height (Degueldre et al. 2016). The complexity of the geologic processes responsible for the depth profile of the ocean floor makes it natural to describe the bathymetry as a correlated random medium. The best way to show their aspects is through heterogeneous or stochastic source models. Numerous studies have been conducted to describe the entire process of tsunami events generated caused by submarine earthquakes, taken into account the random components of bottom deformation in tsunami simulation, see Geist (2002, 2005, 2013, 2016); Omar et al., (2012, 2014, 2016);

Ramadan (2014); Allam et al. (2014); Fukutani et al. (2015); Ruiz et al. (2015) and Ramadan et al. (2017), and by random components of submarine landslides, see Dutykh et al. (2013); Dias et al. (2014) and Ramadan et al. (2014, 2015).

Forecasting tsunami events and providing timely evacuation warnings to communities is one of the most effective ways to reduce the loss of human lives and the damage to communities. The total energy transmitted by tsunami waves is one of the most fundamental quantities for quick estimation of the potential impact of a tsunami (Bernard and Titov 2015). The energy release is probably the best relative measure of earthquake and landslide size. Numerous studies have been examined the energy transmitted by the tsunami waves caused by underwater earthquakes (see, Dutykh et al. 2012, Tang et al. 2012, Jamin et al. 2015, Ramadan et al. 2017). During submarine mass movements, energy is invested in the displacement of the surrounding water. This might lead to the initiation of a series of tsunami waves that propagate towards the coast. Tinti and Bortolucci (2000) analyzed energy transmission from a submarine landslide to a water body using 1D and 2D shallow-water wave models. Dutykh and Dias (2009) investigated the energy of waves generated by bottom motion in the framework of the nonlinear SWEs, for both dispersive and non-dispersive waves and in the framework of the dispersive linearized equations. Zhao et al. (2012) obtained the energy transformation over a uniform sloping beach in terms of the reconstruction of the full velocity field by Boussinesq equations. Ma et al. (2015) conducted a wave energy analysis to investigate how the deformable landslide transfers energy to the surface waves and illustrated the potential and kinetic energies of the impulse wave generation for granular landslide motion. López-Venegas et al. (2015) studied the total energy of the water induced by the submarine landslide in the system (3D–2D coupled models). They concluded that most of the wave energy is isolated in the wave generation region, particularly at depths near the landslide. Whittaker et al. (2015) studied experimentally the effect of the submarine landslide Froude number on the potential energy time series within the wave field. McFall and Fritz (2016) measured the wave train energy, generated by a gravel landslide on planar and convex conical hill slopes.

The tsunami flow velocity is a significant physical parameter to understand tsunami behaviors. To measure, predict, and compute tsunami flow velocities is of importance in risk assessment and hazard mitigation which may provide a clear signal of tsunami flows, where the arrival of the tsunami is indicated by the commencement of distinctive current velocity oscillations (Lipa et al. 2012). This enables us to visualize the tsunami generation process, including the velocity components. Several studies have inferred current velocities from analysis of tsunami deposits. Choowong et al. (2008) estimated a depth-averaged flow velocity ranging between 7-21 m/s from the thickness and grain size of sediment deposited by the 2004 Indian Ocean tsunami in Phuket, Thailand. Didenkulova et al. (2010) presented a linear shallow-water theory for tsunami wave generation by underwater landslides with depth averaged flow velocity. Lipa el al. (2012) measured the orbital velocity components to observe the tsunami signal in HF radar. They formed a time series of the average velocity, which shows the characteristic oscillations produced by the tsunami. Ma et al. (2013) presented the time series of surface horizontal velocities induced by submarine landslides and compared normalized velocity profiles at both supercritical and subcritical regions by the layer-averaged velocity. Lin et al. (2015) showed the velocity field near a moving landslide at different time values.

The objective of this study is to illustrate tsunami distributions predicted in the near-and far-field caused by a dynamic displacement of a stochastic submarine slump and landslide for different values of Froude number and noise intensity. Stochastic effects have been incorporated by including two Gaussian white noise processes in the x– and y–direction to form the stochastic source model. Wave gauges are represented at different locations, in order to make a contribution to the improvement the warning system of tsunami arrival. Of particular interest in this study is to represent the displaced water volume as a result of the stochastic submarine slump and landslide, the potential, kinetic and total energy of the free surface elevation and the surface average velocity flow rates during the generation and propagation processes under the effect of different Froude numbers. The problem is solved using the linearized water wave theory for constant water depth by transforming methods (Laplace in time and Fourier in space), with the forward and inverse Laplace transforms solved analytically, and the inverse Fourier transform computed numerically by the Inverse Fast Fourier Transform (IFFT).

The present study is organized as follows. Section 2 presents the mathematical formulation of the linear water wave problem. It also presents the mathematical description of the stochastic submarine slump and landslide. Section 3 presents the tsunami analysis results caused by the stochastic submarine slump and landslide. The time-evolution during tsunami generation and propagation is described in Section 3.1. Section 3.2 presents the displace water volume and the tsunami energy. Section 3.3 presents the average velocity time series. Finally, Section 4 provides the main conclusions of this study.

2. MATHEMATICAL FORMULATION OF THE LINEAR WATER WAVE PROBLEM

It is considered that the fluid is incompressible and the flow is irrotational in the fluid domain $\Omega = R^2 \times \left[-h, 0\right]$ bounded above by the free surface of the ocean $z = \eta\left(x, y, t\right)$ and below by the rigid ocean floor $z = -h + \zeta(x, y, t)$ as shown in Fig. 1, where $\eta(x, y, t)$ is the free surface elevation, h is the constant water depth and $\zeta(x, y, t)$ is the sea floor displacement function.

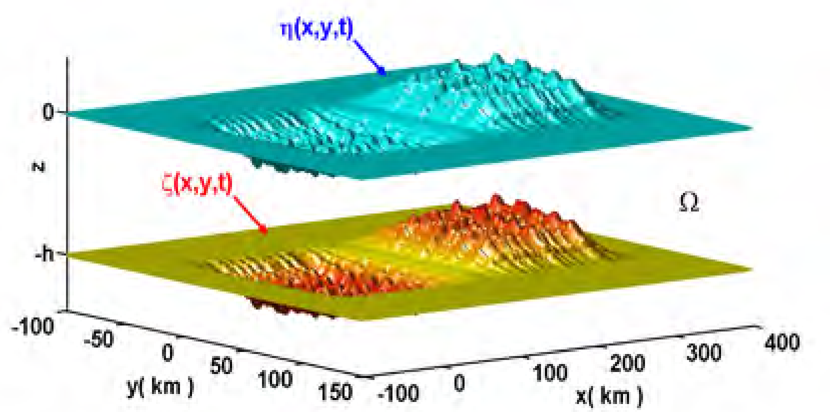


Figure 1. Fluid domain and coordinate system for a very rapid movement of the stochastic submarine slump and landslide model

The linearized problem can be expressed in terms of the velocity potential $\phi(x, y, z, t)$ by the Laplace equation as:

$$\nabla^2\phi(x, y, z, t) = 0 \text{ where } (x, y, z) \in \Omega\,, \tag{1}$$

subjected to the following boundary conditions

$$\partial_z\phi(x, y, z, t)\Big|_{z=0} = \partial_t\eta(x, y, t)\ , \tag{2}$$

$$\partial_z\phi(x, y, z, t)\Big|_{z=-h} = \partial_t\zeta(x, y, t)\ , \tag{3}$$

and

$$\partial_t\phi(x, y, z, t)\Big|_{z=0} + g\,\eta(x, y, t) = 0\,. \tag{4}$$

where g is the acceleration due to gravity. The initial conditions are given as

$$\phi(x, y, z, 0) = \eta(x, y, 0) = \zeta(x, y, 0) = 0. \tag{5}$$

The linear water wave theory has been developed as a fundamental theory in questions of stability for both near– and far–field problem in the open ocean which provides an ample understanding of the physical characteristics of the tsunami, see, Kervella et al (2007); Saito and Furumura (2009); Constantin and Germain (2012); Saito (2013) and Jamin et al. (2015). Additionally, one of the notable consequences of the linear theory is that the height distribution at the surface is not always identical to the bottom, see Jamin et al. (2015) and Saito (2013). Nonlinear effects become significant and dominant as tsunami enters the run-up phase, see Lynett and Liu (2002); Glimsdal et al. (2007); Løvholt et al. (2012) and Samaras et al. (2015).

We applied the transform methods (Laplace in time and Fourier in space) to solve analytical the linearized problem of the long traveling free surface elevation, η, in the open ocean during the generation and propagation processes for constant water depth, h at resonance state (when, $v = v_t = \sqrt{gh}$, i.e. maximum amplification, see Ramadan et al. (2011) . This solution is accurate if the depth of the water, h, is much greater than the amplitudes of and ζ (sea floor uplift) and η (free surface elevation) and if the wavelength of the leading wave of the incoming tsunamis is very long in comparison with the local water depth, which is usually true for most tsunamis triggered by submarine earthquakes, slumps and slides, see Todorovska and Trifunac (2001); Trifunac et al. (2002a, 2002b); Todorovska et al. (2002); Trifunac et al. (2003); Hayir (2006) and Jamin et al. (2015). All these studies neglected the nonlinear terms in the boundary conditions to study the generation of the tsunami waves using the transform methods.

In this paper, an analytical approach was used to illustrate the tsunami wave, the displaced water volume as a result of the submarine slump and landslide, the potential and kinetic energy of the free surface elevation and the average velocity flow rates in the open ocean during the generation and propagation processes for a given stochastic submarine slump and landslide profile $\zeta(x, y, t)$ for different Froude numbers. All our studies took into account constant depths h for which the Laplace and Fast Fourier

Transform (FFT) methods could be applied. After applying the Fourier–Laplace transform of the Laplace equation (1) and the boundary conditions (2) – (4), and using the initial conditions in (5), the velocity potential $\bar{\phi}(k_1, k_2, z, s)$ and the free surface elevation $\bar{\eta}(k_1, k_2, s)$ are obtained, respectively as seen in Ramadan et al. (2015) as:

$$\bar{\phi}(k_1, k_2, z, s) = -\frac{gs\,\bar{\zeta}(k_1, k_2, s)}{\cosh(kh)(s^2 + \omega^2)}\left(\cosh(kz) - \frac{s^2}{gk}\sinh(kz)\right), \tag{6}$$

and

$$\bar{\eta}(k_1, k_2, s) = \frac{s^2\,\bar{\zeta}(k_1, k_2, s)}{\cosh(kh)(s^2 + \omega^2)} \;. \tag{7}$$

where $\omega = \sqrt{gk\tanh(kh)}$ is the gravity-wave dispersion relation and $k = \sqrt{k_1^2 + k_2^2}$ is the wavenumber.

A solution for $\eta(x, y, t)$ can be obtained from equation (7) by performing the inverse transforms. The above linearized solution is known as the linear water solution. The mechanism of the tsunami generation caused by submarine gravity mass flows is initiated by a rapid down and uplift faulting as shown in Fig. 2, then propagated randomly in the positive $x-$ direction with time $0 \le t \le t^*$, to a length L with velocity v to produce an accumulation and depletion zones as shown in Fig. 3. In the $y-$direction, the model propagates instantaneously during the time $0 \le t \le t^*$.The set of physical parameters used in the problem are given in Table 1.

Table 1 Parameters used in the analytical solution of the problem

Parameters	Values for the submarine slump and landslide
-Source width, D , km	50
- propagated length L, km	100
-Water depth (uniform), h, km	2
-Acceleration due to gravity, g, km/sec^2	0.0098
-Tsunami phase velocity, $v_t = \sqrt{gh}$, km/sec	0.14
- submarine velocity (at resonance) $v = v_t$, km/sec	0.14
- Characteristic time t^* (at resonance) $t^* = \frac{L}{v} = 714$ sec $= 11.9$ min	

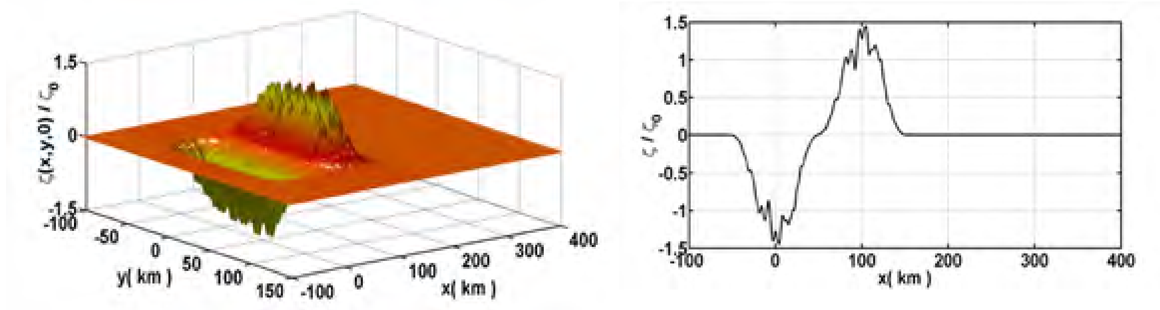


Figure 2. Normalized initial bottom topography representing by a stochastic down and uplift faulting (a) Three−dimensional view (b) Side view

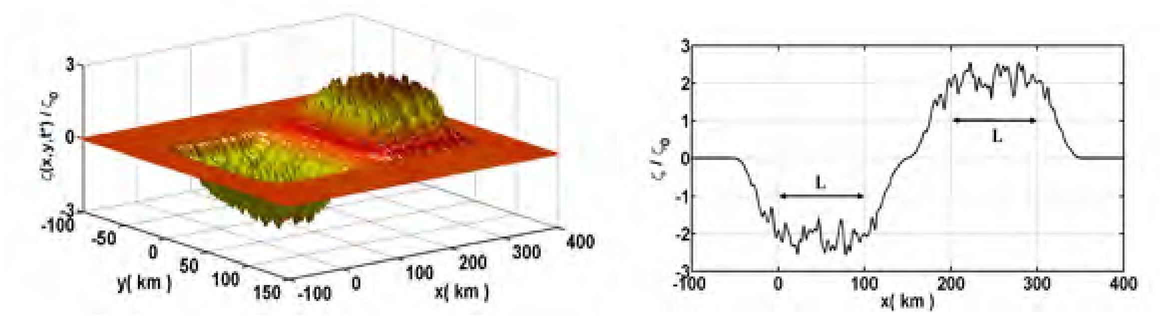


Figure 3. Normalized Bed deformation model representing by a random accumulation and depletion zones at $t = t^{*} = L/v = 100/v$ (a) Three−dimensional view (b) Side view.

Modeling tsunamis generated by submarine slumps and landslides requires modeling the landslide motion. The dynamic stochastic submarine slump and landslide model shown in Fig. 3 for $0 \le t \le t^*$ is given by:

$$\zeta_{\mathrm{down}}(x,y,t) = \left[\zeta_{1\mathrm{down}}(x,y,t) + \zeta_{2\mathrm{down}}(x,y,t) + \zeta_{3\mathrm{down}}(x,y,t)\right]\left(1 + \sigma_x \xi_x(x+50) + \sigma_y \xi_y(y+50)\right), \qquad (8)$$

for $-50 \le x \le 50+ vt$ and $-50 \le y \le 100$.

For $y \in [\,-50,0]$

$$\zeta_{1\mathrm{down}}(x,y,t) = \begin{cases} -\frac{\zeta_0}{4}\left(1 + \cos\frac{\pi}{50}x\right)\left[1 - \cos\frac{\pi}{50}(y+50)\right], & -50 \le x \le 0, \\ -\frac{\zeta_0}{2}\left[1 - \cos\frac{\pi}{50}(y+50)\right], & 0 \le x \le vt, \\ -\frac{\zeta_0}{4}\left[1 + \cos\frac{\pi}{50}(x - vt)\right]\left[1 - \cos\frac{\pi}{50}(y+50)\right], & vt \le x \le 50+ vt, \end{cases} \qquad (9)$$

and for $y \in [\,0, 50]$

$$\zeta_{2down}(x,y,t) = \begin{cases} -\frac{\zeta_0}{2}\left(1+\cos\frac{\pi}{50}x\right), & -50 \le x \le 0\ , \\ -\ \zeta_0, & 0 \le x \le\ vt\ , \\ -\frac{\zeta_0}{2}\left[1+\cos\frac{\pi}{50}(x\ -vt)\right], & vt \le x \le 50+vt\ , \end{cases} \tag{10}$$

and for $y \in [\ 50,\ 100]$

$$\zeta_{3down}(x,y,t) = \begin{cases} -\frac{\zeta_0}{4}\left(1\ +\cos\frac{\pi}{50}x\right)\left[\ 1+\cos\frac{\pi}{50}\ (\ y-50\ )\right], & -50 \le x \le 0\ , \\ -\frac{\zeta_0}{2}\left[\ 1+\ \cos\frac{\pi}{50}(\ y-50\ )\right], & 0 \le x \le vt\ \ , \\ -\frac{\zeta_0}{4}\left[1+\cos\frac{\pi}{50}(x\ -vt)\right]\left[\ 1+\ \cos\frac{\pi}{50}\ (\ y-\ 50\ )\right], & vt \le x \le 50+vt\ . \end{cases} \tag{11}$$

$$\zeta_{up}(x,y,t) = \left[\zeta_{1up}(x,y,t)+\zeta_{2up}(x,y,t)+\zeta_{3up}(x,y,t)\right]\left(1+\sigma_x\xi_x(x-50-vt)+\sigma_y\xi_y(y+50)\right),\tag{12}$$

for $50+vt \le x \le 150+2vt$ and $-50 \le y \le 100$.

For $y \in [\ -50,0]$

$$\zeta_{1up}(x,y,t) = \begin{cases} \frac{\zeta_0}{4}\left[1+\cos\frac{\pi}{50}(x\ -vt)\right]\left[\ 1-\ \cos\frac{\pi}{50}\ (\ y+50\ )\right], & 50+vt \le x \le 100+vt\ , \\ \frac{\zeta_0}{2}\left[\ 1-\cos\frac{\pi}{50}\ (\ y+50\ )\right], & 100+vt \le x \le 100+2vt\ \ , \\ \frac{\zeta_0}{4}\left[1+\cos\frac{\pi}{50}\left(x-(100+2vt)\right)\right]\left[1-\cos\frac{\pi}{50}\ (\ y+50\ )\right], & 100+2vt \le x \le 150+2vt \end{cases}$$

(13)

and for $y \in [\ 0,\ 50]$

$$\zeta_{2up}(x,y,t) = \begin{cases} \frac{\zeta_0}{2}\left[1+\cos\frac{\pi}{50}(x\ -vt)\right], & 50\ +vt \le x \le 100+vt\ , \\ \zeta_0, & 100+vt \le x \le 100+2vt\ \ , \\ \frac{\zeta_0}{2}\left[1+\cos\frac{\pi}{50}\left(x-(100+2vt)\right)\right], & 100+2vt \le x \le 150+2vt\ , \end{cases} \tag{14}$$

and for $y \in [\ 50,\ 100]$

$$\zeta_{3up}(x,y,t) = \begin{cases} \frac{\zeta_0}{4}\left[1+\cos\frac{\pi}{50}(x - vt)\right]\left[1+\cos\frac{\pi}{50}(y-50)\right], & 50+vt \le x \le 100+vt, \\ \frac{\zeta_0}{2}\left[1+\cos\frac{\pi}{50}(y-50)\right], & 100+vt \le x \le 100+2vt, \\ \frac{\zeta_0}{4}\left[1+\cos\frac{\pi}{50}(x-(100+2vt))\right]\left[1+\cos\frac{\pi}{50}(y-50)\right], & 100+2vt \le x \le 150+2vt, \end{cases}$$

(15)

where ζ_0 denotes the initial uplift of the smooth bottom topography, $\xi_x(x)$ and $\xi_y(y)$ denote two independent Gaussian white noise processes which are random processes with two real valued parameters σ_x, $\sigma_y \ge 0$ that control the strength of the induced noise in the x− and y−directions, respectively and v is the spreading velocity of the stochastic bottom in the x−direction.

The deformation of the random submarine slump and landslide shown in Fig. 3 could represent the slide with mass movement in the down slope direction, see Fig. 3 in Normark et al. (1993) and the three-dimensional bathymetry of the sea floor north of Puerto Rico, see Fig. 2 in Schwab et al. (1993) and Fig. 1(b) in Brink et al. (2006). So, the evidence of a huge historical tsunami need for investigating the possibility of future tsunami generating by stochastic submarine slumps and landslides.

The considered stochastic submarine slump and landslide source model is spreading unilateral in the x-direction as shown in Fig. 4 where the vertical displacement is negative (downwards) in zone of depletion, and positive (upwards) in zone of accumulation. The schematic representation of the submarine slump and landslide shown in Fig. 4 resembles the debris flow model in Fig. 1 (bottom left) in Løvholt et al. (2017). For $t \ge t^*$ (propagation process), $\zeta_{down}(x,y,t)$ and $\zeta_{up}(x,y,t)$ are the same as (8) and (12) except the time parameter t will be substituted by t*.

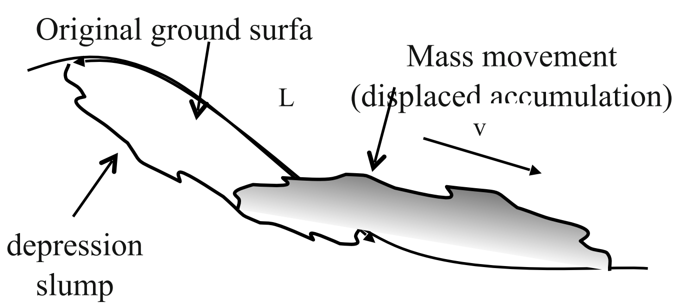


Figure 4. Schematic representation of the kinematic submarine landslide travelling a significant distance L downhill creating a depression slump and a displaced accumulation mass movement spreading uphill with velocity v.

Laplace and Fourier transforms can now applied to the bed motion described by Equations (8) and (12), then substituting into (7) and then inverting $\bar{\eta}(k_1,k_2,s)$ using the inverse Laplace transform and the double inverse Fourier transform to obtain $\eta(x,y,t)$, see Ramadan et al. (2015).

To evaluate the horizontal velocity components along the free surface (z = 0) denoted by $\mathbf{u}\,(U, V)$, and the horizontal gradient $\left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}\right)$ denoted by ∇_h, and the Fourier transform parameters denoted $\mathbf{m} = (k_1\ ,\ k_2)$, hence the horizontal components of the velocity are defined as:

$$\mathbf{u}(x, y, t) = \nabla_h \phi(x, y, t)\,, \tag{16}$$

taking into account that the horizontal velocities are independent of the vertical coordinate, z. The Fourier transforms of the horizontal components taken along the absolute value of the free surface η in case of slump and slide for $0 \le t \le t^*$ (generation process) are given as:

$$\bar{\mathbf{u}}(k_1, k_2, t) = -\, i\bar{\phi}(\ k_1, k_2, t\ )\mathbf{m}\,,$$

$$= i\left[\ g\int_0^t \left|\bar{\eta}(\ k_1, k_2, \tau\ )\right| d\tau\right]\mathbf{m}\,. \tag{17}$$

For $t \ge t^*$ (propagation process), the integration $\int_0^t \left|\bar{\eta}(\ k_1, k_2, \tau\ )\right| d\tau$ in equation (17) is written as $\int_0^{t^*} \left|\bar{\eta}(\ k_1, k_2, \tau\ )\right| d\tau + \int_{t^*}^t \left|\bar{\eta}(\ k_1, k_2, \tau\ )\right| d\tau\,.$

The surface average velocity flow rates are given as $\bar{u} = \frac{Q_x}{\iint dxdy}$ and $\bar{v} = \frac{Q_y}{\iint dxdy}$, where $Q_x = \iint Udxdy$ and $Q_y = \iint Vdxdy$ are called volume flow rates.

We are interested in representing the displaced water volume, the potential and kinetic energies of the tsunami wave due to vertical displacement of the stochastic submarine slump and landslide model in the near- and far-field under the effect of the Froude number to investigate for the tsunami wave amplification and the potential for tsunami generation and propagation.

The volume of water displaced as a result of the submarine slump and landslide can be determined as the integral of the absolute value of the function η taken over the entire tsunami source area. Then the total displaced water volume V(t) is given as :

$$V(t) = \int_{R^2} \left|\eta\right| dxdy\,. \tag{18}$$

The accumulated kinetic energy, $E_K(t)$ generated by the movement of the water particles of the mass flow imparted to the flow region and the accumulated potential energy, $E_p(t)$ induced by the displacement of the free surface from the mean position, can be evaluated at any time by integration over the whole deformation area as (see Ramadan et al., 2017):

$$E_K(t) = \frac{1}{2}\rho\int_{R^2}\int_{-h}^{\eta} \left|\ \nabla\phi\right|^2 dzdxdy = \frac{1}{2}\rho\int_{R^2}\int_{-h}^{\eta} \left(U^2 + V^2 + W^2\right) dzdxdy\ , \tag{19}$$

and $$E_p(t) = \int_{R^2}\int_0^{|\eta|} \rho g z \, dz dx dy = \frac{1}{2}\rho g \int_{R^2} |\eta|^2 dx dy \ , \tag{20}$$

where $\rho = 1000\,\mathrm{kg/m^3}$ is the water density, U and V are the horizontal water velocity fields within the range of R_x and R_y , respectively and W is the vertical velocity field due the seafloor uplift. Taken together, we obtained the total energy $E_T(t) = E_p(t) + E_K(t)$. Both horizontal and vertical velocities are taken into account, so the conservation of total wave energy is well satisfied (Dutykh and Dias 2009). It is assumed that the initial energy of the tsunami is purely potential, by hypothesis the initial kinetic energy is null and hence the initial velocities are also null.

3. RESULTS AND DISCUSSIONS

Modeling submarine landslide -triggered tsunami generation and propagation is now standard for hazard analysis of vulnerable coastlines. The tsunami generation and propagation are illustrated by a vertical time-dependent displacement of a stochastic mass failure model driven by two Gaussian white noise processes in the x– and y–directions. The numerical results demonstrate the waveform in the near-field resulting from the stochastic slump and landslide elongation to one direction (length) that vertically displaces the water column, and the wave amplitudes decaying, due to geometric spreading and dispersion in the far−field. The displaced water volume, the tsunami potential and kinetic energy and the average surface velocities induced by the stochastic submarine slump and landslide source model for different Froude numbers are illustrated in the near− and far−field.

3.1 Time-Evolution during Tsunami Generation and Propagation

Submarine slumps and landslides that produce vertical displacement change the shape of the ocean basin, which affect the entire water column and generate a tsunami. The ratio of the submarine landslide speed to the local phase velocity of the free water waves in water depth h, is known as Froude number and plays a fundamental role in determining the generation and evolution of the induced tsunami (Tinti and Bortolucci, 2000).

Figure 5 presents the top view of the stochastic slump and slide source model at $t^* = L/v$, showing the location of four selected gauges. We chose the locations of these gauges based on different altitudes of the stochastic slump and landslide source model. Wave gauges are used to measure the wave height for different values of Froude number. Observations were made on water level at the four locations, (50, 25), (78, 42), (250, 25) and (278, 42). The measurement points were chosen as a reference point for evaluating the effects of enlargement in the flow of the tsunami generation level.

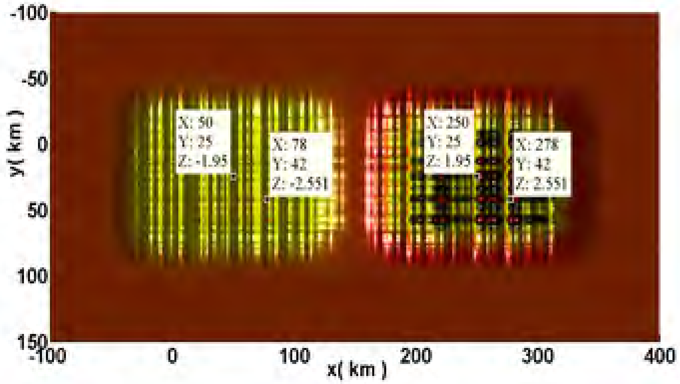
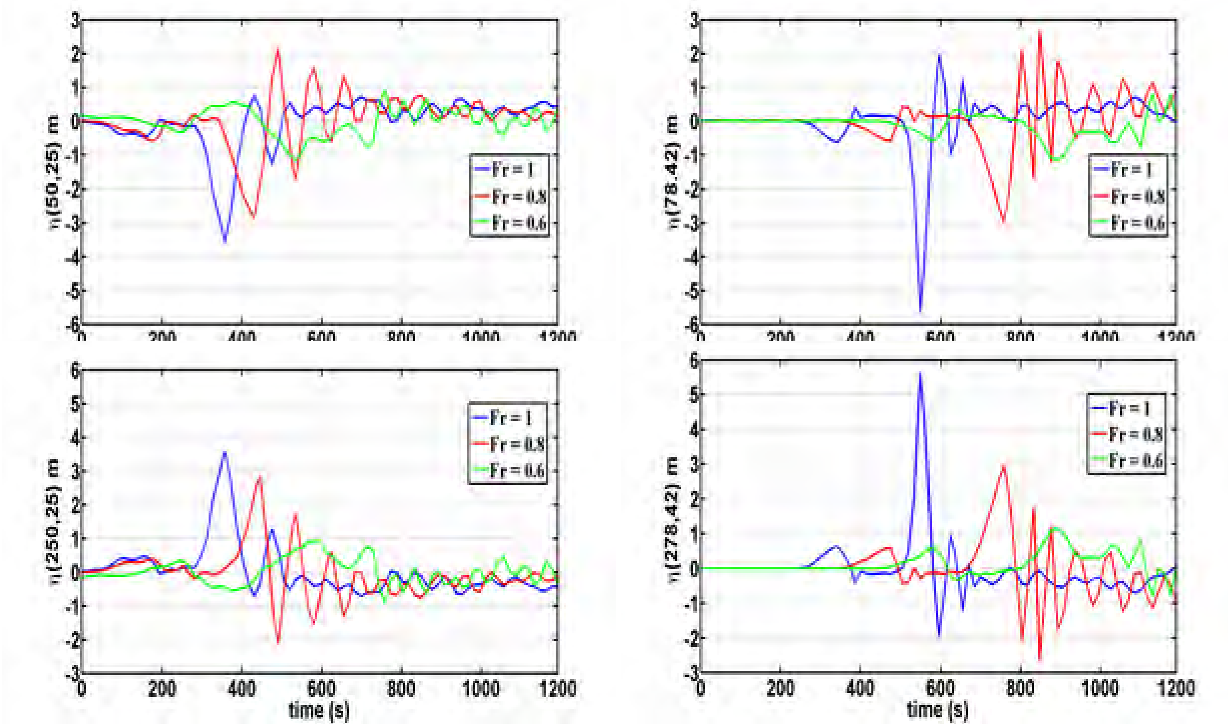


Figure 5. Top view of the stochastic submarine slump and landslide at $t^* = L/v$, showing the location of four selected gauges above the depression slump and the displaced accumulation mass movement, with the following coordinates (x, y) in km: (50, 25) and (78, 42), (250, 25) and (278, 42).

Figure 6 presents the vertical distance of the free surface elevation during the generation time at each gauge for Fr = 1, 0.8 and 0.6 at water depth h = 2 km. The Froude number indicated the duration over which the submarine slump and landslide interacts with the wave field and has a significant effect on the wave

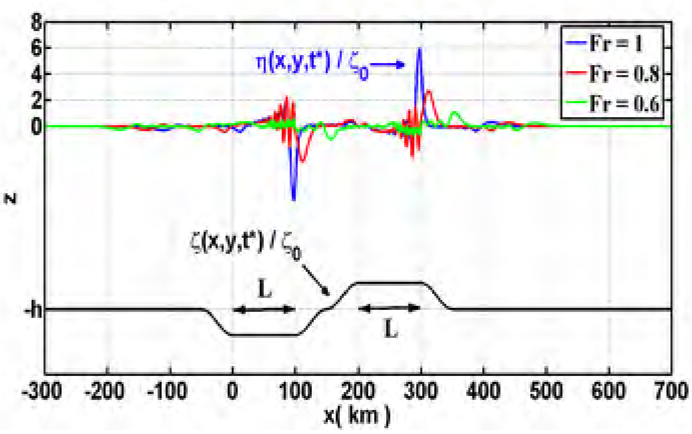


(c) Gauge at (250, 25)

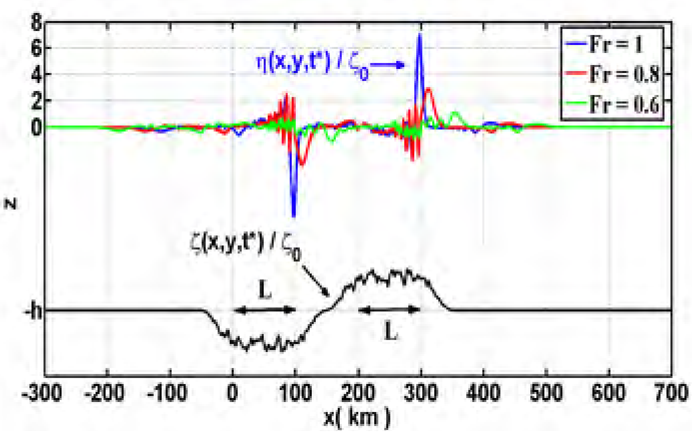
(d) Gauge at (278, 42)

Figure 6. Free surface elevation $\eta(x, y, t)$ at different Froude numbers along the four selected gauges located in Fig. 5 at water depth h = 2 km.

This can be observed in Fig. 6 where by decreasing the landslide Froude number, resulting in a smaller leading wave crest and tough which propagate ahead of the slump and the slide. Therefore, the Froude number was used here to control the duration of this interaction. The maximum free surface elevation attained in Fig. (6c) at wave gauge (250, 25) for Fr = 1, 0.8 and 0.6 to 3.56, 2.83 and 0.95 m at rise time t = 357, 446 and 595 s, respectively and in Fig. (6d) at wave gauge (278, 42) reaches a maximum value of 5.63, 2.97 and 1.17 at rise time t = 550, 758 and 892 s, respectively. Figure 7 represents the normalized tsunami generated and propagated amplitude by the deterministic and stochastic submarine slump and slide source models for different values of the Froude number. It can be seen how water ahead of the front face of the slide is pushed away, creating a positive wave in the slide direction. Above the submarine slump, water is absorbed, which creates a large trough. These waveforms are generated at constant water depth h = 2 km, propagated length L = 100 km, at time t = t* where t* = L\v (time when the sea-bottom mass failure ends). It can be observed how the inclusion of the noise at the lateral slopes and to the central plateau of the submarine slump and landslide source model leads to an increase in the tsunami amplitude in addition to an increase in oscillations in the free surface elevation. In Figure 7, resonance takes place when Fr = 1, and wave focusing and amplification will occur above the spreading edge of the submarine slump and landslide (i.e. tsunami wave generation and slump and slide motion interact in a dynamic coupling). For Fr < 1, the tsunami will run away from the wave-generating submarine slump and landslide, limiting the build-up of the wave. Hence, the wave behavior is largely determined by the Froude number.



(a)



(b)

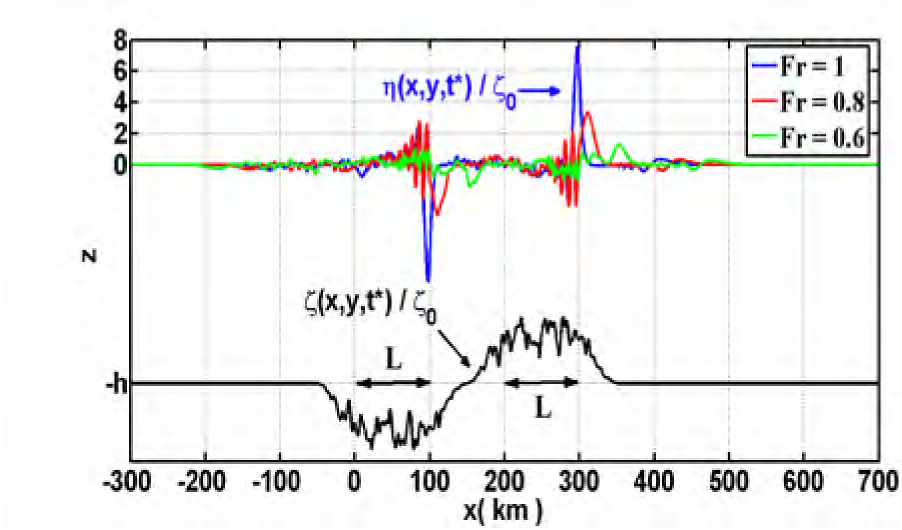


Figure 7. Comparison between the normalized tsunami amplitude generated by the deterministic (a) $\sigma_x = \sigma_y = 0$ and the stochastic submarine slump and landslide source models at (b) $\sigma_x = \sigma_y = 0.4$ and (c) $\sigma_x = \sigma_y = 0.8$ for different values of Froude number at propagated length $L = 100$ and water depth h = 2 km with $v_t = \sqrt{gh}$ and $t^* = L \backslash v_t$.

When the tsunami enters in the propagation regime, amplitude or leading wave height decreases with the distance from the source because of wave divergence and dispersion, which makes the wave travel outward on the surface of the ocean in all directions away from the source area as seen in Fig. 8.The leading wave crest was observed to propagate with relatively minor change in form with time, causing a train of small waves behind the main wave. The first trailing wave becomes larger than the leading one and for large propagation times, the largest amplitudes will be found in the trailing waves. For Fr < 1, the tsunami will cover much larger area than the area of the source because of wave divergence and dispersion as seen in Fig. 9. The leveling of the tsunami wave due to gravity, converts the potential energy of the water into kinetic energy resulting in dispersing wave energy over a larger area, and thereby creating a propagating wave field. The propagation of long waves in the ocean is accompanied by effects of refraction and wave scattering due to reflections by a non-uniform ocean bottom which leads to stochastization of the wave field (Fine et al. 2013).This stochastization is quite evident in the rear area in Figs. 8 and 9, where the area is filled with secondary waves and is transformed into a random wave field. Hence, the stochastic submarine slump and landslide model shows more oscillations in the propagated free surface elevation.

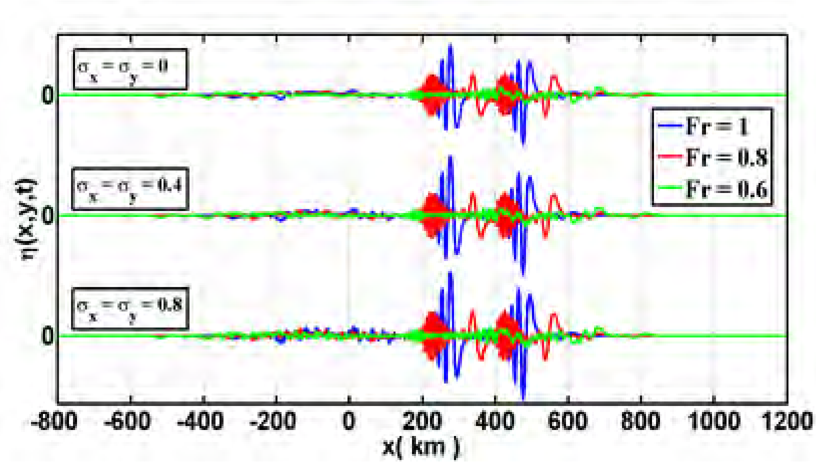
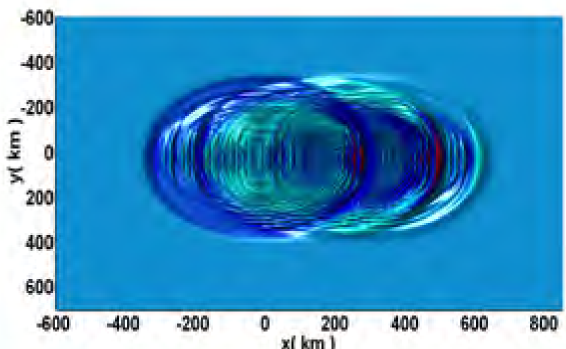
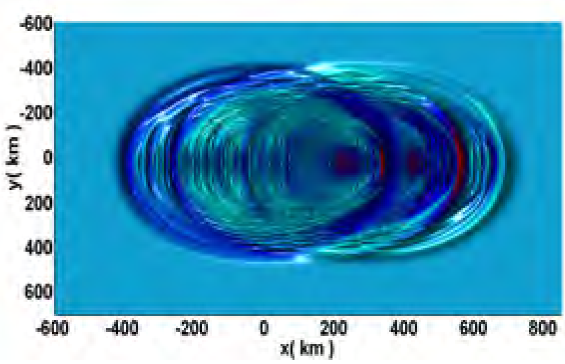


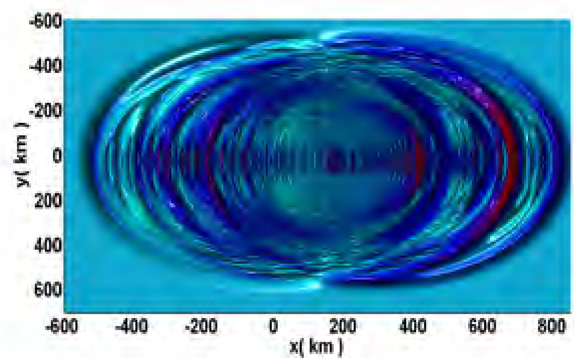
Figure 8. Normalized tsunami propagation waveforms by the deterministic and the stochastic submarine slump and landslide source models for different values of Froude number and different noise at propagated time $t = 3\,t^*$.



(a)



(b)



(c)

Figure 9. Top views of the normalized tsunami propagation waveforms shown in Fig. 8 by the stochastic submarine slump and landslide source model at $\sigma_x = \sigma_y = 0.8$, for (a) Fr = 1 , (b) Fr = 0.8 and (c) Fr =

3.2 Displaced Water Volume and Tsunami Energy

Tsunamis are generated by water volume displacement as a result of ocean-bottom displacement due to faulting or by submarine slump and landslide due to geophysical mass flow events. We are interesting to analyze wave elevation history using the displaced water volume as a result of the deterministic and the stochastic submarine slump and landslide motions and the resulted energy of the free surface elevation. As the vertical displacement of the deterministic and stochastic submarine slump and landslide source models increases during the generation process, results in more displaced water volume in the ocean, which is proportional to the source models spreading distance as seen in Fig. 10. For $Fr = 1$, the displaced water volume by the deterministic submarine slump and landslide source model for propagated length L = 50 and 100 km reaches a maximum of 2.0 and 3.0 km^3, respectively , while in case of the stochastic submarine slump and landslide source model, reaches a maximum of 2.07 and 3.15 km^3. This indicates that the near–field tsunami amplitudes are roughly proportional to the source volume and deformation. It can be observed that the duration over which the submarine slump and landslide interacts with the wave field increases as the Froude number decreases. In the propagation regime, the displaced water volume remains constant as a state of conservation of energy in an open ocean.

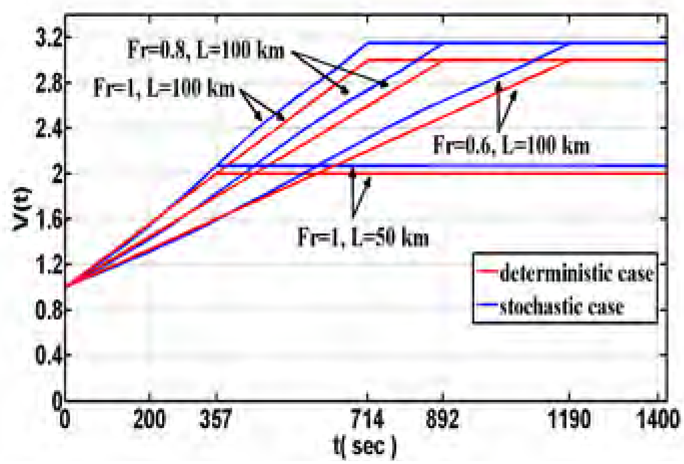


Figure 10**.** Time evolution of the displaced water volume as a result of the deterministic and the stochastic submarine slump and landslide source models to propagated lengths L = 50 and 100 km at time t = 357 and 714 sec, respectively for different Froude numbers.

For better understanding of the submarine slump and landslide generation it would be interesting to examine the energy transfer from the slump and the landslide to the water surface. Figure 11 shows the potential, kinetic and total energy vs. time induced by the deterministic and the stochastic submarine slump and landslide source models during the wave generation and propagation process for different Froude numbers. It can be seen in Fig. 11 that both the potential and kinetic energy increases during the generation region due to the submarine slump and landslide flow and hence increases the total energy. The wave energy reaches a maximum which indicates that the generated waves are mostly developed. The total energy of the maximum elevation, calculated by the deterministic submarine slump and landslide is 4.8×10^{14} , 3×10^{14} and 1.0×10^{14} J for Fr = 1, 0.8 and 0.6, respectively and due to the stochastic submarine slump and landslide yields maximum total energy of approximately 6.8×10^{14}, 4.0×10^{14} and 1.3×10^{14} J. The rate at which the potential and kinetic energy increased depended on the value of the Froude. As the Froude number increased, the amplitude of the energy fluctuations during the constant-velocity phase also increased. Hence, the results shown in Fig. 11 indicated that the energy content of near-field tsunami depend on tsunami source deformation and the Froude number. Vol. 37, No. 1, page 1 (2018)

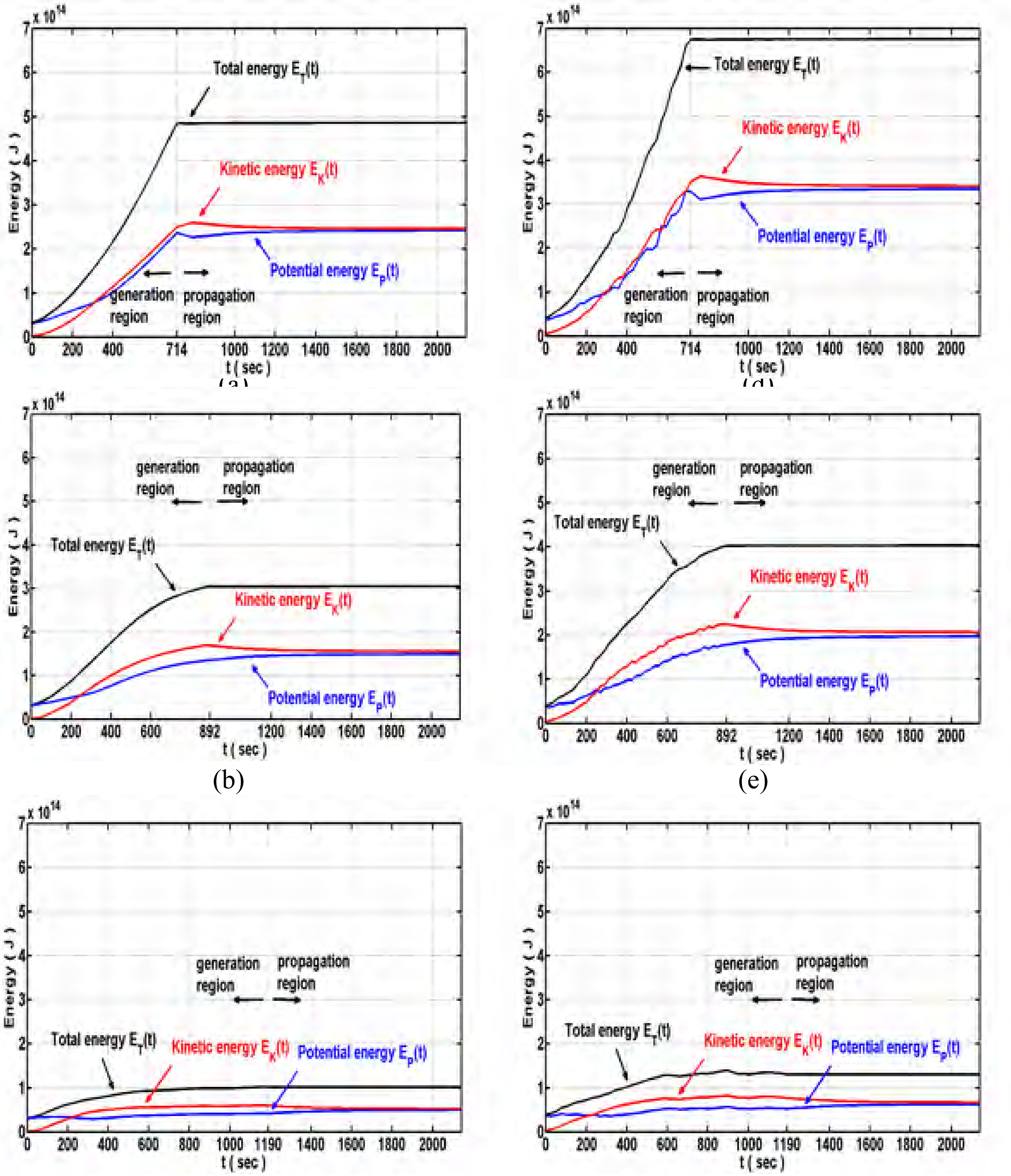


Figure 11. Energy evolution during the generation and propagation process induced by the deterministic submarine slump and landslide source model for (a) Fr = 1, (b) Fr = 0.8 and (c) Fr = 0.6, and by the stochastic submarine slump and landslide source model for (d) Fr = 1, (e) Fr = 0.8 and (f) Fr = 0.6, until propagated time $t = 3\,t^*$.

When the tsunami enters the propagation regime, amplitude or wave height decreases with the distance from the source because of wave divergence and dispersion, and hence decreases the potential energy, while the kinetic energy increases as seen in Fig. 11. This makes the wave travel outward on the surface of the ocean in all directions away from the source area. The potential energy resulting from the generation process is balanced with the kinetic energy of the waves which appears as an exchange between kinetic and potential energy due to the conservation of energy which was verified in the total energy. The energy of the leading wave crest was found to decrease with the propagation distance attributed to the dispersion of the wave energy and migration through the tsunami wave train (Løvholt et al. 2008). This was observed in the propagation region in Fig. 11 where the energy transfer to the trailing waves in the wave train led to the potential energy increases in the propagation region which comprises multiple amplitudes and frequency components formed immediately behind the leading wave. All curves reach an energy saturation plateau for large times, which is higher, the closer to 1 is the Froude number. Saturation is reached later for smaller Froude numbers.

It is also interesting to report previous values computed for the tsunami energy induced by landslides. Levin and Nosov (2009) estimated the energy of the tsunami waves generated by landslide of the order of 10^{16} J. Abril, and Periáñez (2015) estimated the tsunami peak energy by a submarine landslide to be equal to 4.2×10^{15} J. López-Venegas et al. (2015) calculated the potential energy of the tsunami wave produced by the landslide to be 0.95×10^{15} J and the kinetic energy to be 3.5×10^{15} inside the generation area. For tsunami energy induced by submarine earthquake, Ramadan et al. (2017) computed the tsunami maximum total energy of approximately 2.9×10^{14} J.

3.3 Average Velocity Time Series

We are interested in representing the time series of the average velocity flow rates $\bar{u}$ and $\bar{v}$, induced by the displacement of deterministic and stochastic submarine mass failure along the free surface ($z = 0$) under the effect of different Froude numbers. The time series of the average velocity components provides a clear signal of tsunami flows, where the arrival of the tsunami is indicated by the commencement of distinctive current velocity oscillations as it shows the characteristic oscillations produced by the tsunami (Lipa et al. 2011, 2012). The surface average velocity flow rates are written as $\bar{u} = \dfrac{Q_x}{\iint dxdy}$ and $\bar{v} = \dfrac{Q_y}{\iint dxdy}$, where $Q_x = \iint udxdy$ and $Q_y = \iint vdxdy$ are called volume flow rates.

Figure 12 represents the time series of the surface average velocities $\bar{u}$ and $\bar{v}$ of the tsunami generated and propagated waves by the spreading deterministic and stochastic submarine slump and landslide source models of propagated length $L = 100$ km at water depth $h = 2$ km. It can be seen in Fig. 12 that the contribution of the randomness of the stochastic submarine slump and landslide source model affected the average velocity flow rates by distinctive oscillations. Hence, the average velocity flow rates can provide valuable information about the mass flow. In the $y-$direction, the stochastic submarine slump and landslide source model propagates instantaneously as the water surface elevation builds up rapidly, and therefore the horizontal average velocity flow rate $\bar{v}$ develops a spike with drastically frequency oscillations. The oscillations in the propagation region appear due to wave dispersion and the changes in the average velocity flow rates have minimal impacts. The peak average flow rates $\bar{u}$ reaches a maximum of 0.634, 0.856 and 0.956 m/s, for Fr = 1, 0.8 and 0.6, respectively in the case of the deterministic submarine slump and landslide, and a maximum of 0.852, 1.138 and 1.182 m/s, in the case of the stochastic submarine slump and landslide. When the Froude number decreases, the tsunami wavelength decreases and the frequency oscillation and dispersion increases and hence increases the horizontal average surface velocities.

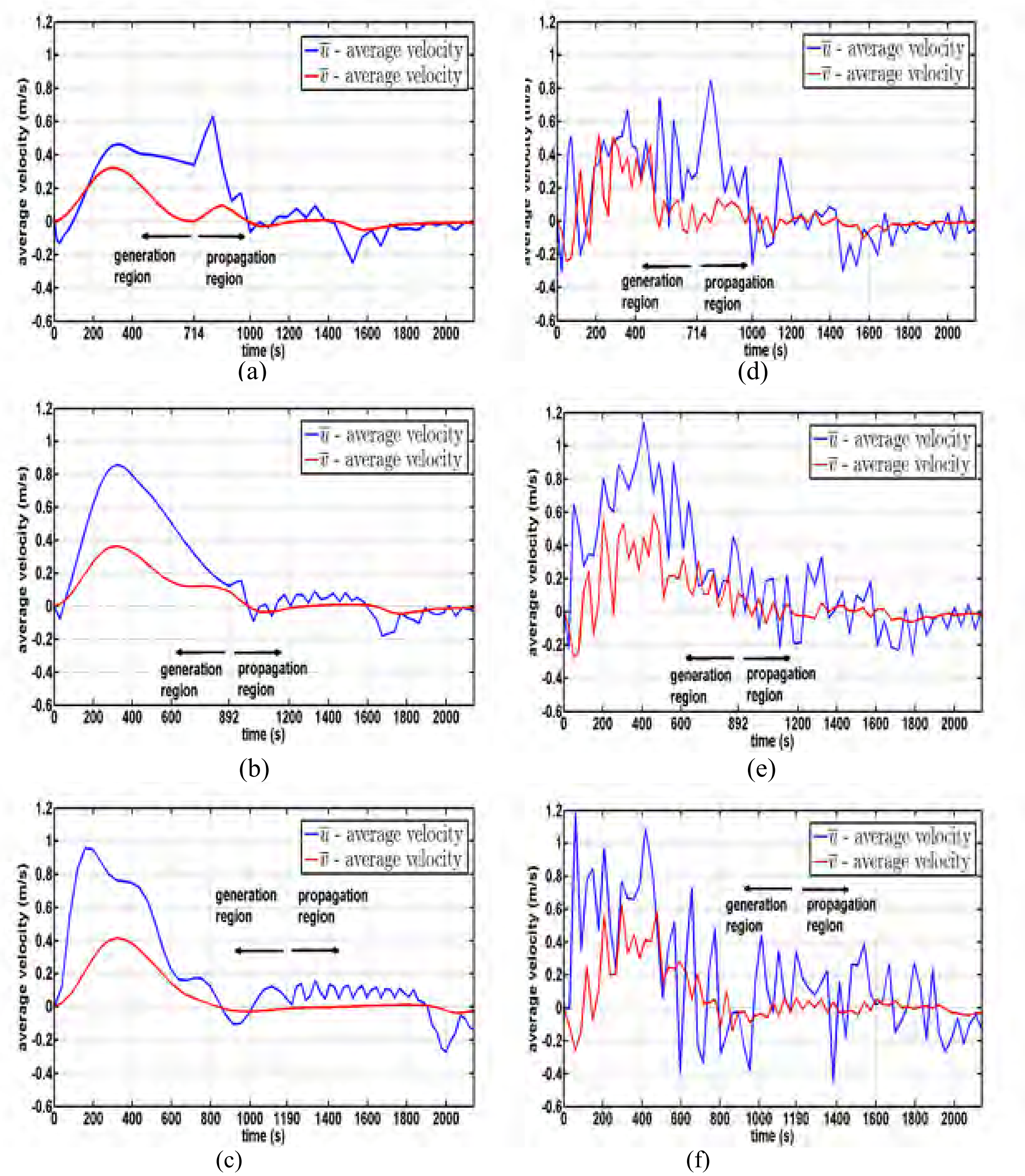


Figure 12. Time evolution of the surface average velocities $\bar{u}$ and $\bar{v}$ during the generation and propagation processes induced by the deterministic submarine slump and landslide source models for (a) Fr = 1 and (b) Fr = 0.8 and (c) Fr = 0.6, and by the stochastic submarine landslide source model for $\sigma_x = \sigma_y = 0.8$, and (d) Fr = 1, (e) Fr = 0.8 and (f) Fr = 0.6.

4. CONCLUSIONS

In this study, the tsunami distributions in the near–and far–field were investigated, resulting from a submarine slump and landslide modeled by a dynamic mass movement of a stochastic source model, driven by two Gaussian white noise processes in the x– and y–directions. We provided quantitative information by examining particular features of the displaced water volume by the stochastic submarine slump and landslide, the potential and kinetic energy and the average velocity flow rates to gain insight into the nature of the tsunami's genesis and propagation and to provide valuable information about the submarine slump and landslide. Wave gauges were measured for helping tsunami warning centers to issue or cancel warnings and to make a contribution to the improvement the warning system of tsunami arrival. Through our analysis, the following understandings and conclusions were obtained:

(1) Increasing the noise intensity will increase the amplitude of the stochastic submarine slump and landslide source model and hence increases the amplitudes and oscillations of the generated tsunami wave.

(2) The increase in the noise intensity was quite evident in the rear area of the propagated tsunami wave.

(3) When the slide velocity is similar to the tsunami phase velocity in the source area (Fr = 1), this indicated that landslide and tsunamis were coupled to generate the large tsunami heights. When the Froude number is less than one, then the tsunami will run away from the wave generating slump and landslide, limiting the build-up of the wave.

(4) The Froude number indicated the duration over which the submarine slump and landslide interacts with the wave field and has a significant effect on the wave amplitudes.

(5) The inclusion of the random noise of submarine slump and landslide deformation provided an additional and a noticeable contribution to the displaced water volume and the potential and kinetic energy of the tsunami wave.

(6) The amount of water displaced increased as the vertical movement of the deterministic and stochastic submarine slump and landslide source models increases (i.e. propagated length increases) during the generation process and then remained constant as entering the propagation regime a sort of conservation of energy.

(7) Exchange between potential and kinetic energy was achieved and reaches a total energy saturation plateau in the propagation process which is higher in the resonance state. Saturation is reached later for smaller Froude numbers.

(8) The Froude number influenced directly proportional the maximum free surface elevation and the energy and inversely the average horizontal velocities of the tsunami wave.

(9) When the Froude number deceases, this led to more widespread effects of the tsunami wave and the frequency oscillation and dispersion increases and accordingly increases the horizontal average velocity flow rates.

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FILTER-M APPLICATION FOR AUTOMATIC COMPUTATION OF P WAVE DOMINANT PERIODS FOR TSUNAMI EARLY WARNING

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ABSTRACT

The purposes of this research is to improve Indonesia Tsunami Early Warning System (InaTews), especially to improve result of automatic computation of P wave dominant period by applying filter-M to ignore noises signal. To reduce the effect of noise and signal defect on the calculation of the P wave dominant period automatically, this study used M-filter. The M-filter used the concept that the dominant period for small and moderate earthquakes is unlikely to exceed twice the maximum dominant period of the great earthquake. The automatic computation of P wave dominant period uses direct method, where the calculation uses time equation (τc) directly applied to seismogram, without inversion so that calculation process becomes faster. M-filter has been developed and used to filter out defective and high-null seismogram signals, so the seismogram is not used for the average computation of the P wave dominant period.

Keywords: *filter-M, dominant period, automatic computation, tsunami early warning*

1. INTRODUCTION

The concept of an earthquake and tsunami early warning system or the one that is called as Earthquake and Tsunami Early Warning System (EETWS) is currently popular, and the potential for EETWS to reduce the destructive effects of earthquake and tsunami has been well recognized. EETWS is a real-time seismic monitoring system that can detect ongoing earthquake and tsunami and alert the target area, before the arrival of the most damaging waves. Madlazim since 2011 (Madlazim, 2011; 2013) has developed a Jokotingkir computer program for tsunami early warning in Indonesia by applying regional and teleseismic (global) methods from Lomax and Michelini (2011; 2013) to measure duration of rupture (Tdur), dominant period (Td) and the 50 seconds exceed duration (T50Ex) earthquakes with greater magnitude that is more than 6 SR which was occurred in Indonesia. The Jokotingkir application has been validated (Madlazim et al., 2015). Madlazim et al in 2016 have also evaluated the parameters of earthquake sources announced by Indonesia tsunami early warning (Madlazim&Prastowo, 2016). While Colombelli&Zollo (2015) have found an early warning method of an earthquake with on-site P wave basis (Colombelli&Zollo, 2015). Tsunami early warning is critically dependent on the speed of determining the tsunami hazard potential in real-time before the wave floods the shoreline. Tsunami energy can quickly characterize the destructive potential of the resulting wave. The traditional seismic analysis is inadequate for predicting the tsunami energy accurately (Titov et al., 2016).

The development and implementation of other faster and more accurate tsunami parameters are needed. Since 2007, Lomax and Michelini have developed methods of measuring tsunami parameters (Tdur, Td, and T50Ex) by using teleseismic data, was implemented in the earliest software, and have been implemented since 2011 for tsunami early warning in France. Then since 2011, Madlazim has developed Jokotingkir software for tsunami early warning for local earthquakes in Indonesia by using algorithms from Lomax and Michelini. Since 2013, the software has been tested on a limited basis in BMKG Jakarta PUSLITBANG and the results were more accurate than tsunami early warning, Ina-Tews (TEMPO Magazine, 2013). However, the application of teleseismic methods for measuring Tdur, Td, and T50Ex from Lomax and Michel was in the trial until 2017 it found some inaccuracies for local earthquakes. Based on the evaluation of BMKG PUSLITBANG 2012 until May 2013, there have been 27 false warning events for the ones with magnitude less than 5,5 SR (Masturyono et al. (2013) and BMKG PUSLITBANG evaluation result from March 2017 until March 2018 has found 15 false warning events for magnitude less than 6.5 SR in this study. We have improved the Jokotingkir software algorithm to calculate the dominant period by applying the M-filter to avoid noise-dominated signal in order to improve the performance of the tsunami early warning system further.

In this study, we have improved the Jokotingkir software algorithm by using M-filtering in calculating the dominant period of P wave by ignoring the noise-dominated signal of the earthquake in order to improve the performance of the tsunami early warning system further. Therefore, the purpose of this study is to develope a tsunami early warning system through the application of M-filters for calculating the dominant period of earthquakes automatically from waveform data recorded by local seismic stations managed by BMKG.

2. METHODOLOGY

The calculation of P wave dominant period uses direct method, where the calculation uses time equation (τc) directly applied to seismogram, without inversion so that calculation process becomes faster. The dominant period of the earthquake is estimated from the dominant period of the P wave because the P wave arrives at the fastest seismic station compared to the S wave and the surface wave. To determine the dominant period (Td), first it is calculated by using time domain (τc) to the following equation:

$$\tau_c = 2\pi \int_{T_1}^{T_2} v^2(t)\mathrm{d}t \bigg/ \int_{T_1}^{T_2} \dot{v}^2(t)\mathrm{d}t,$$

(Nakamura, 1988; Wu and Kanamori, 2005; Lomax and Michelini, 2013)

With T_1 = 0 second (P onset) and T_2 = 55 seconds for seismogram of the teleseismic earthquake (Lomax and Michelini, 2009).

The accuracy of the dominant period calculation automatically uses that formula is influenced by the quality of the seismogram. While the quality of seismogram is determined by; 1. Disturbing noise. 2. Seismogram or earthquake signals. 3. Seismic station quality. Overcoming the influence of the seismic stations quality that records the earthquake wave can be done by using the good quality seismic station management system. Meanwhile, to overcome noise and seismogram defects, especially for earthquakes recorded by local seismic stations whose magnitude ranges from small (magnitude 3) to 8.6, it is required a special method for filtering order not to affect the accuracy of the automatic dominant period calculation.

The flowchart for the calculation from the dominant period automatically that applies the M-filter is shown in figure 1 as shown:

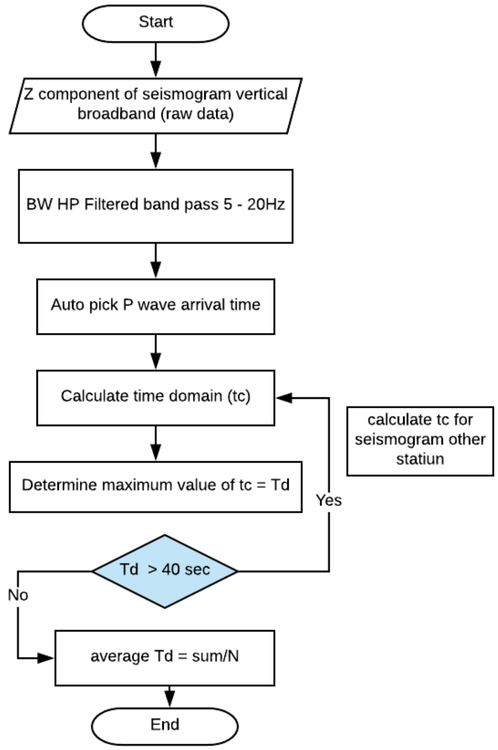
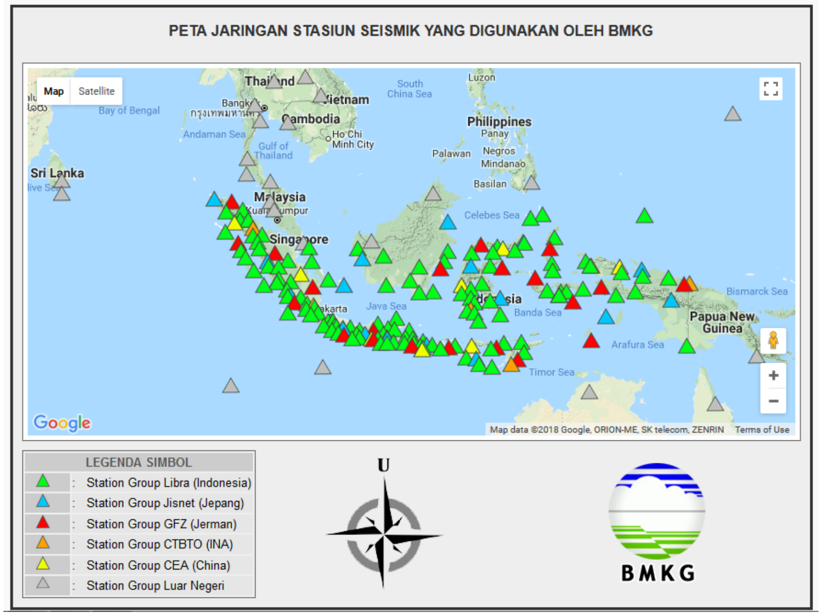


Figure 1. Dominant period computing flowchart that applies the M-filter (blue condition).

To reduce the effect of noise and signal defect on the calculation of the earthquake dominant period automatically, this study used M-filter. The M-filter used the concept that the dominant period for small and moderate earthquakes is unlikely to exceed twice the maximum dominant period of the great earthquake. The maximum dominant period measurement results for large earthquakes (Mw = 6.5 to 8.1) that occur worldwide can be accessed at http://www.earth-prints.org/bitstream/2122/6546/2/Table_S1_TauC_To_v2.1.pdf for 23.8 sec (Lomax and Michelini, 2011). The maximum dominant measurements for maxillary earthquakes are then used for the dominant period measurement filters for earthquakes recorded by local seismic stations in Indonesia, when the dominant measurements of the local earthquake period are about two (2) times the maximum dominant period (about 40 seconds), the researchers ensure that the signal used to measure the dominant period is defective or the noise is dominant compared to the signal of the earthquake, so the signal is not feasible to be used for decision making.

The data used to test the new methods for calculating the local dominant period of earthquakes is automatically accessible online data provided by the Jakarta - Indonesia Meteorological, Climatology and Geophysics Agency (BMKG): http://202.90.198.100/webdc3/ and using seismic stations as shown in figure 1.



https://inatews.bmkg.go.id/new/meta_eq.php

Figure 1: Seismic stations distribution that used in this research.

The data used is the seismogram data of Z component velocity of earthquakes that occur in 2010 until 2018. We used 15 earthquakes that show a false warning (FW) and 13 earthquakes that show a true warning (TW).

3. RESULTS AND DISCUSSION

The automatic computation results of the P wave dominant period of 28 earthquakes data stored in BMKG Jakarta, Indonesia are presented in table 1 below. By using the waveforms data recorded by local seismic stations available in Indonesia, we have estimated the P wave dominant period of earthquakes automatically by using Jokotingkir 2018 version software. It is for earthquake references in OT + 4 minutes to simulate the information available within 4 minutes after the earthquake occurred. Table 1 shows a comparison between dominant period by using Jokotingkir old version and dominant period by using Jokotingkir 2018 version.

Table 1. Result of P wave dominant period calculation from 28 data of the earthquakes used

No.	Origin time (OT)	Mw	Lattitude	Longitude	Tdi	Tdi*T50Ex	Decision	Tdf	Tdf*T50Ex	Decision
1	2018.02.03 12:25:55	4.8	-7.62	128.73	35.34	33.93	FW	1.31	1.11	TW
2	2017.12.22 12:32:28	4.5	-0.81	124.56	30.83	10.48	FW	1.00	0.11	TW
3	2017.11.07 01:14:22	2.9	-4.02	127.73	341.20	51.18	FW	2.22	2.46	TW
4	2017.11.04 23:32:21	4.9	-1.89	139.20	18.87	10.38	FW	10.9	9.80	TW
5	2017.10.11 04:20:11	4.3	4.32	125.45	16.10	14.97	FW	0.95	0.45	TW
6	2017.09.30 16:45:52	4.8	-2.99	136.94	15.34	13.50	FW	1.11	1.15	TW
7	2017.07.17 08:17:15	3.4	-1.99	102.08	51.49	16.47	FW	1.00	0.91	TW
8	2017.06.27 04:55:30	5.1	1.50	126.80	71.76	38.03	FW	0.99	1.04	TW
9	2017.06.05 01:50:59	4.9	-2.24	134.60	7.53	19.89	FW	6.15	3.56	TW
10	2017.04.16 01:08:39	3.1	-2.85	129.18	67.23	78.66	FW	1.08	1.26	TW
11	2017.03.22 24:25:59	3.8	1.16	126.54	43.64	15.27	FW	2/89	2.78	TW
12	2017.12.08 23:51:09	6.3	9.98	140.12	4.86	39.92	FW	5.08	5.28	TW
13	2017.07.06 22:03:57	6.4	11.13	124.96	8.53	10.24	FW	8.37	6.69	TW
14	2017.06.03 12:24:57	6.3	54.16	171.02	2.64	11.39	FW	3.76	1.65	TW
15	2017.10.31 14:42:14	6.5	-21.7	168.9	24.56	23.09	FW	3.16	1.76	TW
16	2017.01.10 06:13:47	7.2	4.44	122.57	10.76	2.26	TW	1.85	1.66	TW
17	2016-03-02 12:49:47	7.7	-4.90	94.23	23.03	12.89	TW	4.69	9.66	TW
18	2014-11-15 02:31:43	7.0	1.98	126.48	12.60	26.85	TW	4.50	7.92	TW
19	2013-04-06 04:42:35	7.0	-3.54	138.46	68.85	277.49	TW	4.37	0.30	TW
20	2012-12-10 16:53:10	7.0	-6.64	129.83	4.99	25.51	TW	5.46	8.08	TW
21	2012-04-11 10:43:09	8.2	0.76	92.43	43.65	1233586.37	FW	3.04	5.38	TW
22	2012-04-11 08:38:35	8.6	2.27	93.14	17.22	641.05	FW	4.69	5.53	TW
23	2012-01-10 18:36:58	7.1	2.43	93.07	155.70	21835.55	TW	2.08	2.30	TW
24	2010-10-25 14:42:21	7.8	-3.46	100.20	43.43	415.27	TW	5.08	11.73	TW
25	2010-09-29 17:11:24	7.2	-5.01	133.73	17.59	188.11	TW	1.30	0.24	TW
26	2010-05-09 05:59:44	7.2	3.67	96.10	3.70	8.74	TW	3.80	6.72	TW
27	2010-04-06 22:15:03	7.6	2.32	97.17	40.05	1236.76	TW	3.83	5.97	TW
28	2009-09-30 10:16:09	7.7	-0.70	99.80	10.53	284.39	TW	3.33	4.39	TW

Note: Tdf is the P wave dominant period value calculated by Jokotingkir software that has been applied the filter-M (Jokotingkir 2018 version). Tdi is the P wave dominant period value calculated by the Jokotingkir software that has not been applied the M-filter (Jokotingkir old version). FW = False Warning. TW = True Warning.

The result of P wave dominant period automatic computation by using Jokotingkir 2018 version software showed higher accuracy compared to the automatic computation of P wave dominant period by using the Jokotingkir old version software. The automatic computation of dominant period by using Jokotingkir 2018 version software can reduce errors (false warning) up to 60.7% to 0% or from accuracy 39.3% to 100%. This is because the Jokotingkir version 2018 software already equipped with an M-filter that has the ability to filter the calculation of the dominant period of a particular station that is likely to be affected by a seismogram defected or dominated by noise. The discriminant use of Td*T50Ex in this study as shown in Table 1 refers to the results of Lomax and Michelini (2009) studies that the discriminant has been shown to be highly correlated with the tsunami's importance (It). In addition, there is an indication of the linear relationship between (Td*T50Ex) and It. Threshold of Td*T50Ex is 10 sec. It means that if Td*T50Ex $\geq$ 10 sec, so the earthquake has tsunami potential (Madlazim, 2013; Lomax and Michelini, 2009).

The earthquakes used in this study include small earthquakes to large earthquakes, both false warning, and true warning. For major non-tsunamigenic earthquakes and tsunamigenic earthquakes registered in the NOAA/WDC Historical Tsunami database (http://www.ngdc.noaa.gov/hazard/tsu_db.shtml), most of the earthquakes with magnitude Mw $\geq$ 7 occur within recent years. As a tsunami impact measurement, we defined the estimation of the size decision whether it is a tsunami or not (tsunami importance, It). This is for tsunamigenic earthquakes based on 0 - 4 descriptive index of tsunami effects and maximum water heights h (in meters) of the NOAA/WDC database, see Madlazim (2013) for more detail It info. It is approximate because it depends heavily on available seismic instrumentation, coastal bathymetry and population density in the incident area. This corresponds to the JMA threshold for issuing "Tsunami Early Warning"; the largest or most powerful tsunami usually has It $\geq$ 10.

4. CONCLUSIONS

A M-filter has been developed and used to filter out defective and high-null seismogram signals, so the seismogram is not used for the average calculation of the dominant period. The calculation results of the dominant period by using Jokotingkir software 2018 version shows a higher accuracy than the calculation of the dominant period by using the old version of Jokotingkir software.

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REAL-TIME RADIOACTIVE PRECURSOR OF THE APRIL 16, 2016 Mw 7.8 EARTHQUAKE AND TSUNAMI IN ECUADOR

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ABSTRACT

On the 16th of April 2016, a Mw 7.8 earthquake with a minor tsunami impacted coastal Ecuador, being the most devastating seismic event registered in northern South America in this century so far. Three hours before, an unusual increase of the environmental radiation level was registered at 222 km distance from the epicenter. Trough this study, we have been able to achieve an undeniable relation between such type of anomalies of geological origin and the seismic activity in Ecuador, solving thus the uncertainties presented in related works around this clear earthquake precursor. In this sense, our results demonstrate a full correlation in earthquake detection, reducing also the uncertainty window to less than a few hours.

Keywords: *Earthquake precursors, environmental radiation, geological radioactivity, Early Warning System, Ecuador*

1. INTRODUCTION

The deadliest of all natural hazards by death toll are earthquakes (Kahn, 2005; Anbarci et al., 2005; Raschky, 2008; Marano et al., 2010; Holzer and Savage, 2013). There are, at least one dozen of known earthquakes, which claimed more than hundred thousand lives, reaching up to more than 700 thousand in two single events in China (Butler et al., 1979; Chen, 1988; Gang, 1989; Hou et al., 1998; Gupta et al., 2001). Frequencies of seismic events have been studied by a variety of authors (McGuire, 1995; Shome et al., 1998; Ruff and Kanamori, 1980; McCaffrey, 2008). However, the most accepted data base is of the National Earthquake Information Center of the United States Geological Survey, where there are annually in average more than 1300 seismic events registered being stronger than magnitudes of 5, more than 130 stronger than magnitudes of 6 or higher, and up to 20 earthquakes with a magnitude of higher than 7. Practically all earthquakes with magnitudes higher than 6 being close to settlements or cities leave fatalities. There is a high amount of studies, which attempt to predict earthquakes (Scholz et al., 1973; Rikitake, 1968; Aki, 1981; Smith, 1990; Varotsos and Lazaridou, 1991; Geller, 1997; Keilis-Borok, 2002; Johnston et al., 2006) and try to be able to identify pre-monitoring signals (Allegre et al., 1982; Asteriadis and Livieratos, 1989; Smith, 1998; Sidorin, 2003; Freund, 2007; Cicerone et al., 2009; Freund et al., 2009; Akhoondzadeh et al., 2010; Pulinets and Ouzounov, 2011; Vigny et al., 2011; Yao et al., 2012; Tramutoli et al., 2013; Eleftheriou et al., 2016). Such studies may allow the installation of an early warning system, which in turn facilitates in even short time to take actions and protect life, property and certain infrastructure from incoming destructive seismic waves (Suárez et al., 2009; Rainieri et al., 2011; Satriano et al., 2011; Oliveira et al., 2015).

During the reactivation of the Cotopaxi volcano in central Ecuador (Toulkeridis et al., 2015), observations of the radioactivity determination in the environment lead to the idea, that such data may be able to interpret and predict the nearby occurring volcanic eruptions and also seismic events of certain magnitude. The main aim of our research is to establish a mechanism in which we will confirm a relation between the radiation of the environment and the potential prediction of strong seismic events, like the destructive earthquake of the 16th of April 2016 in coastal Ecuador (Toulkeridis et al., 2017).

There are several studies related to radiation as pre-earthquake sign (Madariaga, 1977; Gokhberg et al., 1982; Dea et al., 1991; Serebryakova et al., 1992; Virk and Singh, 1993; Zeng et al., 1993; Hartzell et al., 1996; Maeda and Tokimasa, 1996; Ouzounov and Freund, 2004; Tronin et al., 2002; Pulinets and Dunajecka, 2007; Ni et al, 2005; Pulinets et al., 2006; Ouzounov et al., 2007). In a particular study, such anomalies were reported for a variety of medium to strong earthquakes such as the M7.9, Bhuj, Gujarat, India in 2001, the M6.8 Boumerdes, North Algeria in 2003, M6.6 Bam Southeastern Iran in 2003 and the M9.0 Sumatra–Andaman Islands, Northern Sumatra, being a mega trust event in 2004 (Ouzounov et al., 2007). The anomalous variation of the radiation has been determined by infrared satellite data and occurred a few days to weeks (4-20 days) prior to the main events (Ouzounov et al., 2007). These anomalies are speculated to have been triggered close or within active tectonic faults due to a complex interaction of the existing stress, electrochemical and thermodynamic processes between the lithosphere, hydrosphere and atmosphere as part of electromagnetic phenomena related to earthquake activity (Ouzounov et al., 2007). Nevertheless, although the relation between radiation in seismic active areas has been observed in a variety of areas, this is the first time documented on ground data and with a more accurate spatio-temporal earthquake location.

2. GEODYNAMICS AND HISTORICAL COASTAL EARTHQUAKES IN THE ECUADOR REGION

Due to its geodynamic situation along the Pacific Rim, the coastal Ecuadorian continental platform is a regularly target of earthquake activity and tsunami impacts (Gusiakov, 2005; Pararas-Carayannis, 2012; Rodriguez et al., 2016). The active continental margin and associated subduction zone between the oceanic Nazca Plate with the continental South American and Caribbean Plates, both separated by the Guayaquil-Caracas Mega Shear (Kellogg and Vega, 1995; Gutscher et al., 1999; Egbue and Kellog, 2010) give rise to tsunamis of tectonic as well submarine landslide origin (Shepperd and Moberly, 1981; Pontoise and Monfret, 2004; Ratzov et al, 2007; 2010; Ioualalen et al., 2011; Pararas-Carayannis, 2012).

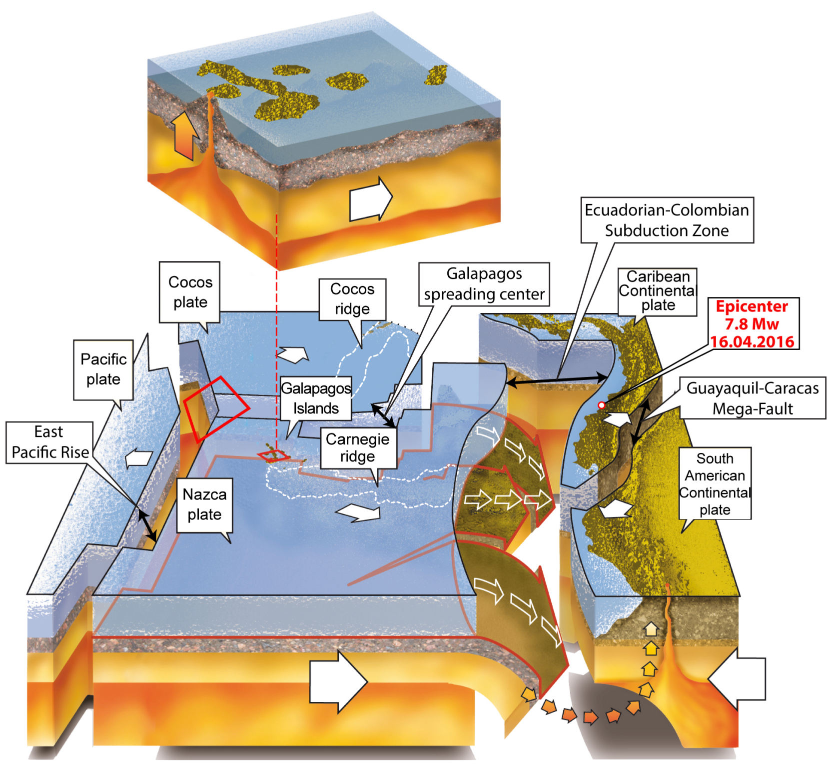


Fig. 1: Geodynamic setting of Ecuador, the Galapagos Islands and the Carnegie Ridge. Adapted from Toulkeridis, 2013 and Rodriguez et al., 2016.

A further origin of earthquakes and tsunamis has been credited to the Galápagos volcanism (Toulkeridis, 2011). The active Galápagos hotspot has produced several voluminous shield-volcanoes, most of which are inactive due to the ESE-movement of the overlying Nazca oceanic plate (Holden and Dietz 1972; Toulkeridis, 2011). The main Galápagos Islands are located south of the E-W-trending Galápagos Spreading Center, east of the N-S-trending East Pacific Rise and some 1000 km west of the Ecuadorian mainland. Due to the volcanic activity and the subsequent plate drifting, two aseismic volcanic ridges were created. The first being the Cocos Ridge is moving to the NE while the second, being the Carnegie Ridge, is moving to the East above the Cocos and Nazca Plates respectively (Harpp et al., 2003). These submarine extinct volcanic ridges are the result of cooling/contraction reactions of magma, as they slowly sunk below the sea surface due to the lack of magma supply, lithospheric movement and strong erosional processes. With time, these submarine volcanic ridges, as well as various microplates, have accreted on the South American continent (Reynaud et al., 1999; Harpp and White, 2001). Nonetheless, such aseismic ridges like the Carnegie Ridge become an obstacle in the oblique subduction process and may generate within the subduction zone a potential valve of marine earthquakes and occasionally tsunamis along the Ecuadorian coast (Pararas-Carayannis, 2012). The Carnegie Ridge collides towards the Ecuadorian continental margin with a velocity of as low as 5 cm per year at a latitude between 1°N and 2°S (Pilger, 1983).

From the known record of the last two centuries, the Ecuadorian shoreline has witnessed a dozen times strong earthquakes and marine quakes, some of which generated tsunamis by mainly local origins with various intensities - one being of up to 8.8 Mw in 1906 (Rudolph and Szirtes, 1911; Kelleher, 1972; Beck and Ruff, 1984; Kanamori and McNally, 1982; Swenson and Beck, 1996; Pararas-Carayannis, 2012), while evidences of paleo-tsunami deposits are scarce (Chunga and Toulkeridis, 2014). Other prominent examples of earthquakes with subsequent tsunamis along the Ecuador–Colombia subduction zone include tsunamis in 1942 (Mw 7.8), 1958 (Mw 7.7) and 1979 (Mw 8.2) within the 600-km long rupture area of the great 1906 event (Collot et al., 2004). While the 1906 event caused the death of up to 1500 persons in Ecuador and Colombia with an unknown financial damage to the existing infrastructure, the 1979 tsunami killed in Colombia at least 807 persons and destroyed approximately 10,000 homes, knocking out electric power and telephone lines (Pararas-Carayannis, 1980; USGS, 2016a).

The evaluation of the last marine quakes, which generated tsunamis, suggests that the probability of a major or great earthquake in this margin region is enormous, especially as there must be substantial strain accumulation in this region (Pararas-Carayannis, 2012). Additionally, given into consideration that the last earthquake in 1979 did not release the amount of energy as the 1906 event, there has been a calculated high probability in the near future, that an earthquake within the Ecuadorian-Colombian trench may generate a tsunami of similar magnitude to that of 1906, which might be even more destructive than the one in the past, particularly if it occurs near high tide (Pararas-Carayannis, 2012). The potential of high losses and damage is given by the fact that the infrastructure of the fishing, tourism and other industries and the movement to live along the beaches, have been highly developed within the last decades along the Ecuadorian coasts. Based on historic known impacts of tsunamis in Ecuador in the last two centuries, the probability of a strike in 2015 has been of about 87% (Rodriguez et al., 2016).

3. THE EARTHQUAKE AND TSUNAMI OF 16 APRIL 2016

In the late afternoon of Saturday, at 18:58:36 (UTC-05:00) local time, a devastating earthquake with a magnitude of 7.8 Mw impacted coastal Ecuador (USGS, 2016b). The seismic event with an epicenter 29 km SSE of Muisne, Province of Esmeraldas (Fig. 1, 2) occurred within a depth of 21 km, killing 663, filling tens of thousands in refugee camps and affecting some two million persons directly. In many aspects, the mentioned earthquake has many similarities with the earthquake of the 14th of May 1942. Nonetheless, the resulting tsunami based most probably on a triggered submarine landslide did not have any remarkable impact (Toulkeridis et al., 2017).

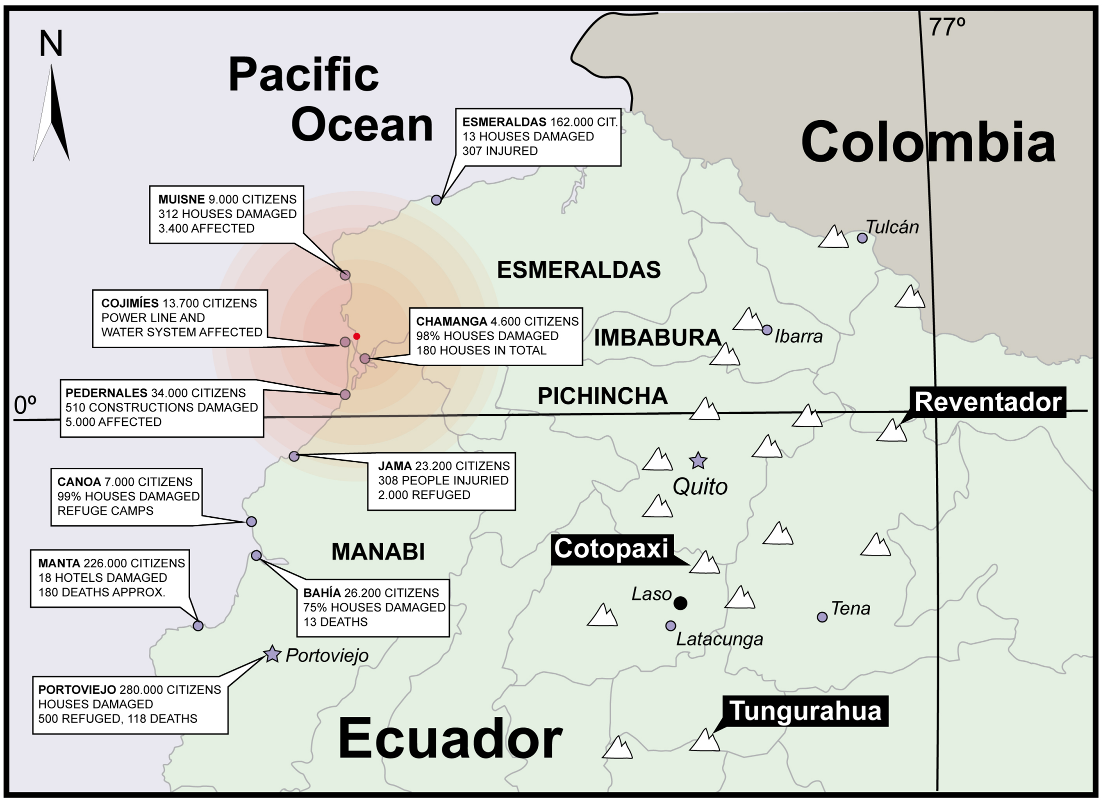


Fig. 2: Epicenter of the 7.8 Mw earthquake (red dot) and a selection of damages in the coastal area. Note location of Reventador, Cotopaxi and Tungurahua volcanoes as well as the station of Laso (black dot), where the radiation of the environment has been determined.

The earthquake impacted a large part of a variety of coastal cities destroying between up to 99% of some close-by villages and cities, Pedernales, Jama, Chone, Portoviejo among others (Fig. 2), in which lines of electricity transmission, infrastructure of water supply, hospitals, schools, private and public buildings, main roads and highways have been severely affected or even completely destroyed. The costs of the damages of the mentioned infrastructure are summing up an approximate loss of some 3.3 billion USD (El Telegrafo, 2016; Toulkeridis et al., 2017).

After the mainshock, 85 aftershocks between 3.8 Mw and 6.8 Mw were recorded by USGS in Ecuador until May 24, last day until we have processed data. The epicenters were localized within a rectangle of coordinates [79.5 W - 81.5 W, 2 S - 1 N], reaching the highest magnitudes around the rupture zone, and 86.05% of them during the first 10 subsequent days.

4. ANALYTICAL PROCEDURES

A LUDLUM MODEL of the 4525 SERIES™ enabled to determine the occurrences of natural and artificial radioactivity in the environment close to the company NOVACERO, which provides a variety of steel products. In order to detect radioactivity especially in vehicles in a pass-through or drive-through scanning modus, the Model 4525 Radiation Portal Monitor (RPM) has been installed in late 2014, some 22 km SW of the Cotopaxi volcano in central Ecuador. The RPM is a system with sensitive gamma and optional neutron detectors for detecting small amounts of radiation. When no vehicle drives through the scanner, the natural background of radioactivity is measured constantly and simultaneously (one measurement per minute). When a radiation alarm occurs, the Supervisor and any Echo stations will sound an audible alert. The system determines if the alarm is a Naturally Occurring Radioactive Alarm (NORM). NORM consists of materials enriched with radioactive elements found in the environment, such as uranium, thorium, and potassium and any of their decay products such as radium and radon. These types of alarms are characterized as having a high background over the entire length of the occupancy rather than the "spike" of a typical gamma alarm.

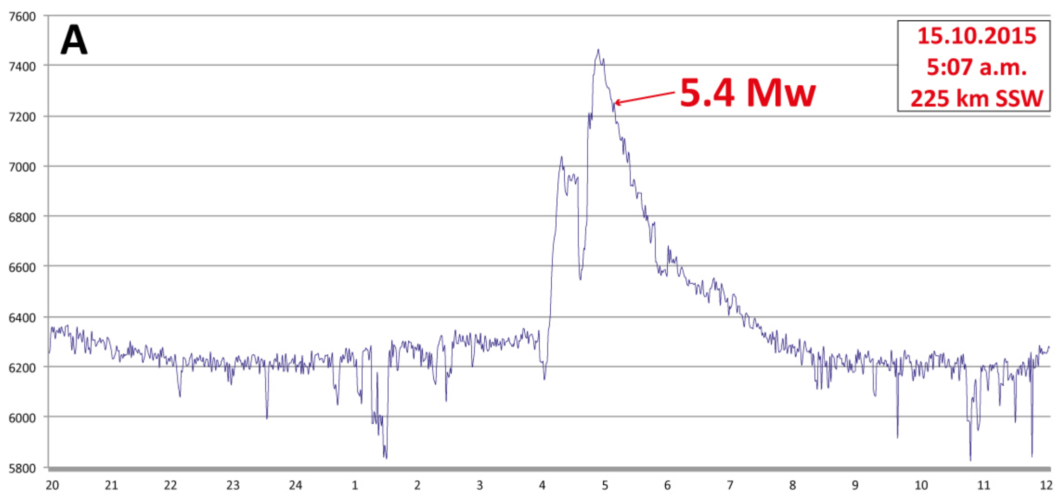
Many factors have to be considered when attempting to do this: (1) Background radiation is not constant. It is continuously changing due to cosmic events, weather (eg. beginning of rainstorms), and other influences. Oilfield pipe, hot water heaters, and industrial piping will sometimes contain scale that is radioactive. Most alarms are the result of NORM; (2) Medical tests that use a radioactive dye or tracer are yet another problem. Patients can be released from the hospital reading several thousand μR/hr or less than 100μSv/hr, and set off RPMs 30 m (100 ft) away; (3) A third problem is that of radiographers and certified welders who use a powerful radiation source to check their material or welds for cracks. This radiation is powerful enough to set off RPMs 3 km away.

5. RESULTS AND DISCUSSION

Radiation of the environment in central Ecuador has been determined almost continuously realizing data at every minute of the day since Mid-January of 2015 up to present day. However, most of the time there has been only the regular day-by-day radiation level of the environment defined as background radiation level (Fig. 3d) with 6200 becs per minute. This radiation of the environment appeared with no significant changes since the beginning of the measurements and has been changed only by the appearance of some seismic events, such originating by volcanic nature or fault-triggered.
Therefore, all the main volcanic eruptions of the close-by Cotopaxi volcano during its visible reactivation in spring of 2015 have been registered by the RPM, prior their occurrences. Other temporal eruptive activity and corresponding environmental radiation inside the same time window originating from the Tungurahua and Reventador volcanoes in Ecuador (Global Volcanism Program, 2016a; 2016b), corresponding craters being in a distance of 73 and 132 km from the RPM

respectively (Fig. 2), were not registered or identified in our data base, most probably due to their low intensity. Additionally, we have been detected a clear pattern in the determination of the environmental radiation of seismic activity in Ecuador since 2015 for all events registered by USGS with magnitudes above 4.9 Mw.

A few hours before an earthquake generation, from 1 hour (Fig. 3a) to 5 hours (Fig. 3b), an unusual high level of radioactivity has been detected by the RPM, reaching levels between 6800 bec/min (Fig. 3b; 3c) and 7465 bec/min (Fig. 3a). This behaviour is related to almost all of the earthquakes recorded. We have also identified the delay in the generation of the earthquake is in almost all cases inversely proportional to the level of radiation reached and to the duration of such anomalies.
According to the general behavior of the precursor anomalies identified, on the early hours of the 16th of April in 2016, an unusual radiation level has been registered by the RPM, which we interpret as a clear pre-monitoring signal of a major seismic event resulting to the most devastating Earthquake of northern South America in this century so far. The alteration of the regular background radioactivity started around 15.30 p.m. and lasted for about almost two hours in which the radiation increased by 650 bec/min, finding a peak level of 6850 bec/min some minutes after the start (Fig. 3c). After reaching this peak level, radiation dropped down to regular level three hours later, sinking down to 6200 bec/min at around 18:45, some minutes prior the Earthquake of 18:58 (Fig. 3c), of which epicenter has been located some 222 km west-northwest of the RPM. This behavior or pattern prior a seismic event has been previously observed with less intense earthquakes as presented earlier (Fig. 3a; 3b).



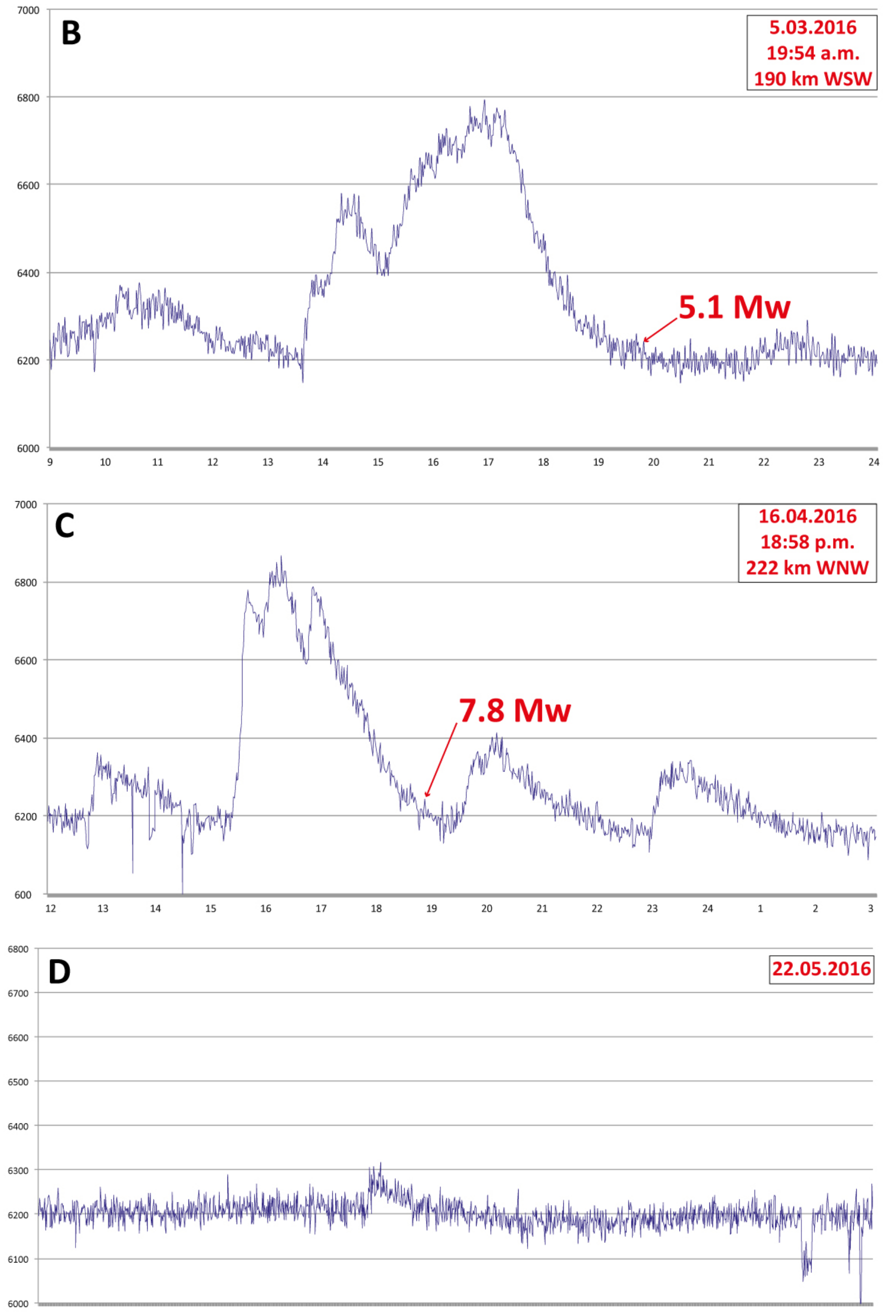


Fig. 3a-d: a) Typical pre-earthquake (5.4 Mw) radiation behaviour of the 15th of October 2015 at 2.50 S, 78.76 W with a depth of 97,1 km (USGS, 2015); b) Typical pre-earthquake (5.1 Mw) radiation behaviour at the 5th of March 2016 at 1.43 S, 80.40 W with a depth of 10 km (USGS, 2016); c) Main 7.8 Mw earthquake of the 16th of April 2016 with different radiation behaviour than regular days. Location of epicenter has been at 0.35 N, 79.93 W at a depth of 21 km (USGS, 2016); d) Regular radiation level of 24 hours of the 22nd of May 2016.

The most plausible origin of such radiation anomalies prior to strong earthquakes might be the result of a complex interaction and coupling behavior of the Lithosphere, Hydrosphere, Atmosphere and Ionosphere (Pulinets et al., 2000; Hayakawa and Molchanov, 2002; Ouzounov et al., 2007). The degree of radiation anomaly certainly depends on the intensity of the earthquake as well as local to regional atmospheric conditions, but will have always a direct link to the magnitude of the earthquake (Ouzounov et al., 2007). As such outgoing long wave earth radiation anomalies and latent increases of temperatures have been noticed prior several strong earthquakes (Dey et al., 2004; Cervone et al., 2005; Pulinets et al., 2006), some of them which even generated severe tsunamis, the application of an early alert system may be applied in a variety of environments such as active continental rims, like the subduction zones around the Pacific Ocean as well as around transform fault zones, like the Guayaquil-Caracas Mega shear in south America or the San Andres fault in the USA, being able to give enough warning time in order to evacuate people from vulnerable places within an adequate period of time.

6. CONCLUSIONS

It has been highlighted the important precursor role of environmental radiation in the precise location of earthquakes in Ecuador. A direct application and benefit of our study may be to achieve an accurate early warning system based on the data presented. The radiation data demonstrate clearly undeniable anomalies, which allow during their development an extremely early warning time towards society and administrators of basic infrastructure to react ahead of a potential catastrophic seismic event. Nonetheless, a more spatial resolution is needed by means of a sensors array, which we propose to be installed based on an efficient and therefore strategic distribution in the entire country of Ecuador. This sensors array will provide then key information for the complex Earthquake Early Warning System, at which we are progressing in Ecuador.

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SCIENCE OF TSUNAMI HAZARDS

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BRIEF HISTORY OF EARLY PIONEERING TSUNAMI RESEARCH – Part A

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ABSTRACT

The year 2015 marked the 50th anniversary of operations of the International Tsunami Warning System in the Pacific Ocean - which officially begun in 1965. Our previous report in this journal described briefly the establishment of early tsunami warning systems by the USA and other countries and the progressive improvements and international cooperative efforts which were expanded to include other regions in establishing the International Tsunami Warning System under the auspices of the Intergovernmental Oceanographic Commission (IOC) of UNESCO, with the purpose of mitigating the disaster's impact. The present paper (Part A) provides a brief historical review of the early, pioneering research efforts undertaken mainly in the U.S.A. and in Canada, initially by scientists at the Hawaii Institute of Geophysics of the University of Hawaii, at the U. S. Coast and Geodetic Survey, at the Honolulu Observatory - later renamed Pacific Tsunami Warning Center (PTWC) - at the International Tsunami Information Center (ITIC), at the Joint Tsunami Research Effort (JTRE) and at the later-established Joint Institute of Marine and Atmospheric Research (JIMAR) at the University of Hawaii, in close cooperation with scientists at the Pacific Division of the National Weather Service (NWS) of and the Pacific Marine Environmenal Laboratory (PMEL) of NOAA in Seattle. Also, reviewed briefly - but to a lesser extent - are some of the additional early research projects undertaken by scientists of the U.S. Coast of Geodetic Survey (USC&GS), of the U.S. Geological Survey (USGS), of the U.S. National Geophysical Data Center (NGDC) in Boulder, Colorado, of the U.S. Army, Coastal Engineering Research Center (CERC) and the Waterways Experiment Station (WES) in Vicksburg, Mississippi, and of researchers at different U.S. Universities and by members of the Tsunami Society, as well as at by many other national and international governmental and non-governmental institutions and Civil Defense Agencies. Part B will expand on international contributions.

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

BRIEF HISTORY OF EARLY PIONEERING TSUNAMI RESEARCH – Part A: USA and Canada

4.6 Marine Geology and Volcanology Studies

4.6.1 Other volcanological and Geologicalstudies (Mount Augustine, Alaska; Cumbre Vieja/LaPalma-Canary Islands; Caribbean-LesserAntilles; The earthquake and Tsunami of 365 A.D in the Eastern Mediterranean

4.7 Development of Deep-Ocean Instrumentation and Telemetry Systems - Establishment of a Regional Tsunami Warning System for the Hawaiian Islands – Establishment of other Regional Warning Systems.

4.8 Preparation of Tsunami Travel Charts in Support of the Tsunami Warning System in the Pacific - Numerical Modeling of Tsunami Wave Refraction

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

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9.2 Critical Assessment of Global and Regional Vulnerabilities and Strategies for Mitigating Tsunami Impacts on Nuclear Power Plants.
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13.4 Change of Name to Tsunami Society International.
13.5 Awards of Tsunami Society International
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CONCLUSIONS

REFERENCES

BRIEF HISTORY OF EARLY PIONEERING TSUNAMI RESEARCH – Part A: Mainly in USA and Canada

1. INTRODUCTION

Scientific knowledge has several distinct and important facets in the development of our civilization. The term “science” refers to a collection of known facts and observations’ which taken together over a period of time provide humanity with an understanding of physical phenomena – thus giving us greater power over nature, as well as a base and the means by which we can improve and protect our lives, our environment and to mitigate deleterious impacts of natural disasters. Thus, the study of the history of a scientific field allows us to have a glimpse of just how we gradually discovered everything we know about the natural laws and how we can improve our understanding and our subsequent progress to build block by block on our cumulative knowledge.

Earthquakes and tsunamis are well known natural hazards that have impacted human settlements for thousands of years. However seismology is a very new science. The study of Tsunami Hazards - as a scientific discipline - did not begin until after the 1946 Aleutian earthquake, so it has been an even newer field of science. A brief introduction in pioneering research in both seismology and the newer interdisciplinary field of “Science of Tsunami Hazards” is provided in this introduction and in the following sections of this report.

1.1 Pioneering Research in Seismology

Although earthquakes from the beginning plagued humanity and millions of lives were lost, the causes of earthquakes were not studied very seriously until the 19th Century. Thus Seismology is a very new science. A book addressing seismic hazards was written by an Irish Engineer, Robert Mallet and was entitled, "The Great Neapolitan Earthquake of 1857: The first book on "Principles of Observational Seismology", which resulted from his investigation of this particular earthquake, was a milestone in the evolution of seismology. The subsequent history of evolution of seismology is quite interesting. Mallet and his contemporary Englishman, John Milne, were the pioneers of such research. However Milne is considered to be the father of seismology because he made a remarkable impact on the study of earthquakes by designing and constructing earthquake measuring devices and by collecting and publishing earthquake data and maps of worldwide earthquake distribution. This early data formed the basis for the initial understanding of earthquakes and for measuring important seismic parameters.

The early history of pioneering research in seismology is extensively documented in the scientific literature and in summary in other publications (Pararas-Carayannis, 2000). The first seismographs in the United States were installed in 1887, at the Berkeley campus of the University of California and at the Lick Observatory at Mount Hamilton, California. Prior to the great San Francisco earthquake of 1906, earthquake research in the U.S. had advanced very slowly compared to efforts in Japan and Europe. However, around the turn of the century, a small number of U.S. Geological Survey scientists and geology professors at a few U.S. universities, begun to contribute earthquake data and to compile lists of historic earthquakes in the U.S. At that time, very little was known about earthquakes, how and where they occurred, or the risks they would present. The modern theory of plate tectonics had not yet been proposed and was still years away. The great 1906 San Francisco earthquake was the event that triggered the interest of scientists and resulted in numerous scientific Investigations. Comprehensive studies of this earthquake and of the San Andreas fault system in California, mark the beginning of modern seismology in the U.S.A. (Pararas-Carayannis, 2000).

Some of the early scientists to study the great 1906 San Francisco earthquake in great detail were Professor Andrew C. Lawson, chairman of the geology department at the University of California, Berkeley, Professor H.F. Reid of Johns Hopkins University, and G.K. Gilbert of the U.S. G.S. These scientists are considered to be some of the best known of the early American seismologists. After the 1906 earthquake, Professor Lawson was appointed chairman of a government-funded commission of scientists from different universities and the U.S. Geological Survey. These scientists were charged with the responsibility of investigating in detail the San Francisco earthquake. The Commission's final report on the great San Francisco earthquake (often referred to as the Lawson report) was published in 1908. The report was a comprehensive compilation of detailed studies by more than twenty scientists on the earthquake's damage, the slip movement along the San Andreas Fault, the seismograph records of the earthquake from around the world, and the underlying geology in northern California. Reid published a comprehensive survey of slip movements along the San Andreas Fault. Also, Reid was the first to propose that earthquakes are elastic dislocations in rock, similar to the snapping of a ruptured rubber band. Reid's concept of elasticity continues to influence today's scientific thinking about earthquakes.

The exhaustive investigation and surveys of the 1906 San Francisco earthquake illustrated the importance of collecting valid, extensive, and repetitive data on earthquakes, their effects, and on the faults on which they occur. The comprehensive Lawson report - combining all of the studies of the 1906 San Francisco earthquake - formed the basis for the understanding of earthquakes in California. The detailed surveys described in this report, showed that earthquake damage was closely related to the design and construction of a structure, as well as to the type of soil or rock on which a structure was built. For example, the 1906 earthquake resulted in maximum damage to buildings and structures that had been built on soft sedimentary soils.

1.2 Pioneering Research in Tsunami Science

Although the devastating impacts of earthquakes were well known as well as those of the destructive sea waves near the seismic source regions, the interrelationships between them were not understood nor that earthquake-generated sea-waves – then known as Seismic Sea waves - could have devastating impact at distant coastal areas, often across an entire ocean. Thus the study of Tsunami Hazards - as a scientific discipline - did not begin until the 1946 earthquake in the Aleutian Islands generated destructive waves that reached Hawaii and other distant locations in the Pacific Ocean. The 1946 tsunami killed 173 people in the Hawaiian Islands and there was no advance warning. This disaster focused attention to the need of establishing an early warning system that could be used to evacuate in a timely fashion the populations of coastal areas to safe locations and to shut down critical infrastructure facilities located in vulnerable coastal regions. Thus, in 1948 an early Tsunami Warning System was established in the USA to detect and rapidly locate earthquakes in the Pacific region, and if one was significant and occurred in an area where tsunami generation was possible, to determine quickly the parameters' and make a decision in providing a timely warning. Also, it was necessary for this early warning system to develop a method and provide accurate arrival times of the tsunami at various places and to report accurately on observed tsunami wave heights. These developments continued for many decades and the challenges in defining tsunami wave heights continued to the present and were outlined in a recent publication by Paula Dunbar, George Mungov, Aaron Sweeney, Kelly Stroker and Nicolas Arcos (Dunbar et.al. 2017)

1.3 Early Applied Research Efforts in Support of a Tsunami Warning System for the Pacific Region

A previous review (Pararas-Carayannis, 2015) summarized: a) the institutional support of early regional tsunami warning systems in the USA and internationally; b) the capabilities and limitations of these early warning systems and c) the cooperation and coordination that later led to the establishment and development of the International Tsunami Warning System in the Pacific - as also described in the scientific literature (Cox, 1963,1968; Spaeth & Berkman, 1964; Murphy & Eppley, 1969; Pararas-Carayannis, 1977, 1986g, 1997, 1986g). At the International Workshop in Sidney, Canada in 1986, George Pararas-Carayannis of ITIC, Iouri Oliounine, the Secretary of UNESCO-IOC and the Associate ITIC Director Norman Ridgway expanded on the roles and significance of the Tsunami Warning System, on the need for improvements of the early operational networks by the development of a comprehensive Communication Plan, on the installations of additional seismic and tidal stations and on the additional need of preparation of tsunami travel time charts (Pararas-Carayannis et.al., 1985). The early institutional efforts and support helped ensure the prompt observations of every major earthquake and tsunami in the Pacific and the dissemination of informational bulletins, watches and warnings.

Part A of the present paper has been prepared as a brief historical documentation of the early pioneering efforts in both applied and theoretical research mainly in USA and Canada - which helped with the progressive understanding of the tsunami phenomenon and the development of a new interdisciplinary field, which became generally known as "Science of Tsunami Hazards". An additional intent of the paper is to pay tribute to some individual scientists – many of who are no longer with us – whose early research efforts and contributions led to a better understanding of tsunamis, to significant operational improvements of the early tsunami warning systems, and of the subsequently established International Tsunami Warning System in the Pacific.

In brief, the study of Tsunami Hazards is a relatively new interdisciplinary field of science. As mentioned, early tsunami research on tsunamis was primarily conducted in Hawaii, in Japan and in Russia (then known as USSR) after World War II, but intensified after the destructive 1946 tsunami from the Aleutian Islands, which hit without warning Hawaii and coastal areas in the Pacific. The early pioneering research work on tsunamis in Hawaii described in this paper, was later extended and expanded by scientists elsewhere in the USA and internationally. A second paper presently under preparation (Part B), will expand on summarizing the numerous and significant contributions in applied and theoretical research of international scientists around the world, which also helped in the understanding of the tsunami phenomenon and the development of the Science of Tsunami Hazards.

Specifically described in the present review (Part A) are the early research projects by individual scientists who had been involved in a variety of other fields of science, but who later became interested in tsunamis and joined institutionally-sponsored programs. Although these programs and some of the names of researchers were provided in a previous report in this journal, there was not sufficient information given on the type of research these scientists conducted in helping to understand the tsunami phenomenon, in documenting historical events or on applied and theoretical research that helped support the Tsunami Warning Systems in the Pacific and elsewhere later. Thus, the present paper summarizes briefly some of the specific research activities of the first 30-40 years of this scientific field, which helped form, the basis of knowledge and the conduct for subsequent research projects to be carried out.

Finally, the preparation of the historical review (Part A) provided in the subsequent sections was extremely difficult and not necessarily presented in the right chronological order. Also, it is vey possible that there have been many omissions in describing other earlier pioneering interdisciplinary research in all aspects of mathematical, geophysical and marine sciences, which preceded the development of "Tsunami Science". The author apologizes for any omissions or for focusing more extensively on the work that was conducted in Hawaii and the USA, with which he was more familiar. Part B will expand on early research work of international scientists around the world.

2. EARLY TSUNAMI RESEARCH IN THE USA AND INTERNATIONALLY – THE EVOLUTION OF THE SCIENCE OF TSUNAMI HAZARDS

The earliest tsunami research conducted at the University of Hawaii has been described in numerous papers by Doak Cox and others (Cox, 1963, 1965). As technology improved plans for tsunami research for the U.S.A. were being formulated at the NOAA Pacific Marine and Environmental Laboratory (PMEL) which had assumed an increasingly important role for coordination in the 1980's (Bernard, 1983). An overview of Tsunami Research covering three decades from 1960 to 1990 was also published in the Proceedings of the Symposium on Theoretical and Observational Aspects of Tsunamis, associated with the 1992, XVII General Assembly of the European Geophysical Society, which took place from 6-10 April 1992 at the University of Edinburgh in Scotland (Pararas-Carayannis, 1992a) and chaired by the Russian academician Sergey Soloviev.

The following sections summarize the focus of early tsunami research in the USA and internationally, a partial listing of participating scientists and organizations and a partial listing of research and developmental projects that had a direct operational significance for the International Tsunami Warning System in improving the evaluation of potential tsunamis and the issuance of prompt and effective warnings - mainly to threatened coastal communities of Pacific nations. It is very possible that the present overview has missed important research projects conducted internationally and that a revision or corrections may be necessary in the future to include such additional work and references.

2.1 Evolution of Early Tsunami Warning Systems and Development of the International Tsunami Warning System in the Pacific and Other Oceans and Seas.

As indicated earlier, the evolution and development of early tsunami warning systems in United States and Japan have been documented extensively in the tsunami literature (Cox, 1963, 1965, 1968; Murphy and Eppley, 1969; Pararas-Carayannis, G. 1977, 1983). After the Aleutian tsunami of April 1, 1946 caused major damage and many casualties in the Hawaiian Islands and elsewhere in the Pacific, it was obvious that a means of providing timely warnings to the threatened populations was necessary. As described in the literature, the early Tsunami Warning System that was established in 1948 in USA was confronted with a number of problems that needed to be solved. Specifically, this early U.S. system needed to detect and rapidly locate earthquakes in the Pacific region, and if one was significant and occurred in an area where tsunami generation was possible, to determine quickly the parameters and make a decision in providing a timely warning. Also, it was necessary for this early warning system to develop a method and provide accurate arrival times of the tsunami at various places. This was a very difficult task, given the state of technology of this early period. A drawback was that in the 1940's photographic methods were still being used to record earthquakes, and there was no real time visual recording equipment in conjunction with existing seismographs. Thus in 1947 and 1948 new instruments were built and installed at three seismic observatories in the United States. Later improvements included modifications by adding electronic amplifiers that included an alarm circuit so that whenever a major earthquake was recorded by a seismograph, an audible and/or visible alarm was tripped, thus insuring prompt observation of every major earthquake. Tide observers in this early tsunami warning system of the U.S. Coast and Geodetic Survey (USC&GS) were provided with instructions as to how to measure observe and report to Honolulu Observatory waves that recorded or visually observed in the coastal areas that had been assigned to them (Spaeth, M.G.; Arens, C. E. et al. 1966). Also a tentative communication plan was needed utilizing existing communications of the U.S. Armed Forces and of the Civil Aeronautics Administration as well as a tsunami travel time chart (Fig. 1) (Pararas-Carayannis, 1983),

The original U.S. Tsunami Warning System consisted of three seismological observatories of the U.S. Coast and Geodetic Survey at Sitka, College, Tucson, and Honolulu, and 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 at Ewa Beach in Honolulu was made the headquarters of this initial Tsunami Warning System. Its initial 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 warning information was also provided to the civil defense agencies of the states of California, Oregon, and Washington.

Subsequently, the great destruction that was caused by the May 1960 Chilean tsunami prompted a large number of countries and territories to join this early Pacific TWS, at least by contributing data and information. The need for greatly improving this system became urgent after the great Alaskan earthquake of 1964, which generated a devastating tsunami that affected a good part of the Pacific. This tsunami focused additional attention to the need for establishing an International Tsunami Warning System.

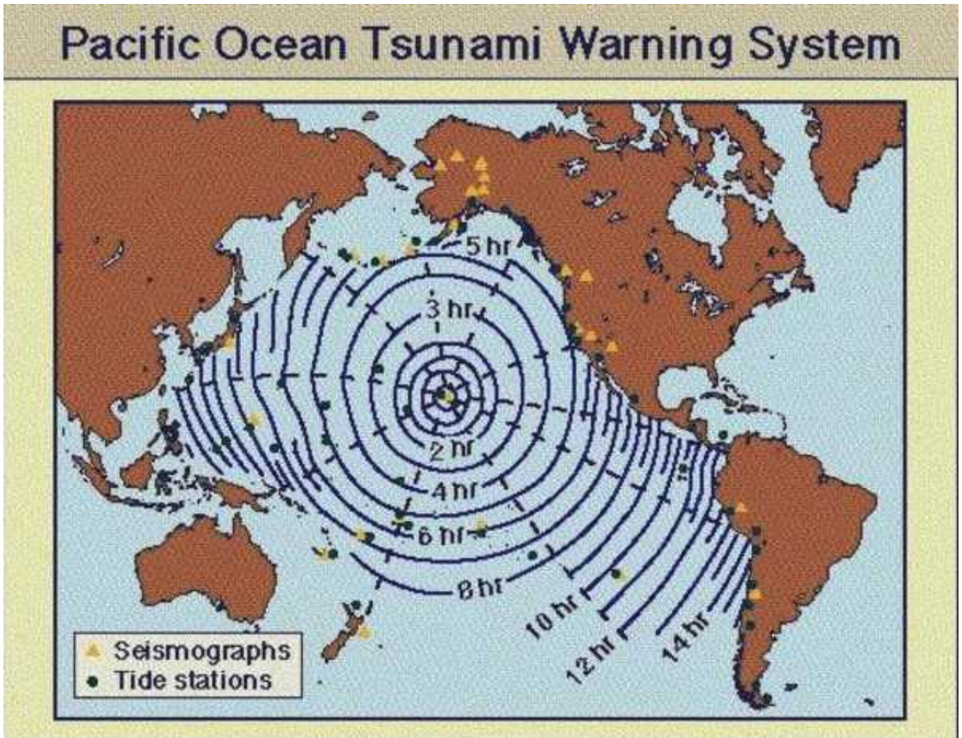

Figure 1. Initial tsunami travel time chart and locations of tide gauges and seismographs.

A necessity for this warning system was to provide information on a tsunami's initial wave arrival to warning dissemination centers in the Pacific. To meet this need a tsunami travel time chart for Honolulu was initially prepared. Later, tsunami travel time charts were also prepared for other stations in the System. For the prototype system a detector was actuated by unusual wave motion of the tsunami to ring an alarm. Also, a Communication Plan was drafted by Marc Spaeth of the U.S. Coast and Geodetic Survey (Spaeth, 1962) and a wave-reporting manual by Marc Spaeth C.E. Arens and others at ESSA-NWS (Spaeth.et. al., 1966) for use by the Honolulu Observatory

3. FOCUS OF EARLY TSUNAMI RESEARCH IN SUPPORT OF THE TSUNAMI WARNING SYSTEM IN THE PACIFIC

Scientists at the Hawaii Institute of Geophysics, at the Pacific Tsunami Warning Center (PTWC) and at the International Tsunami Information Center (ITIC) – which was established in 1965 under the auspices of the Intergovernmental Oceanographic Commission (IOC) - contributed significantly over the years towards the development of tsunami research, to improvements of the Tsunami Warning System in the Pacific and to tsunami preparedness around the world. However, since the early 1960's, Doak Cox, Gus Furumoto, Bill Adams, Martin Vitousek, Rockne Johnson, Harold Loomis, Don Hussong, Fred Duennebier, Floyd McCoy, Gary Stice, Frisbee Campbell, George Pararas-Carayannis, Daniel Walker, Tom Sokolowski, Robert Harvey and others were already participating actively in the tsunami research program at the Hawaii Institute of Geophysics of the University of Hawaii in support of a Tsunami Warning System for the Pacific. Most of them had dual appointments, and some were graduate students, worked part-time, or were paid from other University projects and from external

funding based on grants of the U.S. National Science Foundation, the U.S. Office of Naval Research, the U.S. Atomic Energy Commission, the State of Hawaii or private contractors. Later, several of these grants supporting tsunami research projects, were administered by the Research Corporation of the University of Hawaii or the Office of the Dean.

In 1963, after the early tsunami research group was established at the Hawaii Institute of Geophysics (HIG) of the University of Hawaii, a series of recommendations were made and several reports were written for improvements and enhancements of the early U.S. Seismic Sea Wave Warning System in the Pacific – subsequently renamed as Pacific Tsunami Warning System (PTWS). Some of these early recommendations were adopted, the work was funded and subsequently executed - thus helping to improve the assessment of potential tsunamis and the speed by which tsunami warnings were issued at that time by the Honolulu Observatory of the U.S. Coast of Geodetic Survey (USCGS)

After 1965, ITIC was established to coordinate matters pertaining to a more effective international cooperation in support of PTWC. George Pararas-Carayannis was the first employee of ITIC and assisted in these efforts Captain David Whipp, then Pacific Field Director of (USCGS) the U.S. Coast and Geodetic Survey (U.S.C.&GS) provisionally assigned also the title of Director of ITIC. Shortly thereafter the title of the Director of ITIC was assigned to the new Pacific Field Director, Captain Robert Munson, who was assisted by Pararas-Carayannis. Subsequently, after reorganization of what was then known as ESSA (Environmental Science Service Administration) and later became NOAA (National Oceanic Atmospheric Administration – which included the National Weather Service (NWS), Captain Munson was promoted to Admiral and became the Director of the newly established uniform service known as the NOAA Corps. Pararas-Carayannis continued as Oceanographer of ITIC with close cooperation with IOC in Paris and with a dual appointment at HIG at the University if Hawaii. Subsequently, Robert Eppley was assigned briefly as Director of ITIC and in 1973, Pararas-Carayannis became Director. In later years, Syd Wigen of Canada was appointed as the first Associate Director of ITIC and also helped with such efforts between 1976 to 1978. Norman Ridgway from New Zealand was the next Associate Director of ITIC. Ridgeway moved to Hawaii to help with such international coordination. A subsequent Associate Director of ITIC was Salvador Farreras at CICESE in Ensenada, Mexico, who helped with these efforts from April 1995 through April 1996. At the 6th Session of ICG/ITSU meeting in Lima, Peru, the Chilean delegation made the offer of having Dr. R. Nunez of their Navy Hydrographic Office in Valparaiso, to serve as Associate Director of ITIC and his term begun in 1998. However, neither Salvador Farreras nor Dr. Nunez moved to ITIC in Hawaii.

The scope of the early tsunami research program at HIG, the Joint Tsunami Research Effort (JTRE) and later of ITIC and at the Joint Institute of Marine and Atmospheric Research (JIMAR) in Hawaii - was as diversified as the background and expertise of the scientists in the program – particularly after 1963. The following sections list only a few examples of studies of operational improvements of the Tsunami Warning System and of early theoretical and applied research projects in the United States – mainly in Hawaii – but also some of the studies conducted by foreign organizations and scientists cooperating with their counterparts in the U.S.A. More on the significant contributions of international scientists will be summarized in a forthcoming paper.

3.1 Methodology for Establishing Tsunami Risk - Preparation of Inundation Charts and Zones of Evacuation in Hawaii.

One of the more significant priorities in 1963 was the preparation of potential tsunami inundation maps of coastal areas in Hawaii and the designation of safety zones for evacuation of the public during tsunami warnings. Working with Doak Cox, George Pararas-Carayannis began preparing contoured bathymetry charts of the Hawaiian Islands (Pararas-Carayannis, 1965) using old boat sheets of the U.S. Coast and Geodetic Survey (USC&GS). The contoured bathymetry and topographic maps of the U.S. Geological Survey (USGS) were used to subsequently extrapolate profiles of potential tsunami inundation areas for the preparation of inundation zones and for the designation of safety zones for public evacuation. The charts of the inundation/evacuation zones that were developed were then incorporated in Hawaii's telephone books, along with instructions for tsunami preparedness by the public. Maximum tsunami run-up data from post-tsunami surveys of major events that struck the Hawaiian Islands were also transferred from the U.S. Geological Survey topographic maps and contributed to the designation of safer evacuation zones.

In later years, there was further development of methodology for determining the tsunami risk and for standardizing methods for determining potential tsunami inundation and the delineation of safe evacuation zones. This was achieved through the use of appropriate numerical modeling, the standardization of engineering criteria and through improved coastal management policies. George Pararas-Carayannis - who at the time was at the U.S. Coastal Engineering Research Center (CERC) of the U.S. Army Corps of Engineers in Washington D.C. - and was also member of the American Nuclear Society - was tasked by the President' Council on Environmental Quality (CEQ) in Washington D.C. to review policy issues related to tsunami-related safety issues of offshore nuclear power plants (Pararas-Carayannis G., 1973b). Thus, he co-authored the American National Standard on safety guidelines at Power Reactor Sites, for the American Nuclear Society's, Nuclear Power Engineering Committee (Pararas-Carayannis, 1974a). Furthermore, as consultant under contract of the Nuclear Regulatory Agency on the tsunami safety issues of the San Onofre nuclear plant in California, and in connection with the safety of the nuclear power plant at Crystal River in Florida, he was asked to develop, calibrate and verify a bathystrophic numerical model for storm surges and flooding generated by major hurricanes in the Gulf of Mexico and the Gulf of Texas (Pararas-Carayannis, 1975a). This publication helped to better understand the local and cumulative effects (of tides, coastal geomorphology, refraction, resonance, etc) that also influence tsunami run-up.

3.2 Use of Atmospheric Data for Evaluation of Potential Tsunamis

Another early recommendation by the HIG tsunami research group pertained to the use of atmospheric data for the evaluation of potential tsunamis and the issuance of warnings (Pararas-Carayannis & Vitousek, 1966). Since at that time the Seismic Sea-Wave Warning System (SSWWS) (as it was then called) could not determine with sufficient rapidity the nature of the crustal displacements at the source by seismological methods alone, it was recommended that microbarograph data be used to determine if an earthquake involved large vertical crustal movements which could contribute to tsunami generation and also provide advance warning information since atmospheric waves propagate at a velocity of approximate1y 1050 ft/sec ± 30 ft/sec, nearly twice the speed of tsunami waves. In fact the report that was written in support of this recommendation included the rather distinct pressure fluctuation (0.1 mb), which was caused by the1964 Alaska earthquake and recorded by a microbarograph located in La Jolla (Van Dorn, 1964) (see Figure 1). The atmospheric waves from Alaska arrived in La Jolla a litt1e more than two and one-half hours before the arrival of the tsunami waves – thus Ca1ifornia would have known for certain that a tsunami bad been generated and would have had at least two and one-half hours of warning time. The report recommended that additional confirmation that a tsunami had been generated and clues as to the directivity of the waves would have been obtained if an array of microbarograph stations existed. Using data from the Hiroshima A-bomb museum the report showed the period of the blast wave, its recorded amplitude of 0.2 mmHg (0.26 milliard) and the velocity of the atmospheric wave being 971 ± 36 ft/sec.

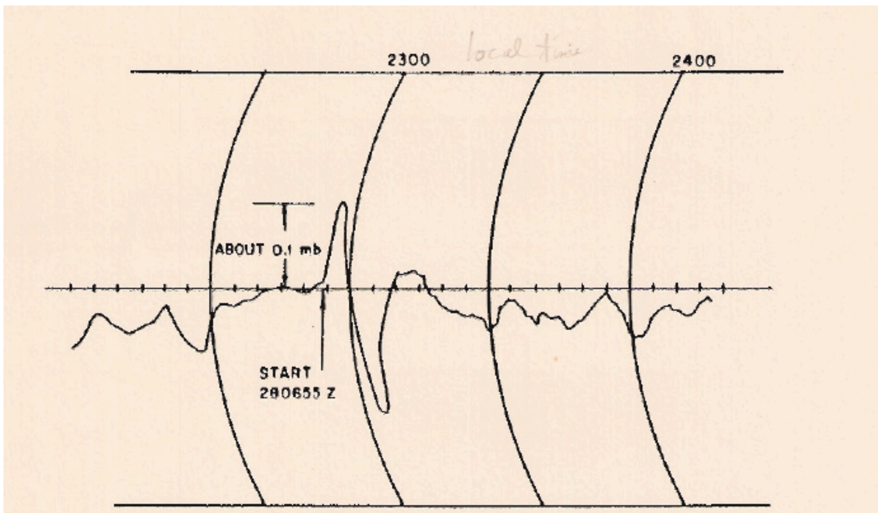

Figure 2. Microbarograph record from La Jol1a, [California] showing atmospheric tsunami from the Alaska earthquake (signature is typica1 of that for large dipole source) (from Spaeth and Berkrnan, 1965).

3.3 Recommendation on the Relative Susceptibility of the Hawaiian Islands to Waves Generated by Storms and Nuclear Explosions

An additional recommendation of the initial HIG research group pertained to the assessment of the relative susceptibility of the Hawaiian Islands to waves generated by storms and nuclear explosions (Pararas-Carayannis & Adams, 1966). Thus a proposal was prepared and submitted for funding to the U.S. Atomic Energy Commission (AEC - later renamed U.S. Nuclear Regulatory Commission, NRC). The proposal did not receive direct funding, but such work had been undertaken already in connection with other funded programs. For example, Gordon Groves of HIG was working on the dissipation of tsunamis and barotropic motions by ocean currents (Groves, 1964), with Motoyasu Miyata of the Peoples' Republic of China, on weather-induced long waves in the Equatorial Pacific (Groves & Miyata, 1967) and with support from NSF, with Niels Christensen on the spectral decomposition of numerically generated planetary seiches (Groves & Christensen, 1968).

As early as 1962, Walter Munk, Gaylord Miller, Frank Snodgrass, Gilbert Freeman and Edward Bullard at the Scripps Institution of Oceanography in La Jolla, California, had begun studies of storm-generated long ocean waves from the Antarctic and the Southern Pacific and specifically their decay characteristics. Their studies included the patching of the long-wave spectrum across the tides, the decay of tsunamis with distance and the dissipation of tidal energy over California's continental borderland (Munk, 1962a.b.; Munk, Miller& Snodgrass, 1962; Munk and Bullard, 1963). Also, Gaylord Miller, as part of his Ph.D. thesis, studied both tsunamis and tides (Miller, 1964) and upon completion of his degree, came to Hawaii and joined the Joint Tsunami Research Effort (JTRE) at the University of Hawaii. George Pararas-Carayannis, working with Gaylord Miller and Jean Foytik, developed numerical modeling methods for the calculation of tsunami refraction for both flat earth and spherical earth approximations, using different grid systems and further verified and calibrated the results with historical tsunami run-up data (Pararas-Carayannis & Miller, 1968; Pararas-Carayannis, Miller & Foytik, 1968). Harold Loomis, a professor of Mathematics at the University of Hawaii and a member of JTRE, subsequently made specific studies of tsunami run-up in the Hawaiian Islands (Loomis, 1976b) and, based on surveys of tsunamis that struck the Hawaiian Island, Dan Walker prepared comprehensive maps that provided the run-up measurements of the major tsunamis.

3.4 Recommendation - Field Office Addition of the Tsunami Warning System in the Atlantic

Given the history of tsunamis in the Atlantic Ocean and the Caribbean Sea (Grand Banks of Newfoundland in November 1929, the Great Lisbon earthquake and tsunami of November 1755 AD; the prehistoric Second Storegga Slides, etc.) another recommendation of the HIG research group pertained to the addition of a Field Office to monitor and warn about repetition of such events. In support of this recommendation, a preliminary catalog of tsunamis in the Atlantic Ocean was compiled and appended to the recommendation (Adams & Pararas-Carayannis, 1966).

3.5 Preparation of Charts for Rapid Earthquake Epicenter Determination in Support of the Tsunami Warning System.

Another of the early recommendations of the HIG research group was to find faster and more accurate ways for the Honolulu Observatory (HO) to determine earthquake epicenters by the use of initial seismic signals (Pararas-Carayannis et al, 1965). HO at that time was still using a large globe and a tape to measure "p" and "s" signal time differences, as were reported from different observatories (via teletype machines) in order to estimate distances and to triangulate for earthquake epicenter determinations. Obviously, this was an archaic method that needed improvement thus, subsequently the large globe at HO was donated to the museum of the Smithsonian Institute in Washington D.C. To improve the methodology for more rapid earthquake epicenter determinations, concepts from other fields of science were furthermore looked for possible applications in support of the early U.S. Tsunami Warning System (then still named U.S. Seismic Sea Wave Warning System - SSWWS), and later after in support of the newly established International Pacific Tsunami Warning System. In support of this recommendation for better earthquake epicenter determinations and with grant support by the U.S. Office Naval Research and the State of Hawaii, scientists at HO and the HIG research group, begun to look for alternate and timelier epicenter determinations. Tom Sokolowski, Gaylord Miller, James Sasser and George Pararas-Carayannis addressed this need.

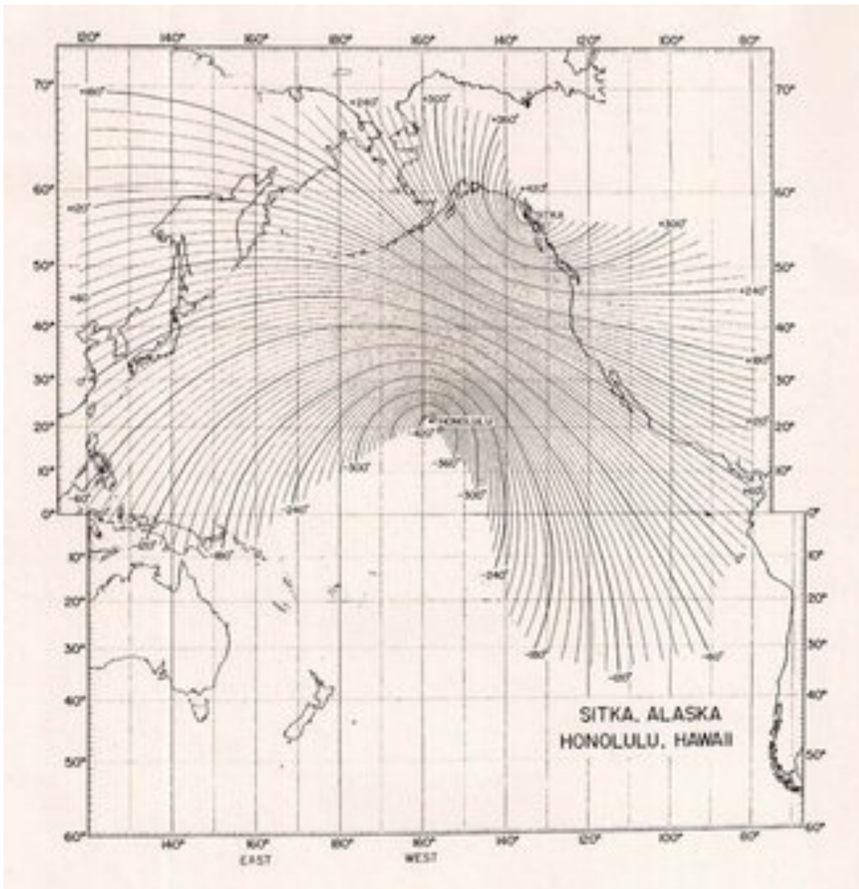

Figure 3. Example of a transparent chart of theoretical time differences in the arrival of P-waves at Sitka, Alaska and Honolulu (Sitka & Honolulu), (Pararas-Carayannis and Sasser, 1965a, 1965b).

Thus in 1965, George Pararas-Carayannis, applied the concept of Loran-A Navigation System of time differences in the arrival of radio waves, to time differences in the arrival of seismic signals at pairs of seismic stations. With programming assistance from James Sasser, a modified version of a spherical hyperbola program was applied to the travel times of compressional P-waves for the production of charts (as in Figure 3) of time differences in the arrival of the p-waves at pairs of seismic stations, which were reporting to Honolulu Observatory. Specifically, the theoretical time differences in the arrival of P-waves at different seismic stations around the Pacific (taken from the Jeffries-Bullen Tables) were compiled and plotted by digital computer and by hand. The time-difference curves were then plotted on transparencies for each pair of seismic stations. Three or more superimposed transparent charts of such time differences in the arrival of the seismic signals provided triangulation for a much faster earthquake epicenter determination that was available at that time (Pararas-Carayannis and Sasser, 1965a, 1965b; Pararas-Carayannis, 1968a). The seismic stations that were initially paired for the production of these charts, included Honolulu, Hawaii; Tucson, Arizona; Hong Kong; College and Sitka, Alaska. The same charts were refined later and corrected for crustal density and gravity anomalies along trenches and along tectonic plate collision zones. Thus, and as shown in the figure below, the numerically developed charts of differences in seismic p-wave arrivals at different seismic stations around the Pacific became a more rapid method for the Honolulu Observatory to locate the epicenters of potentially tsunamigenic earthquakes. Three such charts of time differences in the arrival of P- waves at pairs of stations were used by HO for an approximate determination of the earthquake's epicenter.

3.6 Quadripartite Seismic Array for rapid earthquake epicenter determinations

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Tom Sokolowski and Gaylord Miller also worked on a quadripartite seismic array that was installed on the island of Oahu, Hawaii by the USCGS to supply additional data for the Tsunami Warning System for quicker earthquake epicenter determination. The nuclear explosion LONGSHOT on October 29, 1965 on Amchitka Island was used to calibrate the quadripartite array epicenter location system. Specifically, a moving cross-correlation determined the P wave time delays between the various station pairs. Time delays were then used in a least-squares method to obtain azimuth and emergence angles. Thus, the emergence angle was used with the Jeffreys-Bullen travel-time curve to obtain the distance to the earthquake source for a rapid earthquake epicenter determination (Sokolowski & Miller, 1967).

3.7 Additional Research on Tsunami Propagation and Decay

Tsunami related research on gravity wave propagation on water of variable depth in basins was also conducted at Harvard University by George Carrier (Carrier, 1966). Special emphasis in such studies was given to the low-frequency part of the spectrum and to the geometrics of beaches. Both reflection phenomena and the dispersive character of wave propagation were accounted for by these studies, as well as the nonlinear aspects contributing to large amplification during wave breaking. Additionally examined were stochastically driven dynamic systems - such as the scattering of tsunamis as they propagate over the irregular topography of the deep waters of the ocean. The mathematical problem to which these studies led was pertinent to many other phenomena, however the analysis was concentrated on the propagation of gravity waves over an irregular bottom topography and to the lateral oscillations of an elastic string whose ends undergo random longitudinal displacements. The studies concluded that several facets of the mathematical problem were rather fascinating but the results did not suggest that scattering is not the most important part of tsunami propagation (Carrier, 1970).

3.8 Research on the Hydrodynamics of Long Period Waves

As mentioned earlier, studies of long period waves were initiated by Walter Munk and others at the Scripps Institution of Oceanography in the early 1960's and continued at HIG and elsewhere. Long period waves pertain to regular sea-swell to tides, with a range of about 12 minutes to 12 hours. The periods of tsunami waves range from a few minutes to as much as 30 to 40 minutes or more. To a large extent interest in long waves derived from the occurrence of tsunamis and of their propagation in the deep ocean as well as of their terminal decay characteristics. Thus, scientists at the Scripps Institution of Oceanography and other institutions in Canada and elsewhere, initiated studies of the hydrodynamics, energy, diffusion, absorption, trapping and leaky modes, decay, dissipation of such long period waves and of tsunamis in particular (i.e. Munk, 1961, 1962; Munk et al, 1962; Munk & Bullard, 1963; Miller, 1964; Van Dorn, 1966; Loomis, 1966; 1975; Groves & Miyata, 1967; Munk et al., 1972; Snodgrass et al, 1962, 1972; Murty & Henry, 1972; Murty, 1977).

As previously stated, Gaylord Miller at Scripps Institution of Oceanography - before joining JTRE - had studied with Walter Munk and Frank Snodgrass, long period waves over California's continental borderland, the decay of tsunamis and the dissipation of tidal energy (Munk et al, 1962). Also - as mentioned - Gaylord Miller had completed his Ph.D. thesis on tsunamis and tides (Miller, 1964). Thus, when he came to Hawaii, the early numerical modeling studies at JTRE used similar numerical methodology in studying more specifically the hydrodynamics of longer period waves such as tsunamis, their propagation in the deep ocean and their terminal decay characteristics. The development of numerical models for tsunami propagation and travel time charts and the relative spectra of tsunamis and tides. was based on such initial studies.

Harold Loomis, a member of JTRE, worked also on the hydrodynamics of long period waves, their normal modes of oscillation in confined bays and harbors, the effects of resonance on long wave amplification (Loomis, 1966; 1975). Using spectral analysis of tsunami records from different tidal stations, the objective was to learn more about the behavior of tsunamis in the Hawaiian Islands generated by the earthquakes of 13 and 20 October, 1963 in the Kurile Islands, those generated by the Good Friday Alaska earthquake of March 28, 1964, and of the local tsunamis generated by the earthquake of November 29, 1975 along the coast of the island of Hawaii (Loomis, 1975).

The attenuation of progressive, dispersive, oscillatory wave systems by dissipation within the viscous boundary layer in a long laboratory physical channel was studied by Bill Van Dorn at Scripps both experimentally and theoretically, for conditions of uniform wave depth and uniform impermeable slopes (Van Dorn, 1966). His research provided useful conclusions of how boundary conditions at the sides and bottom of a channel affect wave dissipation, which had relevance to the physical modeling of tsunamis. The dispersion of Kelvin-type long waves were also studied along a single-step topography as well as quasi-geostrophic waves that are related to topographic structure (Larsen, 1969).

Although not directly related to tsunami work, Gordon Groves at JTRE and Motoyasu Miyata from the Peoples Republic of China, worked on weather-induced long waves and examined the entire available historic record of sea level changes and surface weather at Canton Island, Phoenix Islands, and established a linear relationships in the frequency range 0 to 0.8 cycles per day. Peaks in the sea-level spectrum at periods of four days and five days were found to be strongly coherent with local weather especially the meridian wind component. Thus the possibility that these oscillations were a manifestation of a global seiche was determined to be doubtful. Also, a weaker spectral peak at period 2.7 days appeared to be unrelated to local weather. The mechanism of the enhancement at any of the three frequencies was not determined. However these studies concluded that the spectra of the local weather records did not exhibit a "fine structure", but there was evidence that the "appropriate" weather input function did not have the four-day peak. It was uncertain whether the five-day peak in sea-level activity resulted from a peak in the weather input function or in the ocean's response (Groves & Miyata, 1967). Of course, at that time the longer impact on sea level fluctuations at islands due to thermally driven equatorial and counter equatorial currents was not known and the El Nino impact or its causes had not yet been determined.

3.9 Numerical Modeling Studies on the Dissipation of Long Period Waves and Tsunamis

Also, Gordon Groves, had worked on the influence of currents on the dissipation of tsunamis and barotropic motions (Groves, 1964), as well as on numerical modeling of long period seiches in rectangular basins simulated with Ransen's method and by using boundaries both coincident and inclined with the grid coordinate axes and comparing the results with the theoretical solutions (Groves, 1970). Together with Niels Christensen, and with National Science Foundation support, Gordon Groves worked on the spectral decomposition of numerically generated planetary seiches (Groves & Christensen, 1968).

3.10 Research on the Linear and Non-linear Behavior of Tsunamis

There were additional studies on the linear and non-linear behavior of tsunamis. Gordon Groves, Robert Harvey and Eddie Bernard worked on the dissipation of tsunamis, their spectral decomposition and the non-linear behavior at islands and continental coastlines (Groves et al, 1967). Groves and Harvey, using marigrams from Hilo and Midway Island, researched further the nonlinear behavior of tsunamis and the approximation of transformation from deep to shallow water, as well as the near shore distortion of tsunami waves as represented by the first three terms of the multidimensional Taylor expansion, the constant, linear and bilinear operators (Groves & Harvey, 1967). Similarly, Doug Luther collaborated with Eddie Bernard at PMEL in Seattle in the study of infra-gravity waves (the other long-period ocean waves).

Also Murty & Henry in Canada conducted studies on the importance of tsunami resonance and on amplification of the waves along the complex topography of the west coast of Canada. Specifically, they considered tsunami propagation into the Fisher-Fitz Hugh complex on the Canadian west coast, particularly in the Juan de Fuca Strait and the Cousins inlet. The tide gauge data for the 1964 Alaska earthquake tsunami was evaluated through autocorrelation analysis and calculation of spectra in order to analyze the nonlinear coastal effects and the energy processes on the continental shelf off Tofino (Murty & Henry, 1972). Additional studies by Tad Murty in Canada included the dynamics of tsunamis with particular emphasis on wave propagation characteristics in the deep ocean (Murty, 1977). Similarly, Kanoglu and Synolakis examined the long wave runup on linear topographies (Kanoglu and Synolakis, 1998).

In later years Zygmunt Kowalik of the University of Alaska and Tad Murty in Canada used numerical models to compute tsunami amplitudes of a predicted major earthquake in the Shumagin seismic gap

(Kowalik, Z., and T.S. Murty. 1984) and further examined the influence of size, shape and orientation of the predicted earthquake source on the Shumagin gap on a resulting tsunami (Kowalik and Murty, 1987a).

3.11 Modeling Tsunami Generation, Propagation, Wave Breaking and Run-up.

Numerical studies of linear and non-linear behavior of tsunamis continued in subsequent years. For example, Costas Synolakis examined the runup and reflection of solitary waves (Synolakis, 1987a.b). Synolakis also reviewed wave reflection and runup on rough slopes (Synolakis, 1989). Vasili Titov and Costas Synolakis modeled numerically long wave runup using VTCS-3 runup models (Titov & Synolakis, 1996) as well as tidal wave runup (Titov & Synolakis, 1998). Yamazaki, Y., Z. Kowalik and K. F. Cheung extended depth-integrated modeling studies of non-hydrostatic wave breaking and run-up (Yamazaki et.al., 2008) and of tsunami generation, propagation and run-up with grid nesting (Yamazaki et al., 2010)

4. STUDIES OF TSUNAMI ANOMALIES AND PRECURSORY SEISMIC PHENOMENA

Scientists at HIG and JTRE continued to work on tsunami anomalies and precursory seismic phenomena as predictors of potential tsunami generation and coastal inundation.

4.1 Studies of T-phases and of Other Seismic Signals

A great deal of early research at HIG concentrated on studying acoustic signals from earthquakes, and from explosive and non-explosive volcanic activity. The following is only a partial listing of such research. For example, Rockne Johnson, John Northrop and Robert Eppley worked on acoustic waves from submarine volcanic eruptions and from earthquake sources in the Pacific (Johnson, Northrop, & Eppley, 1963). Also, Johnson and Northrop used the T-phase signatures recorded by a hydrophone net during the VELA UNIFORM Aleutian Islands Experiment in August-September, 1964, in order to help determine earthquake sources, strengths and rupture lengths and make comparisons of T-phase strengths with earthquake magnitudes (Johnson, 1964; Johnson & Northrop, 1966). Later, with support from the Office of Naval Research, Johnson, Roger Norris and Frederick Duennebier, examined abyssally generated T phases (Johnson, Norris & Duennebier, 1967). Also, with support from the Office of Naval Research (ONR) Frederick Duennebier and Rockne Johnson compiled and examined a two-year record of T-phase source locations together with U.S. Coast and Geodetic Survey earthquake epicenters in the Pacific Basin for the same time period. It was shown that the T phase sources have a higher density in regions which insonify the hydrophone array and an accuracy equivalent to or better than the C & GS determined epicenters in regions where geometry is favorable, or where abyssal T phases are generated (Duennebier & Johnson, 1967).

Also, in an effort to isolate the properties of the abyssal T phase generating mechanisms, the frequency-time characteristics of spectral variations were studied. Early arrivals, or forerunners, were found to have the properties of anabyssally generated T phase. Abyssal T phase generation was found not to be confined to regions of high latitude where the SOFAR channel is bounded by a surface channel, as in the equatorial latitudes. Corrections were applied to the observed spectrum to find the frequency characteristics of the abyssal and slope mechanisms. At low frequencies, the slope mechanism was found to be a more efficient generating mechanism than the abyssal mechanism, the two being nearly equal in efficiency at high frequencies. Several possible mechanisms for abyssal generation were reviewed, with the conclusion that no satisfactory model for abysssal generation had been proposed (Duennebier, 1968).

4.2 Studies of Ionospheric Pertubations from Large Earthquakes

Augustine (Gus) Furumoto of HIG-Seismology worked on delayed ionospheric oscillations of Rayleigh waves from large earthquakes, which could be detected and recorded by high-frequency Doppler sounding techniques. Specifically, he used the 10 MHz recording of Rayleigh waves to estimate the initial phase of the source of the Kuril earthquake of 11 August 1969. From such recordings of ionospheric perturbations, the initial motion from this quake appeared to be downward and, because of the rapidity of such recording, this approach to source mechanism estimation was considered to be a useful indicator of potential tsunamigenesis for use by the Pacific Tsunami Warning System (Furumoto, 1970).

4.3 Research on Frequency-Energy Distribution of Earthquakes in Establishing Probabilities of Recurrence

Additionally with NSF funding, Furumoto worked on the frequency-energy distribution of earthquakes, the possibility of occurrence of major earthquakes in Hawaii and the intensity and probability of recurrence of a tsunamigenic and destructive Hawaiian earthquake similar to that 1868 (Furumoto, 1966). Also, with Frisbee Cambell and Donald Hussong, research was undertaken on the seismicity of Hawaii, specifically analyzing seismic refraction data from traverses along the Hawaiian Ridge from Kauai to Midway Island to determine velocity layers and the crustal structure of the Hawaiian Archipelago (Furumoto et al, 1971).

This research showed that the area of subsidence is smaller for older volcanic islands than for newer ones. It was also indicative of the viscous behavior of the earth's material as it related to subsidence of the older islands and explained variations in seismic velocities in the earth's mantle, the lower crustal layers as well as determining depths to the Mohorovic discontinuity along the Hawaiian ridge and trough - depths which ranged between 10 and 15 km along the Leeward Islands but were deeper (18 km) near major islands. Although not of direct application to tsunami-related work, this research was useful in understanding tectonic processes that could result in earthquakes in Hawaii (Furumoto et. al., 1971; Furumoto 1976).

Similar studies of seismic refraction were used to determine, not only the crustal structure of the Hawaiian Archipelago but also of northern Melanesia and of the Central Pacific Basin (Furumoto, et al., 1973). The crustal structure of the Hawaiian Archipelago, northern Melanesia, and parts of the

Central Pacific Basin were also studied by seismic refraction methods. The systematic variation which was found in crustal thickness in the Hawaiian Islands was explained by a hypothesis of differential subsidence. The crustal structure of the northern Melanesia pointed to existing tensional forces in an east-west direction and compressional forces in a north-south direction. In the Central Pacific Basin, the investigation described a 7.4-km/sec layer in the lower crust, which seemed to be present over a wide area. Although not directly related to tsunami work, such research helped determine better the earth's structural anomalies and stresses that may relate to potentially tsunamigenic earthquakes.

4.4 Theoretical Studies and Mathematical Models and Analysis on Tsunami Propagation

Rudolph Preisendorfer' work at JTRE was mostly theoretical but contributed significantly to the understanding of tsunamis. He worked on recent tsunami theory by first reviewing five major areas of analysis on generation and uniform propagation; scattering and diffraction; guiding, trapping and radiation; oscillations and resonances; and shoaling, breaking, and run-up. He used three basic hydro dynamical models: The velocity potential model, the linear wave model and the nonlinear wave model (Preisendorfer, 1971). Also he worked on classic canal theory, multi-moded, long surface waves, on linear surface-wave transport in non-uniform canals, on the time dependent or steady state (time-harmonic) wave amplitudes (Preisendorfer, 1972, 1973). Additional work, while at HIG and JTRE, included studies of multimoded, two-flow, long surface waves and marching long surface waves through two-port basins (Preisendorfer, 1975, 1976).

Additionally, Lester and Ellen Spielvogel at JTRE worked on tsunami mathematical models and analysis – more specifically on asymptotic theory for waves with radial symmetry and on the speed of solitary waves and run-up of waves on sloping beaches. Also, they studied radially symmetric free-surface waves and derived equations for waves of different orders of magnitude for an exact relationship between the speed of a solitary wave and its decay at infinity (Spielvogel L. 1972; Spielvogel E. & Spielvogel, L., 1972, 1973). Furthermore, Lester Spielvogel studied finite irrotational surface waves in homogeneous inviscid incompressible fluids in circular channels (Spielvogel, L., 1972) and deep-water amplification and run-up of single waves on a sloping beach (Spielvogel L., 1973).

4.5 Studies of Compressional and Shear Wave Arrivals at Hydrophones from Nuclear Explosions and Earthquakes.

Beginning in 1978, Charles McCreery, Dan Walker, George Sutton, and Fred Duennebier worked on studies of oceanic mantle phases (Walker, 1965) and on the systematic analysis of compressional and shear wave arrivals at hydrophones on Pacific Island stations from underground nuclear explosions and earthquakes (Walker, 1980; McCreery et. al. 1983). Bill Adams worked on estimates of special dependence of the transfer functions of a continuum (Adams, 1964) and Gus Furumoto researched extensively Hawaii's seismicity and the frequency-energy distribution of earthquakes (Furumoto, 1966). Charles McCreery, Dan Walker, and George Sutton (1983) - using Wake Island bottom hydrophones - examined the spectra and noise from nuclear explosions and earthquakes.

4.6 Marine Geology and Volcanology Studies

Ralph Moberly and Floyd McCoy Jr. at HIG worked on the marine geology of the sea floor of the Eastern Hawaiian Islands. Also, Gary Stice and Floyd McCoy Jr. worked on the Geology of the Man'ua Islands in Samoa. Floyd McCoy developed a keen interest in the Bronze Age eruption of the volcano of Santorini in Greece and wrote about the volcano's eruption phases and the tsunami it generated (Heiken & McCoy, 1984). He also continued with extensive investigations of the volcano of Santorin and together with Costas Synolakis at the University of California and with Gerassimos Papadopoulos, in Greece, later co-authored numerous papers of this research results from modeling and studies of sedimentary deposits (McCoy & Heiken, 2000 a, b; McCoy et. al., 2000).

Also, George Pararas-Carayannis developed an early interest on how the tsunami waves generated from the caldera collapse and from the southern and eastern flank collapses of the volcano of Santorin in 1625 B.C. occurred and how this disaster impacted the Minoan Civilization in Crete and the Eastern Mediterranean Sea. Thus, he conducted numerous field investigations of Minoan palaces in Crete at Kato Zakros, Faistos, Agia Triada and at Amnisos - the sunken port of Ancient Knossos (Pararas-Carayannis, 1973, 1974). In subsequent years he continued his investigation of the Bronze Age tsunami source mechanism and its impact on the ancient world of the Eastern Mediterranean (Pararas-Carayannis, 1992b).

4.6.1 Other volcanological studies

Mount Augustine, Alaska: Other volcanological studies were made by Zygmunt Kowalik, J. Keinle and Tad Murty who examined tsunami generation from the eruptions of Mount Augustine volcano in Alaska (Kowalik et al., 1987b).

Cumbre Vieja, La Palma – Canary Islands / Piton de La Fournaise, Reunion Island /Krakatau/ Lesser Antilles Volcanoes in the Caribbean Sea - In subsequent years Charles Mader modelled a potential tsunami from a landslide at La Palma, Canary Islands (Mader, 2001), while George Pararas-Carayannis examined the geochemistry of magmas and the effusive and explosive mechanisms of volcanoes in generating tsunamis in general (Pararas-Carayannis, 2002). Subsequently, he evaluated specifically the threat of mega tsunami generation from postulated massive slope failures of island volcanoes on La Palma, Canary Islands and on the Island of Hawaii, (Pararas-Carayannis, 2002a) and of the volcano Piton de La Fournaisse at Reunion Island in the Indian Ocean. Later, he also evaluated the near and far-field effects of tsunamis generated by the 1883 paroxysmal eruptions, explosions, caldera collapses and slope failures of the Krakatau Volcano in Indonesia, (Pararas – Carayannis, 2003) and assessed the risk of Tsunami generation from active volcanic sources in the Eastern Caribbean Region (Figure 4) (Pararas-Carayannis, 2004; 2006).

Specifically examined by Pararas-Carayannis were the inter-plate tectonic interaction and the active geo-dynamic processes that have created the Caribbean volcanoes of the Lesser Antilles (i.e. Soufriere Hills on Montserrat, Mt. Pelée on Martinique, Soufriere on St. Vincent, the Kick'em Jenny near

Grenada, etc.), which are characterized by both effusive and explosive activity and are often associated with caldera collapses, nuees ardantes and gravitational flank instabilities which often have generated local destructive tsunami waves.

Figure 4. Volcanoes of the Eastern Caribbean Island Arc (modified web graphic of West Indies University)

Also, Efim Pelinovsky N. Zahibo and other Russian scientists evaluated in great detail the tsunami risk of the volcanoes of the Lesser Antilles with particular emphasis on Soufriere Hills on the island of Montserrat (Zahibo and Efim Pelinovsky, 2001, Pelinovsky et.al., 2004). More on the significant contributions of the Russian (and other scientists at the West Indies University and Puerto Rico) will be presented in Part B at a subsequent publication.

Cumbre Vieja. La Palma, Canary Islands - In later years, following a report which had concluded that a destructive Atlantic tsunami could be generated from a flank collapse of the Cumbre Vieja volcano on the island of La Palma in the Canary Islands (Figure 5.), George Pararas-Carayannis examined the assumptions and input parameters that had been used by the probabilistic numerical models, evaluated the geologic evidence and historic events, concluding that massive flank collapses of Cumbre Vieja on La Palma or Kilauea in Hawaii were extremely unlikely to occur in the near geologic future. Based on this analysis he also reached the conclusion that the flanks of these island volcanoes will continue to slip aseismically, as in the past. Also, that sudden slope failures can be expected to occur along faults paralleling rift zones, but these will occur in phases, over a period of time, and not necessarily as single, sudden, large-scale, massive collapses. He further concluded that most of the failures would occur in the upper flanks of the volcanoes, above and below sea level, rather than at the basal decollement region on the ocean floor. He further stated that the sudden flank failures of the volcanoes of Mauna Loa and Kilauea in 1868 and 1975 and the resulting earthquakes, generated only destructive local tsunamis with insignificant far field effects. Caldera collapses and large slope failures associated with volcanic explosions of Krakatau in 1883 and of Santorin in 1490 B.C., generated catastrophic local tsunamis, but no waves of significance at distant locations. He stated that for mega-tsunami generation, even from the larger slope failures of island stratovolcanoes, is extremely unlikely to occur. Greater source dimensions and longer wave periods are required to generate tsunamis that can have significant, far field effects.

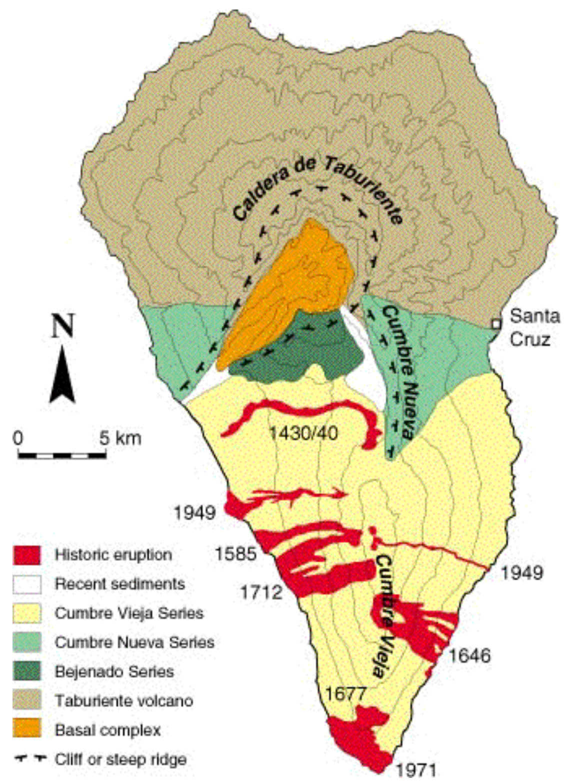

Figure 5. Geological map of La Palma Island showing sites of historic eruptions of the Cumbre Vieja volcano from vents along its north-south trending rift zone.

In support of these conclusions and in response to a Discovery Channel program alleging potential destruction of coastal areas of the Atlantic by tsunami waves which might be generated in the near future by a volcanic collapse in the Canary Islands, the Tsunami Society formed a committee with George Curtis chairing, concerning the occurrence of "mega-tsunamis". The Society's position paper stated that while the active volcano of Cumbre Vieja on La Palma is expected to erupt again, it will not send a large part of the island into the ocean, though small landslides may occur. Furthermore it was stated that such volcanic collapses are extremely rare events, separated in geologic time by thousands or even millions of years.

The Earthquake and Tsunami of 365 A.D, in the Eastern Mediterranean – Impact on the Ancient World - Later, Pararas-Carayannis also investigated the impact of the 365 A.D. earthquake and tsunami on the port of Ancient Falasarna on the western coast of Crete, the rest of the island and on the Eastern Mediterranean (Libya, Egypt, Cyprus and Palestine), based on a numerical study prepared with Charles Mader (Pararas-Carayannis & Mader, 2010) and, as shown in the figure below, a rupture model of the quake based on geodetic measurements of crustal displacements on land (Papadimitriou & Karakostas, 2007), which were extrapolated to the Island of Antikythera to the northwest of Crete and past the island of Gavdos to the abyssal plain of Herodotus in the Libyan Sea, to the southeast.

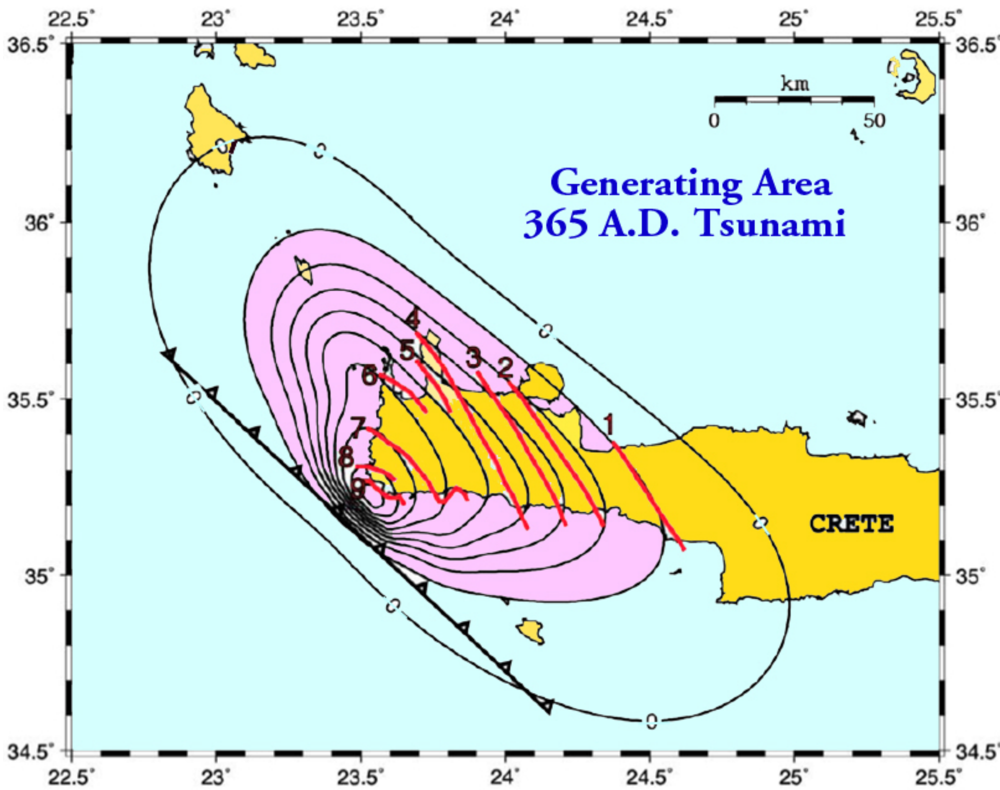

Figure 6. Crustal Displacements in meters from the 365 A.D. earthquake and volumetric determination of the Tsunami Generating Area Along the Western Coast of the Island of Crete (Pararas-Carayannis & Mader, 2010; mod. Extrapolated from land geodetic measurements (Papadimitriou & Karakostas, 2007)

4.7 Development of Deep-Ocean Instrumentation and Telemetry Systems - Establishment of a Regional Tsunami Warning System for the Hawaiian Islands – Establishment of other Regional Warning Systems.

In the early 1960's, it was recognized that high-risk regions existed around the world where tsunami warnings could not be issued in time to be of any usefulness. There was an urgent need for the development of regional warning systems that could utilize updated instrumentation, communications and data transmission technologies so that the potential tsunami hazard could be rapidly evaluated and warnings disseminated. Thus, shortly after the establishment of JTRE at the Hawaii Institute of Geophysics, a project of high priority was to work on instrumentation and high-resolution data telemetry systems and to set up an early experimental local Tsunami Warning System for the Hawaiian Islands. Martin Vitousek was the HIG scientist who had begun pioneering work on such technology and had worked extensively on tsunami instrumentation and telemetry systems. Together with Gaylord Miller, they used vibrotron instrumentation to measure tsunami and other low-frequency waves in the deep ocean. Also, Martin Vitousek and Bill Adams, in cooperation with the Hawaii Volcano Observatory of the USGS and the Hawaii Civil Defense Agency, established a system of data telemetry of sea level from the existing tide gauges but, in addition, for two deep-sea pressure sensors which 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 on the ocean floor about 100 km north of the main Hawaiian Islands.

Frank Snodgrass at Scripps was also working on a precision digital tide gauge, which used a vibrating wire pressure transducer to provide sea level measurements to the nearest one-tenth millimeter (Snodgrass, 1964; 1972). These early developments were the predecessors to the DART ocean buoy systems presently in use around the world's oceans for the detection of tsunamis. This work was subsequently succeeded by extensive research at the Pacific Marine Environmental Laboratory (PMEL) in Seattle, State of Washington in USA.

The need for rapid regional Tsunami Warming Systems for South America and elsewhere was also recognized at the fourth session of ICG/ITSU held in Wellington, New Zealand in 4-7 February 1974. In 1975, George Pararas-Carayannis, then Director of ITIC, was tasked to review the feasibility of developing such regional warning centers using geosynchronous satellites, and to provide guidelines for implementation with U.N. support. Such a report was prepared, was also translated in Spanish and distributed by IOC to member countries (Pararas-Carayannis, 1976a, 1977). IOC prepared the final report for funding which was submitted to UNDP in New York.

Significant subsequent progress in the development of Regional Tsunami Warning Systems for Chile and elsewhere using satellites and deep water gauges – known as the Tsunami Hazards Reduction Utilizing Systems Technology and abbreviated as THRUST - was performed by scientists at ITIC, PMEL, U.S. NOAA, the National. Geophysical Data Center in Boulder, Colorado, and with support of the Agency of International Development of the U.S. State Department (AID) and by other U.S. and international organizations. The results of this work were published extensively (Bernard, Lander, & Hebenstreit 1982; Bernard, Hebenstreit, Lander & Krumpe, 1984; Bernard & Behn, 1985, 1986;

Bernard, Behn, &. Milburn 1988; Bernard. Behn, Hebenstreit, González, Krumpe, Lander, Lorca, McManamon, & Milburn, 1988; Bernard, 1989; Bernard, Behn, Hebenstreit, González, Krumpe, Lander, Lorca, McManamon, & Milburn, 1990; Bernard & Milburn,1991). M.C. Eble and Frank González at PMEL reported on deep-ocean bottom pressure measurements in the northeast Pacific, which were conducted using the new instrumentation (González, et.al., 1987; Eble & González, 1991). In support of defining better tsunami seafloor changes before and after a tsunamigenic event, Frank González, C. Fox, and Eddie Bernard conducted such research (Gonzalez et al., 1988a,b), and further examined the frequency modulation at two deep ocean stations for purposes of calibration (González & Kulikov 1990). Frank González, Charles Mader, M.C. Eble, and Eddie Bernard used such deep-water ocean data for the 1987-88 Alaskan Bight tsunamis for model comparisons (González et.al. 1991).

Subsequent development of recording deep-sea gauges and buoy systems to house the satellite telemetry of tsunami data, was one of the most important improvements to the Tsunami Warning Systems. A recent retrospective review of this technology, authored by George Mungov, Marie Eblé and Richard Bouchard, pertained to a Reflection on 10 years of processing deep-ocean tsunami observations, which routinely have been now incorporated into operational procedures of tsunami warning centers around the globe in support of tsunami research and operations for both data archiving and dissemination purposes. This work begun in the early 1980's by the U.S. National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory in close collaboration with the National U.S. National Buoy Center and the National Geophysical Data Center and continues by many researchers to the present time (i.e. Mungov, Eble & Bouchard, 2012; Dunbar, et.al. 2008; Eblé, et.al, 1989; Eblé & González, 1991).

4.8 Preparation of Tsunami Travel Charts in Support of the Tsunami Warning System in the Pacific - Numerical Modeling of Tsunami Wave Refraction

In order to provide accurate warnings, the PTWC needed to provide tsunami travel information and estimated time of arrival (ETA) of the first wave at any given coastal region. Thus, in the early 1960s and thereafter, Gaylord Miller and George Pararas-Carayannis begun preparing tsunami travel time charts for new stations in the Tsunami Warning System using a spherical earth numerical model. For further refinements in coupling the deep/shallow water interphases and to eliminate errors in the finite differences reiteration process in local bays and shallow continental shelves - as well as caustics of refracted energy rays - while working at ITIC and in close cooperation with JTRE, Pararas-Carayannis also worked with Gaylord Miller and Jean Foytic on flat-earth finite differences approximation numerical models which used variable rectangular and triangular grid systems (Pararas-Carayannis & Miller, 1968d ; Pararas-Carayannis et al, 1968 e, 1969 a), to make best use of the ocean bathymetry given the density of data, and for final corrections of all tsunami travel charts. By 1969, Pararas-Carayannis had completed charts for Acapulco, Attu, Canton, Eniwetok, Kwajalein, Johnston, La Jolla, Marcus, Nauru, Samoa, Wake, Adak, Crescent City, Dutch Harbor, La Punta, La Jolla, Los Angeles, San Francisco, Seward, Sitka and Tofino (see example of a travel time chart for Tofino, Canada in Fig. below). These charts were used for several years by the Pacific Tsunami Warning Center for the issuance of tsunami watches and warnings.

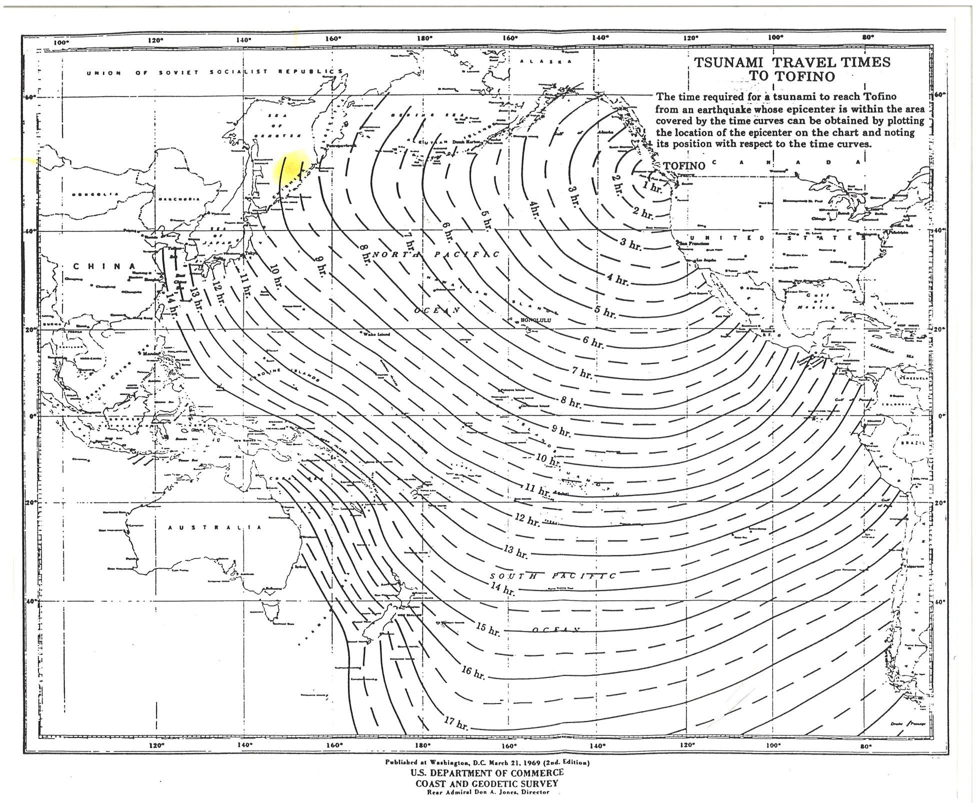

Figure 7: Tsunami Travel Time chart for Tofino, Canada produced by ITIC in 1969 for the US Coast and Geodetic Survey for the Pacific Tsunami Warning System

4.9 Development of Planning and Zoning Criteria

The tsunami risk is not evenly distributed along a threatened coastline. Because of the extreme selective nature of tsunami destruction along given coastlines, the development of planning and zoning criteria was deemed necessary for proper coastal management and for population evacuation during tsunami warnings. Furthermore, it was recognized that the high cost of coastal land in many areas, dictated an accurate assessment of the tsunami risk, rather than arbitrary conservative zonation. Thus there was a need to establish the total risk at any point along a threatened coastline, as well as the probability of occurrence, for insurance purposes. Microzonation maps of the tsunami hazard were deemed to be of greater usefulness in developing proper coastal management criteria. It was also concluded that for critical areas it would be necessary to also perform detailed numerical modeling studies which would indicate the spatial variation of the tsunami hazard along a given coastline, where expected tsunami height could be quantified and evacuation limits designated (Pararas-Carayannis, 1988a). Specifically, this work at ITIC proposed international cooperation in this area and endorsement of a standardized technique for accomplishing this objective - initiatives which would be consistent with the scope of the proposed IDNDR for the reduction of the tsunami disaster.

4.10 Research on Tsunami Response of Island Systems.

In later years and based on classical linear long-wave equations, numerical models were developed at PMEL that used finite-difference methods to study tsunami response of multiple-island systems such as the Hawaiian Islands (Hebenstreit, et al., 1980) and variations from different azimuthal tsunami approaches from South America, Alaska, Aleutians-Kuriles-Japan-Philippines, and the Southwest Pacific (Hebenstreit & Bernard, 1985).

4.11 Numerical Modeling Studies

Charles Mader, who at the time worked at the U.S. Los Alamos Laboratory in New Mexico, was also co-operating closely with researchers in Hawaii. In support of the Tsunami Warning System, he refined his pioneering work on the numerical simulation of tsunamis (Mader, 1974). Specifically, his initial work involved the modeling of two dimensional, time-dependent, nonlinear, incompressible, viscous flow of realistic models of tsunami waves interacting with the continental slopes and shelves – thus determining the effects of shoaling, the increase in height of the initial wave and the increase of subsequent wave heights by as much as a factor of four. The modeling also helped understand the damping action of submerged barriers on both tsunami height and reflection of energy.

As computer technology further developed, numerical modeling studies continued. Eddie Bernard worked on a numerical study of the tsunami response of the Hawaiian Islands (Bernard, 1976) and with A.C. Vastano on the numerical computation of tsunami response for island systems in general (Bernard &Vastano, 1977). Although the two- and three-dimensional numerical methods for modeling water waves had been available in the 1980's, they had seldom been used. A major obstacle to their use was the need for access to large and expensive computers. However by the 1980's, inexpensive personal computers were adequate for many applications of these numerical methods. A code named SWAN was used by Charles Mader and Sharon Lukas in JIMAR at the University of Hawaii to further examine the application of the SWAN Long Wave Code (Mader & Lukas, 1985), and by Mader, Martin Vitousek, and Sharon Lukas, to numerically model Atoll Reef Harbors (Mader, Vitousek & Lukas 1988). The SWAN code was also used to model the 1946, 1960, 1964 tsunamis, and Mader with Robert Tangora and B.D. Nichols, the 1975 Hawaiian tsunami earthquake generated in Hawaii (Mader, Tangora & Nichols, 1982). Also Mader modeled the resulting landslide caused by this 1975 event (Mader, 1984) in Hawaii, other Hawaii tsunamis, the 1964 Crescent City California tsunami and the 1994 underwater landslide generated tsunami at Skagway, Alaska (Mader, 1997). The 3 November 1994 underwater landslide was also modeled by Synolakis, Yalciner in Turkey, borrero and Plafker (Synolakis et al., 2002).

Using the same numerical methods, Charles Mader continued publishing in Tsunami Society's Journal "Science of Tsunami Hazards" numerical studies of tsunami flooding (Mader, 1990) and with George Curtis on tsunami inundation of Hilo harbor, Island of Hawaii (Mader & Curtis, 1990; 1991) as well as with Curtis and George Nabeshima (Mader & others, 1993). In another such study with Eddie Bernard George Curtis and K. Satake, the tsunami inundation of Eureka and Crescent City in California were modeled (Mader et al, 1994). The numerical studies of inundation continued with modeling tsunami inundation from a theoretical fall of an asteroid near Hawaii (Mader, 1996) and from the 1994 landslide-generated tsunami in Skagway, Alaska (Mader, 1997). The 1994 landslide-generated tsunami in Skagway, Alaska was also studied extensively by Zygmunt Kowalik at the University of Alaska (Kowalik, 1997).

Charles Mader continued numerical studies on asteroid tsunami generation in Japan (Mader, 1998a), and the modeling of the potential impact that the Eltanin asteroid could have on generating a catastrophic tsunami (Mader, 1998b). He continued the numerical modeling of water waves and in 1998; he published a book entitled "Numerical Modeling of Water Waves" (Mader, 2004).

In later years, Zygmunt Kowalik at the University of Alaska and Paul Whitmore of the Alaska Tsunami Warning System cooperated on the investigation of two tsunamis that had been recorded at Adak, Alaska (Kowalik and Whitmore, 1991). Also, Kowalik and Murty in Canada worked on another project of numerically simulating two-dimensional tsunami run-up (Kowalik and Murty, 1993).

Charles Mader's subsequent work involved the writing of a book entitled "Numerical Modeling of Detonations", published in 1998, which described the basic fluid dynamics associated with water waves and the numerical methods for modeling them. This work had been developed primarily at the U.S. Los Alamos National Laboratory with examples of their applications - some performed while Mader was working at the Joint Institute for Marine and Atmospheric Research at the University of Hawaii, and some as Mader Consulting Co. research projects, and the rest as a Fellow of the Los Alamos National Laboratory. The common water wave theories were reviewed in Chapter 1 of this book. A computer code called WAVE for personal computers that calculates the wave properties for Airy, third-order Stokes, and Laitone solitary gravity waves became available on the NMWW CD-ROM. The incompressible fluid dynamics model used for shallow water, long waves was described in Chapter 2 of this book. A code for personal computers using the shallow water model was named SWAN and became also available on the NMWW CD-ROM.

Using such numerical simulation methods, Charles Mader modeled the dynamics of cavity generation (Mader, 2003), the 1755 Lisbon tsunami, the La Palma Landslide Tsunami (Mader, 2001), and with Michael Gittings at Los Alamos, the 1958 Lituya Bay Mega-Tsunami (Mader, & Gittings, 2002) – all published in the journal Science of Tsunami Hazards.

In later years Zygmunt Kowalic continued his work on basic relations between tsunamis and their physics (Kowalik, 2003), on tsunami energy flux as a tool in locating tsunami secondary sources (Kowalik, Z. (2008), and worked with T. Proshutinsky, and A. Proshutinsky, on examining tide-tsunami interactions (Kowalik et al., 2006), Also, he studied such interactions for the Cook Inlet in Alaska with A. Proshutinsky (Kowalik & Proshutinsky, 2010), and published reports in Science of Tsunami Hazards and other journals.

Earlier, Zygmunt Kowalik, working with W. Knight. T. Logan and Paul Whitmore numerically simulated the global tsunami that resulted from the 26 December 2004 great Indonesian earthquake (Kowalik et al. 2005a), with special emphasis on tsunami energy flux distribution and focusing

(Kowalik et al., 2005b; 2006). Beget and Zygmunt Kowalic (2006) worked on the confirmation and calibration of tsunamis produced by the Augustine Volcano in Alaska. Kowalik, Z., J. Horrillo, W. Knight, and T. Logan, also looked at the tsunami scattering effects and impact on Crescent City from the Kuril Islands tsunami of November 2006 (Kowalik et al., 2008). Wave dispersion studies in the Indian Ocean were also conducted by Horillo, Kowalic and J. Shigihara (Horrillo et.al., 2006), and modeling of dispersive and nondispersive effects of tsunami propagation over the North Pacific by Horrillo, W. Knight, and Kowalik (Horrillo et. al., 2012).

Mader's later edition of the first book, entitled "Numerical Modeling of Explosives and Propellants" published in 2008, was a well-written, comprehensive treatise regarding what is being done with state-of-the-art, high-performance computers that allow for the adaptation of new codes which can result in accurate simulations of waves generated from a variety of source mechanisms – whether earthquakes, landslides, explosions, or the impact of asteroids. Furthermore, the book included important theoretical principles of water wave theory and the governing mathematical equations of Eulerian conservation of mass, momentum and energy, which are used to describe different forms of water waves. Finally, it included new codes for specific applications to computer modeling. These new codes allowed for the rapid solution of highly complex Navier-Stokes and other equations that describe wave generation, wave energy propagation and which allow the prediction of near and far field wave characteristics from different sources and the effects on the distribution of wave energy and its attenuation across a body of water – based on refined rectangular meshes and finite difference schemes.

5. DOCUMENTATION OF MAJOR TSUNAMIGENIC EARTHQUAKES

The tsunamigenic earthquakes of 1960 and 1964, as well as many other events, were extensively studied by researchers throughout the world. Comparisons with dislocation models involving predominantly dip-slip movement on major complex thrust faults along zones of tectonic plate convergences (Spaeth & Berkman, 1964, 1969; Plafker, 1964, 1965, 1972a,b; Plafker and Mayo, 1965; Plafker, G. and R. Kachadoorian, 1966; Plafker and Meyer, 1967). These two tsunamigenic earthquakes, as well as those of 1946, 1952, 1963, 1975 and 1985 and many other subsequent events, were studied extensively by numerous researchers in the USA and internationally. Many protocols for coordinating post-tsunami field reconnaissance have been written in the past but continue to be improved to the present with the most recent report published in 2014 by Rick Wilson, Nathan Wood, Laura Kong, Mike Shulters, Kevin Richards, Paula Dunbar, Gen Tamura and Ed Young (Wilson et.al. 2014). Many of the major tsunamigenic earthquakes are described in http://www.drgeorgepc.com/NavigationGuide.html , The following sections review only some of the early investigations that were carried out in the first 3-4 decades following the 1946 tsunami. The present review does not include the numerous other investigations of subsequent major tsunamis that occurred in the new millennium.

5.1 Investigations of the Great Chile Earthquake and Tsunami of 23 May 1960

The impact of the 24 May 1960 Chilean tsunami in the Hawaiian Islands, in Northern California and islands of Polynesia was reported by a number of investigators and published in the literature (Cox &

Mink 1963; Cox, 1963; Magoon, 1962; Plafker, 1972). Run-up heights in the Hawaiian Islands ranged from 2 to 17 feet except in Hilo where the wave formed a bore and reached 35 feet (Cox & Mink, 1963). Sixty-one people were killed and 282 injured in spite of the warning issued 5 hours in advance of the arrival of the tsunami. Orville Magoon at the U.S. Army Corps of Engineers, published a report on the structural damage to coastal structures caused by the 1964 and other tsunamis (Magoon, 1965).

5.2 Investigations of the Great Alaska Earthquake and Tsunami of 27 March 1964

The Great Alaska Earthquake and Tsunami of 27 March 1964 was the second largest earthquake in recorded history after the 1960 Chilean event and was extensively studied by researchers at HIG, the U.S. Geological Survey, the U.S. Army Corps of Engineers, and by researchers at several government and academic institutions under the joint sponsorship of the National Academy of Science and the National Academy of Engineering (Plafker, 1964, 1965, 1972a,b; Roberts & Chien, 1964; Berg et al., 1964; Brown, 1964; Grantz et al., 1964; Van Dorn, 1964a, 1964b, 1973; Pararas-Carayannis & Furumoto, 1965; Pararas-Carayannis, 1966, 1967, 1972; Press & Jackson, 1965; Coulter & Migliaccio, 1966; Plafker & Mayo, 1965; Wood, 1966; Plafker & Kachadoorian, 1966, 1972; Plafker & Meyer, 1967; Furumoto, 1967; Wilson & Torum, 1968; Spaeth & Berkman, 1964, 1969; Cox & Pararas-Carayannis, 1968, 1969; Cox, 1972; Plafker, 1972 a,b). The 1964 Alaska Earthquake and Tsunami intensified the program of tsunami research at the Hawaii Institute of Geophysics (HIG). Additional funds were given by the State of Hawaii and by the National Academy of Engineering for the university research group to investigate this 1964 tsunami.

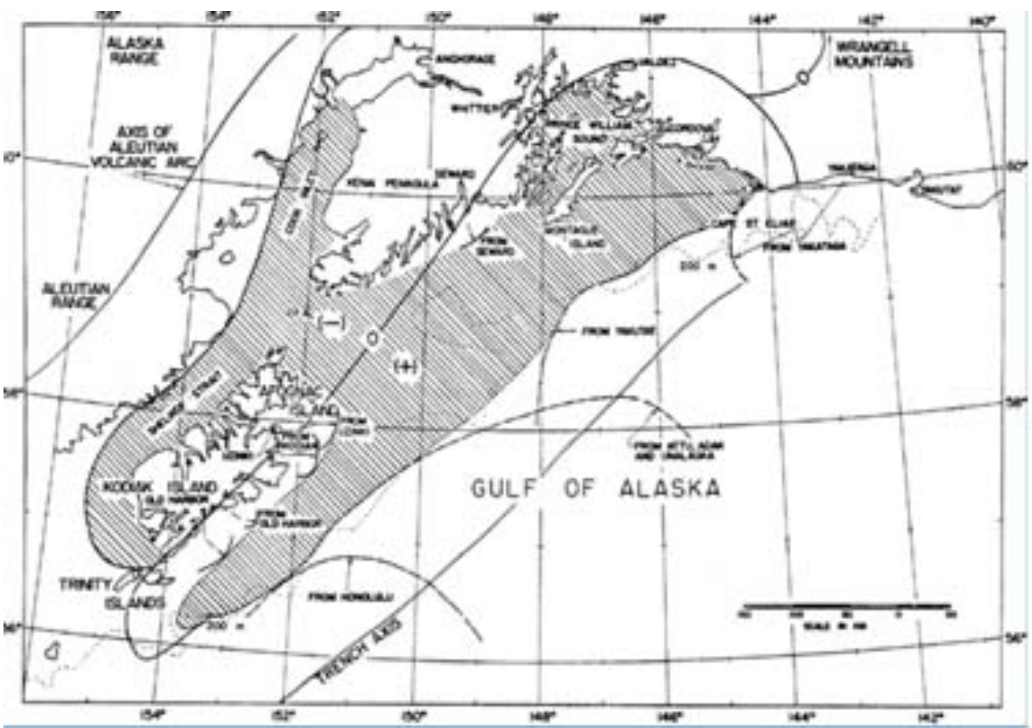

Figure 8. Generating area of the 1964 Alaska tsunami (Pararas-Carayannis and Gus Furumoto, 1965)

As shown in the figure above, an investigation by George Pararas-Carayannis and Augustine Furumoto determined the limits of the areas of subsidence and uplift of the 1964 earthquake by using reverse refraction of the tsunami waves from recording tidal stations back to the region of their generation. Also estimated from geodetic changes, were isopachs of the volume of crustal displacements and of the dipole nature of movements along the axis of rupture. The energy of the earthquake and of the tsunami were estimated from empirical relationships. The earthquake's source mechanisms based on wave activity within Prince William Sound and in the Gulf of Alaska - and the possible generating mechanisms – were analyzed and also confirmed by analysis of the Rayleigh wave from the seismic record of the only recording, broad-band, strain seismograph at Kipapa Station, Hawaii. There were no other broad-band instruments at the time. The parameters that gave the best fit to the observed data were: a rupture length of 800 km, a rupture velocity of 3 km/sec, and azimuth of rupture line of S30 deg W. The results of this analysis compared favorably with field data of elevation changes, with the distribution of epicenters of aftershocks, and with the area of generation of the tsunami as obtained from extensive sea wave reverse refraction diagrams. Finally, the results of this joint investigation were correlated and cross-referenced with data from the field investigations headed by George Plafker and others of the USGS. Apparently, there was good agreement (Pararas-Carayannis & Furumoto, 1965; Pararas-Carayannis, 1966, 1972). The final report, as well as reports prepared by Doak Cox, by Harold Loomis and many other investigators were included in the final volume of the National Academy of Science on the Great Alaska Earthquake of 1964.

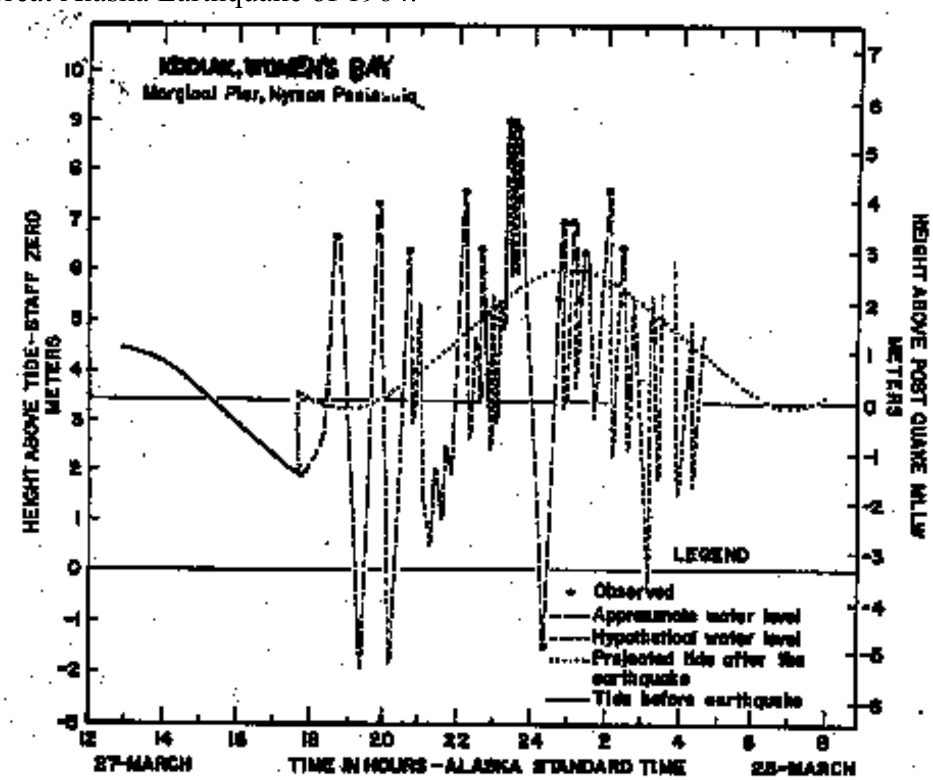

Figure 9. Tide gauge record of the 1964 tsunami at Kodiak Island (after Pararas-Carayannis, 1965, 1966,1967)

5.3 Investigations of the November 29, 1975 tsunami along the coast of the island of Hawaii – Slope Failure of Kilauea Volcano

The major earthquake of November 29, 1975 (surface wave magnitude of 7.2) and the destructive local tsunami on the Island of Hawaii generated a flurry of field surveys and subsequent studies of the mechanism of tsunami generation along the southern flank of the Kilauea volcano. Immediate field investigations were undertaken by ITIC and USGS. Additional field investigations and studies were conducted subsequently – mostly by ITIC, HIG, JTRE and by U.S. Geological Survey scientists. This particular earthquake involved uplift, subsidence and slope failure along the southern region of the Island of Hawaii (Figure 10). It was determined that maximum horizontal crustal displacement was approximately 7.9 meters. Near Keauhou Landing, maximum vertical subsidence was approximately 3.5 meters. The displacements decreased to the east and west from this area. In fact, subsidence rapidly decreased to the west. At Punalu'u, the shoreline actually uplifted by about 10 centimeters (Pararas-Carayannis, 1976 a & b). Subsequent surveys determined a subsidence of about 3 meters at Halape Park to the east. A large coconut grove area adjacent to the beach subsided by as much as 3.0 and 3.5 meters. Further to the east, the subsidence decreased to 1.1 meters at Kamoamoa, 0.8 meters at Kaimu, 0.4 meters at Pohoiki, and 0.25 meters at Kapoho. According to the Volcano Observatory of the U.S. Geological Survey, even the summit of Kilauea subsided by about 1.2 meters and moved towards the ocean by about the same amount. A small, short-lived eruption took place inside Kilauea's caldera.

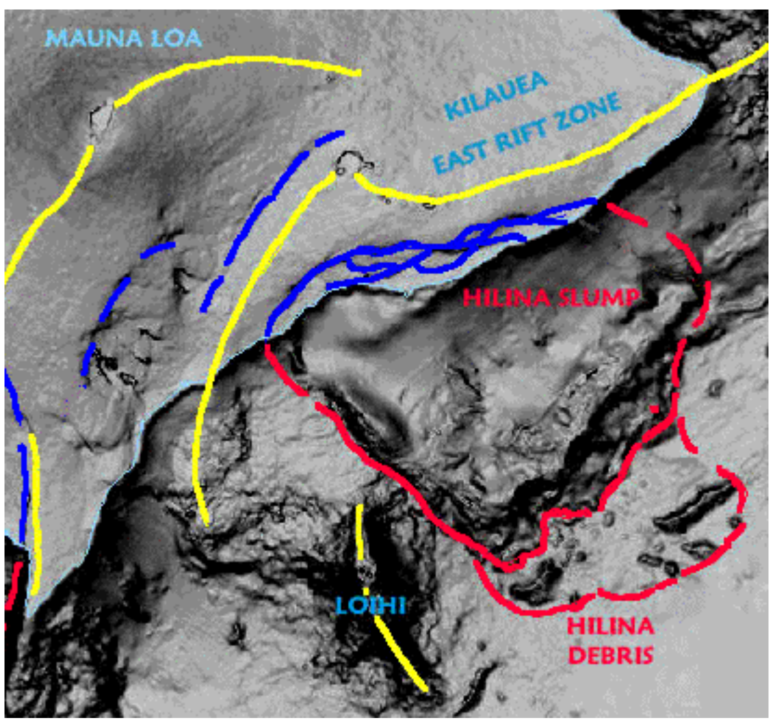

Figure 10. Hawaii's southern slope showing coastal faults parallel to the east rift zone of the Kilauea volcano, and the Hilina Slump along which slope failures have been occurring and tsunamis have been generated (drawing modified after Morgan et al. 2001).

The affected offshore block was approximately 70 km long, and 30 km wide with the long axis of the displaced block being parallel to the coast. This entire offshore region rose approximately 1.2 meters. The total volume of displaced material was roughly estimated to be only 2.52 cubic km Furthermore, inspection of tide gauge records showed the initial wave motion to be upwards at all stations. The significance of this observation was that the offshore crustal displacement was an uplift, as the onshore section subsided and moved outward. This was indicative that the resulting slope failure and earthquake were not entirely due to gravitational effects of instability, but may have been partially caused by compressional lateral magma migration from shallow magmatic chambers of Kilauea or by lateral magmastatic forces along an arcuate failure surface or along a secondary zone of crustal weakness on the upper slope of the Hilina Slump (Pararas-Carayannis 1976 a, b). In fact, recent paleomagnetic studies show that differential rates of movement and rotation occur between sections of the slump (Rileya et al., 1999).

Finally, it was interesting to further note that Hilo was greatly affected by the earthquake shock waves in 1868 and in 1975, but not by the tsunami waves. This is suggestive of the directionality of slumping and of the limited dimensions of distinct slope failure events along the southern flanks of Kilauea and Mauna Loa volcanoes. Neither of these two volcanic slope failures generated a mega tsunami that posed a threat at locations distantly from the source. Slope failures and subsidences along Kilauea's southern flank have occurred with frequency in the past. However, the failures appear to have occurred in phases, over a period of time, and not necessarily as single, large-scale events, involving great volumes of material.

In addition to field investigations of the 29 November 1975 tsunami, Sklarz, M.A., L.Q. Spielvogel, and H.G. Loomis at JIMAR and elsewhere conducted simulation studies of this event using finite-element modeling and variations of open boundary interferences (Sklarz et al., 1979a,b). There were further investigations of earthquakes and tsunamis by ITIC, including a major event in the Lesser Sunda Islands (Pararas-Carayannis, G., 1978c; http://drgeorgepc.com/Tsunami1977Indonesia.html)

5.4 Investigations of Sub Aerial and Submarine Landslides and Rock Falls

Additional studies of sub aerial and submarine landslides and rockfalls were undertaken by numerous other investigators over the years. Steven Langford and Richard Brill searched highly precise bathymetric records of the U.S. Navy Oceanographic Office (NAVOCEANO) for hypothesized giant submarine landslides on the Hawaiian Ridge but did not find evidence supporting it (Langford & Brill, 1972).

As previously stated the 1975 Hawaii Island landslide tsunami was investigated by George Pararas-Carayannis who concluded that the resulting slope failure on the southern slope of the volcano of Kilauea was not entirely to gravitational effects of instability, but may have been partially caused by compressional lateral magma migration from shallow magmatic chambers of the volcano or by lateral magmastatic forces along an arcuate failure surface or along a secondary zone of crustal weakness on the upper slope of the Hilina Slump (Pararas-Carayannis, 1976 a, c). Later, paleomagnetic studies by

Rileya, Diehla, Kirschvink and Ripperdanc indicated that the Hilina Slump on the southern flank of the Kilauea volcano was not uniform but was affected by differential rates of movement between sections of the slump (Rileya et al., 1999).

James Lander, Patricia Lockridge, and H. Meyers, published a report on Subaerial and Submarine Landslide Generated Tsunamis. As previously mentioned, Charles Mader investigated the 1994 underwater landslide that generated a tsunami at Skagway, Alaska (Mader, 1997), modeled the landslide that generated the 1975 tsunami on the Island of Hawaii (Mader, 1984), the 1958 Lituya Bay tsunami (Mader, 1999), the LaPalma landslide tsunami Mader, 2001) and with Michael Gittings, the 1958 Lituya Bay mega-tsunami (Mader &. Gittings, 2002). Okal at Northwestern University and Synolakis at the University of California further examined tsunami from dislocational flank failures and landslides (Ocal & Synolakis, 2003).

Figure 11. Lituya Bay. The giant waves that rose to a maximum height of 1,720 feet (516 m) at the head of Lituya Bay, on July 9, 1958.

5.4.1 Analysis of the 9 July 1958 Tsunami Generation Mechanism in Lituya Bay, Alaska

On July 9, 1958, a large 8.3 magnitude earthquake along the Fairweather fault struck Southeastern Alaska. A combination of disturbances triggered by the earthquake generated a mega-tsunami wave that rose to a maximum height of 1,720 feet (516 m) at the head of Lituya Bay (Miller, 1960).

The extreme height of the wave and the mechanism of its generation were puzzling. There were questions as to whether there was sufficient water volume in the inlet at the head of the Bay for such an extreme wave to be generated and to reach such an enormous height. Several mechanisms for the extreme wave generation were proposed but none could be supported conclusively by the data on hand at the time. Suggested scenarios for the "mega-tsunami" included a combination of tectonic movements associated with the earthquake, collapse of a tidal glacier front, the possible sudden drainage of a subglacial lake on the Lituya Glacier and the major subaerial rockfall that occurred in Gilbert Inlet, immediately after the earthquake.

A study of all postulated mechanisms of mega-tsunami generation in Lituya Bay was undertaken by George Pararas-Carayannis to determine which was the main mechanism that really contributed to the generation of the extreme wave. Based on such analyses of generation, he concluded that the mechanism for the generation of the giant 1,720 foot wave run-up at the head of the bay and of the subsequent waves along the main body of Lituya Bay must have been not due to a landslide - as originally believed - but due to a giant rockfall triggered by the strong earthquake ground motions of the earthquake along the Fairweather fault (Pararas-Carayannis, 1999). This rockfall acted as a monolith, - thus resembling an asteroid – and impacted with great force the bottom of Gilbert Inlet. The impact created a radial crater which displaced and folded recent and Tertiary deposits and sedimentary layers at the glacier's front. The displaced water and the folding of sediments broke and uplifted 1,300 feet of ice along the entire front of the Lituya Glacier. Also, the impact resulted in the water splashing action that reached the 1,720 foot elevation. The rockfall impact, in combination with the net vertical crust uplift of about 1 meter and an overall tilting seaward of the entire crustal block on which Lituya Bay was situated, generated a solitary gravity wave which swept the main body of the bay (Pararas-Carayannis, 1999; http://www.drgeorgepc.com/Tsunami1958LituyaB.html

5.4.1a Proposed Asteroid Model Validation based on the Lituya Bay Rockfall Event - Verification of the Impulsive Rockfall Source Mechanism - The sub aerial rockfall was considered as the most significant contributor to the mega-tsunami wave generation at the Gilbert Inlet of Lituya Bay. However, and as stated, a simple mechanism of mass collapse of a portion of the mountain and water volume displacement alone could not account for the extreme wave height. The following account provides some of the background material related to the tectonic setting and seismicity of the region, the chronology of events that followed the earthquake of July 9, 1958, and Pararas-Carayannis's conclusion and explanation of a rockfall mechanism (the P.C. model) which could account for the observed mega-tsunami wave height, even if there was a water volume limitation, as well as a proposal of how this event could be used for asteroid model validation.

The proposal was based on the following justification. Wave generation based on simulating the time history, large energy content and other input parameters of the Lituya Bay rockfall, corrected for scale factors of volume, trajectory path, terminal impact velocity, water depth and energy imparted to the water body, could provide meaningful initial conditions to determine and separate the nonlinear portion from the mathematical solutions which use the Navier-Stokes equations to describe the gravity wave portion of an asteroid-generated tsunami - at least in its propagative phase, following impact, as it travels in the ocean. Subsequent mathematical, full Navier-Stokes modeling of mega-tsunami generation at the U.S. Los Alamos National Laboratory by Mader and Gittings using the PC model scaled parameters supported this mechanism and further illustrated that there was sufficient volume of water to account for the giant wave run-up. Mader and Gittings, using the non-linear shallow water code known as "SWAN" - which included Coriolis and frictional effects, and subsequently with the Navier-Stokes, Eulerian compressible hydrodynamic code known as "SAGE" - which included the effects of gravity (Mader, 1999; Mader & Gittings, 2002). The PC scenario of the impulsive rockfall mechanism, with crater creation and air bubble explosion could account for the giant wave of 1,720 feet at the head of Lituya Bay - even in the absence of sufficient volume of water at Gilbert and Crillon inlets. The PC model hypothesis was further verified and validated with physical modeling experiments conducted by Hermann Fritz and other scientists at the Swiss Federal Institute of Technology (ETH) in Switzerland, using a scaled rectangular prismatic water wave channel model)(Figure 12) (Fritz et al., 2001).

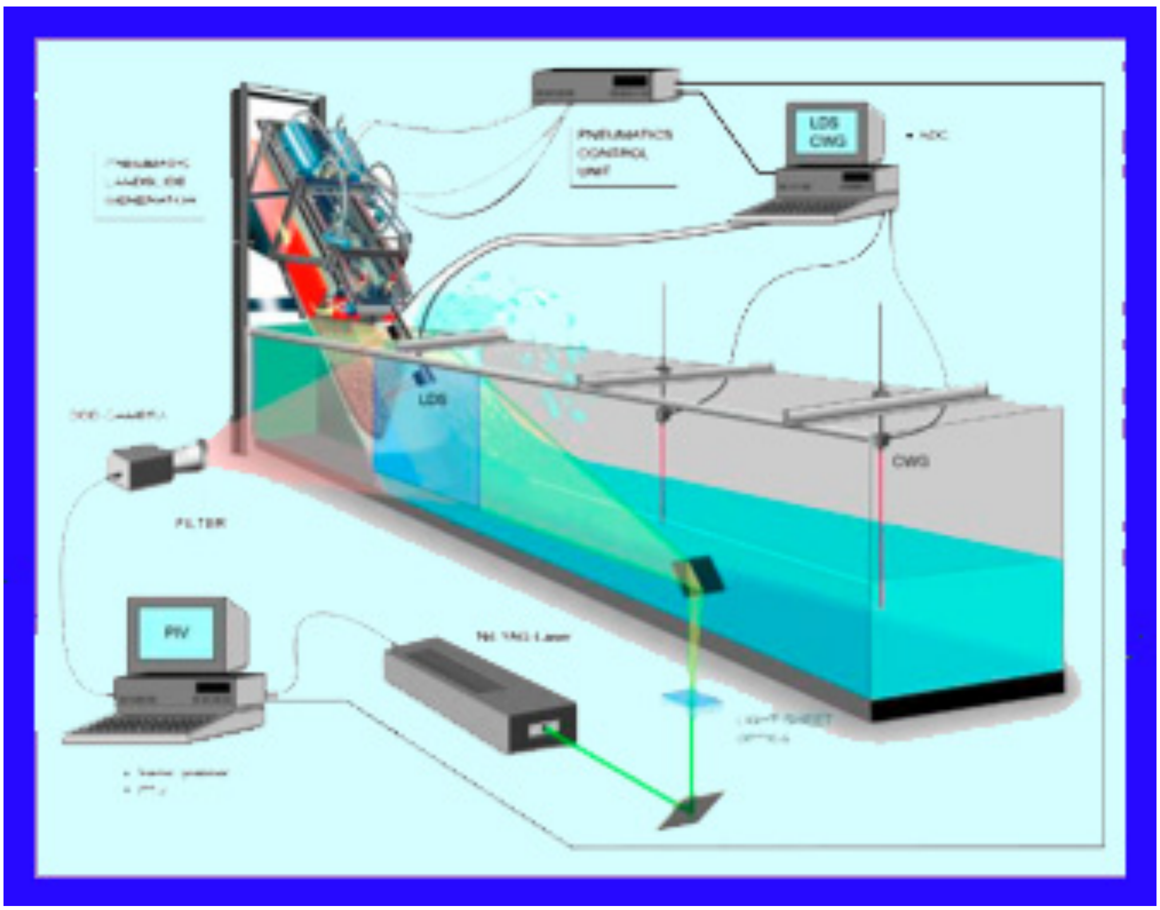

Figure 12. The rockfall model hypothesis was further verified with physical modeling experiments (using a scaled rectangular prismatic water wave channel model) conducted by scientists at the Swiss Federal Institute of Technology (ETH) in Switzerland.

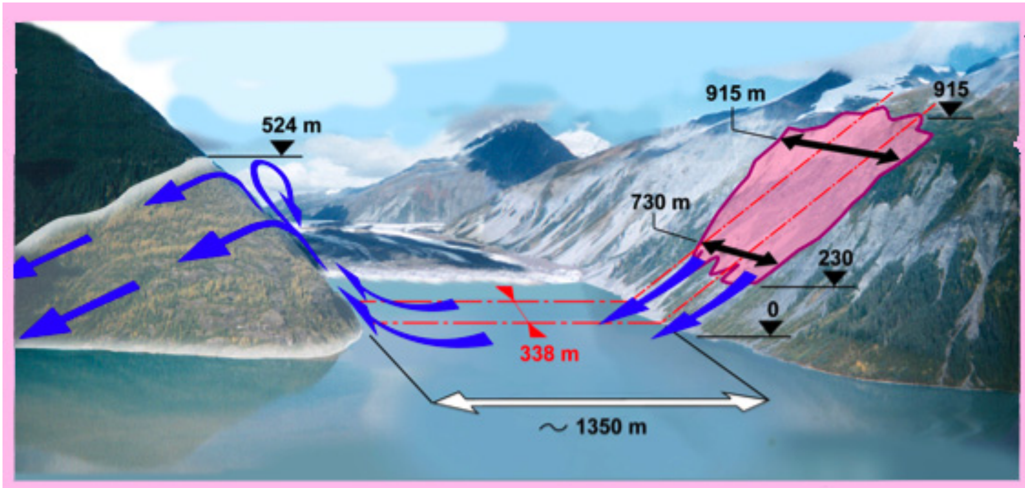

Figure 13. Lituya Bay Case: Rockslide impact and wave run-up (After Hermann Fritz, et.al., 2001)

5.5 Investigation or The Mexican Earthquakes and Tsunami of September 19 and 21, 1985.

The major earthquake measuring 8.1 on the Richter scale, which struck the Western Coast of Mexico on Thursday, 19 September 1985, generated a small tsunami (Figure 14). The major earthquake (aftershock or separate event?) on 21 September 1985 with magnitude 7.5 generated also a small tsunami. Both tsunamis propagated across the Pacific and were recorded by several tide stations in Central America, Colombia, Ecuador, French Polynesia, Samoa, and Hawaii. No reports of damage were received from any distant locations, and only minor damage due to the first tsunami was reported in the source region along the west coast of Mexico.

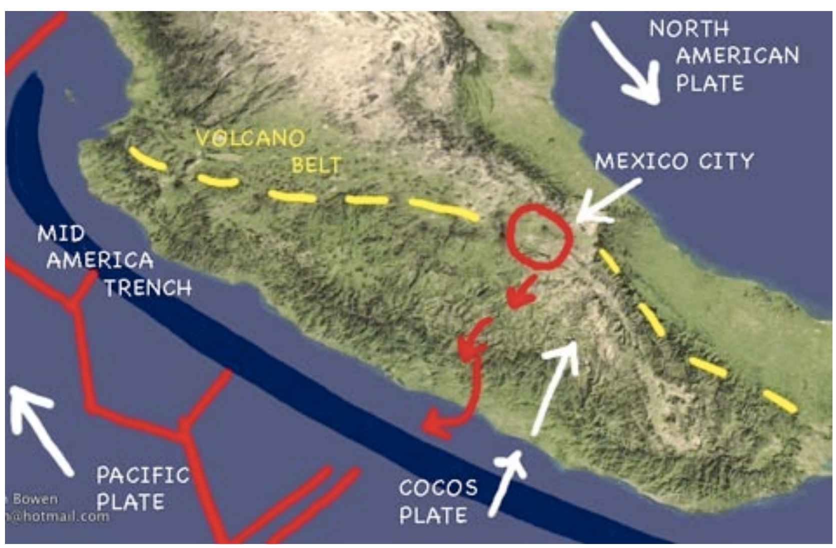

Figure 14. Interaction of Tectonic Plates that Caused the 19 and 21 September 1985 quakes in Mexico

A survey was undertaken in Mexico by the International Tsunami Information Center (ITIC) (George Pararas-Carayannis) of the coastal area from Manzanillo to Zihuatanejo. Tsunami run-up measurements were taken and interviews with local residents in the coastal areas were conducted. Subsequently, a survey of earthquake damage was undertaken in Mexico City. A source mechanism study of the tsunamis was subsequently conducted using seismic and geologic data and empirical relationships. Earthquake and tsunami energies were estimated and the tsunami generation areas defined. The earthquake energies were estimated to be 5.61 x 10^{24} ergs for the 19 September event while that of the 21 September event at 9.9 x 10^{23} ergs. Tsunami energies were estimated to be 0.7 x 10^{20} ergs for the first event and 0.56 x 10^{20} ergs for the second event. The source area of the first tsunami was determined to be approximately one-half of the earthquake source area, or approximately 7,500 sq, km while the source area of the second tsunami was estimated to be equal to the earthquake area. The relatively small tsunamis generated by these large earthquakes were attributed to the shallow angle of subduction of the Cocos plate underneath the North American plate for this particular region, and to the small vertical component of crustal displacements. However, it was concluded that the angle of subduction increases further south and local earthquakes from that area have the potential of producing large tsunamis on the West Coast of Mexico (Pararas-Carayannis, 1985e, 1985f).

5.6 The 17 August 1999 Koaceli Earthquake and Tsunami in Izmit Bay, Turkey.

On August 17, 1999, a large destructive earthquake struck northwest Turkey and generated a local tsunami within the enclosed Sea of Marmara. This was the strongest earthquake to strike Northern Turkey since 1967. It occurred along the Northern Anatolian fault. Its epicenter was in the Gulf of Izmit. Official estimates indicated that about 17,000 people lost their lives and thousands more were injured. However, it is believed that the death toll may have been much higher. The destructive earthquake, not only generated a local tsunami that was destructive at Golcuk and other coastal cities in the eastern portion of the enclosed Sea of Marmara, but was also responsible for extensive damage from collateral hazards such as subsidence, landslides, ground liquefaction, soil amplifications, compaction and underwater slumping of unconsolidated sediments.

As shown in the figure below, the North Anatolian fault is a major fracture that transverses the Northern part of Asia Minor and marks the boundary between the Anatolian tectonic plate and the larger Eurasian continental block. Because of this unstable tectonic system the area is considered as one of the most seismically active zones of the world. Turkey is being squeezed sideways to the west as the Arabian plate pushes into the Eurasian plate (Pararas-Carayannis, 1999). The north Anatolian fault forms the edge of this Turkish (Anatolian) crustal block so that destructive earthquakes happen regularly along it as different sections break. Based on the historic record Pararas-Carayannis concluded that major earthquakes can be expected to occur again frequently in the region. Although most of the earthquakes along the great North Anatolian fault involve primarily horizontal ground displacements - and such tectonic movements do not ordinarily generate tsunamis - some of the earthquakes along the western segment of the fault have triggered major slumps that have generated tsunamis. At least 9 major tsunamis have been reported to have occurred in the Marmara Sea in the past (Kuran and Yalciner, 1993).

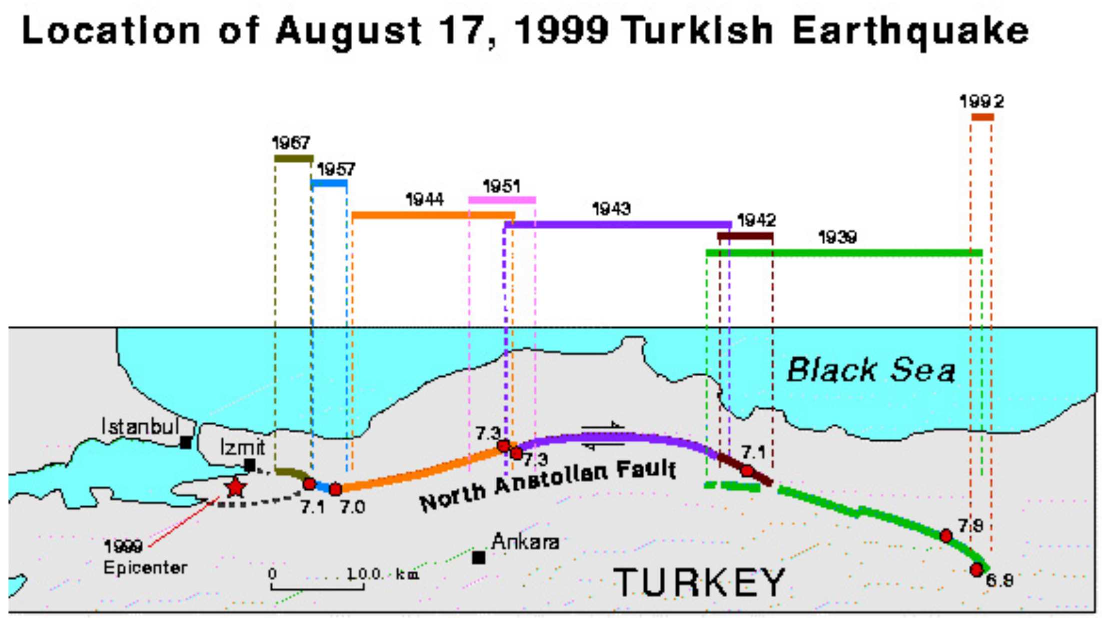

Figure 15. Location of the 17 August 1999 tsunamigenic earthquake near Izmit, Turkey along the North Anatolian plate showing also segments ruptured in chronological sequence (after http://www.drgeorgepc.com/Tsunami1999Turkey.html)

The Koaceli earthquake and tsunami was studied extensively by scientists from Turkey and elsewhere. Ahmet Yalciner, Y. Altinok and Costas Synolakis took part in a stydy of the tsunami waves in Izmit Bay (Yalciner, A.C., Altinok, Y. and Synolakis, C.E., 2000).

This disaster brought attention in the need to identify in this highly populated region, local conditions that enhance earthquake intensities, tsunami run-up and other collateral disaster impacts. Such a study was carried out by George Pararas-Carayannis, Barbara Theilen-Willige of the Technical University of Berlin and Helmut Wenzel of the VCE Holding GmbH, in Vienna, described how standardized remote sensing techniques and GIS-methods could help detect areas as the Sea of Marmara that are potentially vulnerable, so that disaster mitigation strategies can be implemented more effectively. Apparently, local site conditions in the Izmit region exacerbated the earthquake intensities of the 1999 event and the collateral disaster destruction in the Marmara Sea region. However, the study indicated that by using remote sensing data, the causal factors could be determined systematically and that with proper evaluation of satellite imageries and digital topographic data, specific geomorphologic/topographic settings that enhance disaster impacts in the Sea of Marmara could be identified. With such a systematic GIS approach - based on Digital Elevation Model (DEM) data – the geomorphometric parameters that influence the local site conditions were detrmined for the Sea of Marmara region.

In describing the seismotectonic setting of the Sea of Marmara region, and the local site conditions that influence earthquake intensities and extreme secondary collateral impacts such as the ground liquifaction and subsidence that earthquakes can have, George Pararas=Carayannis, Barbara Theilen-Willige of the Technical University of Berlin and Helmut Wenzel of the VCE Holding GmbH, used standardized remote sensing methodology and GIS-methods to detect and identify potentially vulnerable areas to earthquakes, tsunamis and other hazards (Pararas-Carayannis, G.; Theilen-Willige, B. & Wenzel, H., 2011. The same remote sensing methodology was used in the study of other disasters in other areas of the world.

6. PREPARATION OF HISTORICAL TSUNAMI CATALOGS AND DATABASES

The preparation of databases and historical tsunami catalogs was considered to be a major requirement in evaluating potentially recurring tsunamis and in the issuance of tsunami warnings. Thus, in the early 1960s the HIG tsunami research group begun compiling historical tsunami data for the Pacific, Hawaii, Alaska, the Atlantic and Indian Oceans and for the Caribbean and Mediterranean Seas. The documentation of historical tsunamis included thorough reviews and verification of published reports in a variety of journals, searches of newspaper archives, of archives of the Bishop Museum in Hawaii, of Franciscan Mission records in California, of archives in Seville Spain, of archives at the British Museum and even of cemetery records in Japan.

The compilation of historical catalogs begun initially under the direction of Doak Cox at HIG in cooperation with George Pararas-Carayannis and Dr. Kumizi Iida of Nagoya University in Japan, who was at the time a visiting scholar at the University of Hawaii. After joining ITIC where the directorship of the World Data Center A - Tsunami had been transferred, George Pararas-Carayannis continued to work on historical tsunami databases, updating catalogs of tsunamis for the Pacific, Alaska, Hawaii, Samoa and the Atlantic, and additionally continued work on an Atlas of Tsunami Marigrams and in digitizing the analog mareographic records of historical tsunamis for an Atlas of Tsunami Marigrams (Pararas-Carayannis, 1967) - based on data supplied by Mark Spaeth and Saul Berkman at the U.S. Coast and Geodetic Survey headquarters in Washington D.C.(Pararas-Carayannis, G., 1968b). Additionally, a series of reports on tsunami wave heights was compiled (Pararas-Carayannis, 1968b) when ITIC was initially designated to be the World Data Center A- Tsunami. Additionally, with support of the U.S. Nuclear Regulatory Commission and NOAA, Pararas-Carayannis developed annotated bibliographies and a very extensive tsunami library for the use of JTRE and visiting scientists at the Hawaii Institute of Geophysics and ITIC. Also, he continued to develop an extensive historical tsunami database and to coordinate matters related to the functions and data requirements of Pacific Tsunami Warning System with guidance from IOC and the ICG/ITSU.

6.1a. Catalog of Tsunamis in the Pacific

Kumizi Iida (of Nagoya University, Japan), Doak Cox and George Pararas-Carayannis at HIG began compiling in the early 1960's historical tsunami information, which was subsequently published as a Preliminary Catalog of Tsunamis in the Pacific Ocean as HIG reports (Iida, et al. 1967, 1972). This historical catalog was very useful in tsunami evaluation and issuance of warnings by the Pacific

Tsunami Warning Center. The work on further documenting historical tsunami information continued in the 1970's and included searches of newspaper records, of the archives of the Bishop Museum in Honolulu of the Franciscan records in California and of cemetery records in Japan. The search on historical tsunamis along the coasts of South America was further extended by Pararas-Carayannis to the Spanish records in Seville, Spain, beginning with the Pissarro's first invasion of Peru in 1524. There was also close communication and exchange of tsunami historical data with Sergey Soloviev in the then Soviet Union, who was also working on a catalog of tsunamis in the Pacific Ocean (Soloviev, 1969).

6.1b Catalog of Tsunamis in Alaska

The Alaska historical Tsunami Catalog was subsequently updated and published as a World Data Center A-Tsunami report (Cox and Pararas-Carayannis, 1968, 1969; Cox et al, 1976). The historical tsunami historical data was also of great help to Alaska's and Hawaii's Civil Defense Agencies.

6.1c Catalog of Historical Tsunamis in the Hawaiian Islands.

A catalog of tsunamis in the Hawaiian Islands was prepared and published initially as an HIG report (Pararas-Carayannis, 1968, 1969). The catalog was further revised, updated and was published as a World Data Center A-Tsunami report (Pararas-Carayannis & Calebaugh, 1977). Based on such historical data on the Hawaiian Islands, the tsunami danger zones were better determined and the first tsunami evacuation maps were prepared and published as charts in Hawaii's telephone books for public awareness and preparedness.

7. PREPARATION OF ADDITIONAL HISTORICAL TSUNAMI CATALOGS

As stated, the preparation of historical catalogs of tsunamis in the Pacific (Iida et al. 1965), in the Hawaiian Islands (Pararas-Carayannis, 1969) and in Alaska (Cox & Pararas-Carayannis, 1968, 1969) became a very useful tool for tsunami evaluations and warnings by both PTWC and ATWC. A preliminary catalog of historical tsunamis in the Atlantic Ocean was appended to a recommendation for establishing an additional Tsunami Warning System in the Atlantic (Adams & Pararas-Carayannis, 1966). When the function of the World Data-Center A-Tsunami was transferred to the U.S. National Geophysical Data Center (NGDC) in Boulder, Colorado, this work and the compilation of revised and updated historical tsunami catalogs was continued by J. Calebaugh, for Hawaii (Pararas-Carayannis and Calebaugh, 1977) and Alaska (Cox et al., 1976) and were published as World Data Center Reports.

7.1 Catalog of Tsunamis in the Samoan Islands

In 1979, ITIC was contracted by the U.S. Army Corps of Engineers, Waterways Experiment Station – trough the Research Corporation of the University of Hawaii - to do a study of historical tsunamis in

America Samoa and to compile a catalog, as part of their on-going Type 16 Flood Studies. The compilation required a thorough review of all available historical records in both American and Western Samoa (Pararas-Carayannis, 1979b) and the preparation of a final tsunami catalog for the Samoan Islands submitted to the U.S. Army, Waterways Experiment Station in Vicksburg, Mississippi (Pararas-Carayannis and Dong, 1980).

7.2 Catalogs of Tsunamis for Other Regions

Following the transfer of the World Center A - Tsunami to the NGDC in Boulder, Colorado – the documentation of historical tsunamis was continued by James Lander, Patricia Lockridge, Ronald Smith, Lowel Whiteside and others. Patricia Lockridge compiled listings of databases that could support investigations of geological hazards – including tsunamis – which was published in Science of Tsunami Hazards (1984). Patricia Lockridge and Ronald H. Smith compiled a map and a catalog of tsunamis in the Pacific Basin from 1900-1983 (Lockridge and Smith, 1984a &b). Also, Patricia Lockridge compiled a catalog of tsunamis for Peru-Chile (Lockridge, 1985). Additional historical tsunami catalogs for United States and U.S. Possessions were prepared by James Lander and Patricia Lockridge (Lander and Lockridge, 1989). James Lander, Patricia Lockridge and M. Kozuch worked on catalogs of historical tsunamis that affected the United States and the U.S. Trust Territories (Lander & Lockridge, 1989) and with M. Kozuch on tsunamis that affected the West Coast of the United States from 1806 to 1992 (Lander et al, 1993). James Lander also reviewed the tsunamis that had affected Alaska from 1737 to 1996 (Lander, 1996), the west coast of the United States from 1806 to 1992 (Lander, J.F., P. Lockridge, and M. Kozuch, 1993), and Alaska from 1737 to 1996 (Lander, 1995 a & b; 1996). Also Patricia Lockridge with Lowell Whiteside and James Lander published in Science of Tsunami Hazards a report on Tsunamis and Tsunami-like Waves of the Eastern United States (Lockridge et al., 2002)

With L.S. Whiteside and Patricia Lockridge, Lander also compiled a brief history of tsunamis in the Caribbean Sea published in Science of Tsunami Hazards (Lander et al., 2002). Additionally, James Lander, Lowell Whiteside and Paul Hatori co-authored a paper on the Tsunami History of Guam, also published in Science of Tsunami Hazards (Lander et al., 2002). In later years, James Lander, Lowell Whiteside and Patricia Lockridge published again in Science of Tsunami Hazards a brief history of tsunamis in the Caribbean Sea, another catalog of "Two Decades of Global Tsunamis between 1982 and 2002" (Lander, Whiteside & Lockridge, 2002a. b.) and of tsunamis and Tsunami-like waves of the Eastern United States (Lockridge et al, 2002). O'Loughlin and James Lander compiled and published a history of 500 years (from 1498-1998) of tsunamis in the Caribbean Sea (O'Loughlin & Lander, 2003).

8. EFFORTS FOR THE DEVELOPMENT OF REGIONAL TSUNAMI WARNING SYSTEMS IN SOUTH AMERICA AND THE SOUTHWEST PACIFIC

These efforts were not research projects but pertained to the development of technology and its application and adaptation for the purpose of improving the Tsunami Warning System in the Pacific but also for shortening the time that warnings could be issued for critical areas by establishing regional warning systems. At the *Fifth Session* of ITSU/ICG in Lima, Peru (23-27 February 1976), based on the fact that at least six hazardous tsunamis had occurred with great loss of life and property in areas where warnings could not be issued promptly, it was concluded that if appropriate regional systems existed, warning information could be released to the public within minutes - thus permitting evacuation of most of the coastal population to safer places. This had been made more feasible since new operational concepts had been developed by that time that could utilize modern technology of computers and instrumentation, including shore-based seismic and tidal sensors and real-time telemetry that could improve significantly the performance of such regional tsunami warning systems. At that particular ITSU/ICG meeting in Lima, there was further consensus on the need for regional tsunami warning systems in South America, the South-West Pacific and the Eastern Mediterranean Sea. Such regional projects would have considerable benefits for the countries involved and such efforts would be well within the scope and intent of the subsequently proposed International Decade for Natural Disaster Reduction (IDNDR). However, considering the regional nature and the complex content of such proposed regional tsunami warning systems, it was also recognized that strong support was needed by the concerned Member States and that national counterpart contributions were essential if funds were to be made available by the United Nations Development Program (UNDP).

Although the need had been clearly identified at the *Fifth Session* of ITSU/ICG in Lima, Peru, such efforts in establishing a Regional Tsunami Warning System for South America began in 1979. The first mission by the Director of ITIC (George Pararas-Carayannis at the time) resulted in thc drafting of a proposal, which was submitted for funding to UNDP through UNESCO in October 1980. Since no response was received, the project document was redrafted and resubmitted to UNDP, through the IOC Secretariat and UNESCO. Unfortunately a regional project for South America was not funded by UNDP, as there were other priorities.

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

Subsequently, at its Eighth Session in 1982 ICG/lTSU recommended, through Resolution ITSU-vIII.4 that the highest priority be given to 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 and Papua New Guinea), and drafted a project proposal, which was well supported by the Group. At its Ninth Session in 1984, the International Co-ordinatíon Group recognized further that national programmes would become an integral part of a regional warning system and also that updated technology, educational programmes and warning procedures would need to be developed by the Member States of ICG/ITSU.

Thus in 1986, and as part of the THRUST project under the U.S. State Department, Agency for International Development (AID), a mission was funded and George Pararas-Carayannis went to Chile to help with the preparation of a standard operating plan for the Tsunami Warning in that country in collaboration with the Instituto Hidrografico de la Armada de Chile. The 97-page Plan written in English, was subsequently reviewed, corrected, translated in Spanish with help from Emilio Lorca of the University of Chile and adopted (Pararas-Carayannis , 1986b).

As for the Southeast Pacific region, following a 1984 experts mission there, another project proposal was drafted, which was well accepted by the IOC Coordination 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 repeated again, leading to project formulation.

Based on this request, a mission of experts was organized which included George Pararas-Carayannis (Mission Leader), Ron Richmont (Australia), and Kazuhiro Kitazawa of IOC (Mission Secretary). In May 1989 the mission visited the countries concerned and reviewed the national networks of tide stations and seismic observatories to determine appropriate ways and means to strengthen the 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 along Sumatra, Papua New Guinea, Solomon Islands, Vanuatu and the potential of destructive tsunamigenic earthquakes in this region. The mission established short and long period objectives; training and public education needs, as well as needed equipment and installations. Subsequently a report was prepared, a master plan for the region was drafted and a funding proposal was finalized for submission by IOC to UNDP (Pararas-Carayannis, 1980, 1989). Again the project received the endorsement of the UNDP Regional Office in Jakarta, Indonesia, but the countries involved in the region stated that they had other more important priorities for funding. The 2004 earthquake and catastrophic impact of the tsunami in Sumatra, Thailand, India, and elsewhere in the Indian Ocean could have been ameliorated if a regional system had been established - as it had been highly recommended by the1984 experts mission to the region.

8.2 Other Master Plans for the Development of Regional Tsunami Warning Systems

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 Indonesia, Philippines, Peru, Colombia, Mexico and elsewhere (Pararas-Carayannis, 1978, 1979, 1980b, 1982, 1984, 1985a, b & e) and to propose development of Regional TsunamiWarning Systems for countries impacted by such hazards.

9. TSUNAMI RISK ASSESSMENT AND OTHER HAZARD MITIGATION STUDIES

The methodology for assessing effectively the tsunami risk for potentially vulnerable coastlines was extensively studied and specific recommendations were made by a number of early researchers (Cox, 1963; Pararas-Carayannis, 1983, 1985d, 1986d, 1986e, 1988, 1990a, 1994a, 1995, 2004a, 2006, 2006a, 2007; Bernard et. al., 1982; 1988; 1990; Wiegel, 1976). Such risk assessment studies were not limited to earthquake-induced events but also included evaluation of risks from other tsunami generating mechanisms such as volcanic explosions, caldera collapses, landslides and methane hydrate explosions.

For example, George Pararas-Carayannis, who was ITIC Director at the time, provided and published a chapter in a book on Natural and Man-Made Hazards, with specific guidelines and methodology needed for the evaluation of the tsunami risk in terms of frequency of occurrence and severity of impact.

Additionally, he provided guidelines on preparedness and planning for tsunami hazard mitigation, emphasizing the need for historical studies and modeling that could lead to better definition and understanding of the hazard zones (Pararas-Carayannis, 1988).

9.1 Design and Safety Guidelines for Nuclear Power Plants.

Damage of nuclear power plants by tsunamis can result by the direct and indirect action of hydrostatic and dynamic pressures, foundation failures, overtopping and flooding. Reliable assessment of the potential tsunami hazard at a coastal site and adequate engineering design of a critical structure such as a nuclear power plant require analysis and understanding of all aspects of a tsunami system leading to its terminal behavior. Description of the space-time history of tsunami waves generated by impulsive disturbances, whether locally or distantly, require consideration of historical events and processes in the following regimes of the event: (a) generation; (b) propagation and dispersion; and (c) termination. Processes in each regime during the development of a tsunami are under their own unique hydrodynamic constraints but are dependent on what has preceded. In predicting tsunami wave characteristics at some distance from the generating source, the error structure may be pyramidal. Thus, essential to any method of tsunami prediction at a distant or a nearby coast where such a critical structure is located, required full consideration and study of tsunami generative mechanisms. If the tsunami generation mechanics cannot be deduced with a reasonable degree of accuracy, it is not likely that the tsunami terminal aspects at the nuclear power plant will be reliably predicted. Prediction of tsunami height at a distant or at a nearby coast requires knowledge of the magnitude and type of ground displacements in the tsunami generating area and of the characteristics of the surface waves resulting from such action. Although all mechanisms involved during tsunami generation are not fully understood, it is possible to obtain a suitable tsunami initiating function through the use of experimental data, historical data and established empirical relationships for each type of generating mechanism. Reliable computation of the tsunami propagation effects over and across the ocean can be obtained with proper modeling to provide an adequate description of the tsunami energy flow through the use of physical and numerical studies. Similarly, the terminal aspects and near shore modification of the tsunami wave system can be approximated to provide the engineering criteria necessary for the assessment of the potential tsunami hazard at a coastal site where a nuclear power plant is located. The assessment must take into consideration not only the flooding by tsunami waves but also the withdrawal during the recession which could change the pressure characteristics of the plant's cooling pumps.

As previously reported, the U.S. Atomic Energy Commission (AEC), was very interested in the assessment of the relative susceptibility of the Hawaiian Islands and of other areas in the Pacific to waves generated by storms and nuclear explosions (Pararas-Carayannis & Adams, 1966). The subsequently renamed Nuclear Regulatory Commission (NRC) became also very interested on the impact tsunamis could have on proposed or existing nuclear facilities and on coastal and offshore nuclear power plants - thus contacted and consulted with the U.S. tsunami research community and scientists of the American Nuclear Society. In the early 1970's George Pararas-Carayannis – then with the U.S. Army Corps of Engineers' Coastal Engineering Research Center (CERC) in Washington D.C., and a member of the American Nuclear Society, was asked to review environmental impact statements regarding the safety of nuclear plant sitting (San Onofre, California; Crystal River Florida, etc), of hurricane and hurricane surge effects, of earthquakes and of the impacts tsunamis could have. He was also asked to and participate in hearings of the President's Council on Environmental Quality (CEQ) (1973), regarding such issues and in the drafting of the American Nuclear Society's National and International Environmental Standards for nuclear power plants' safety (Pararas-Carayannis, 1979d). In later years NRC's Division of Site Safety and Environmental Analysis funded the preparation by ITIC of an annotated tsunami bibliography for the period 1862-1976. Pararas-Carayannis, Bonnie Dong and Richard Farmer, authored such a bibliography (Pararas-Carayannis et.al, 1982; U.S. Nuclear Regulatory Commission, 1982).

9.2 Critical Assessment of Global and Regional Vulnerabilities and Strategies for Mitigating Tsunami Impacts on Nuclear Power Plants.

From the beginning of planning tsunami mitigation programs, it was realized that global population expansion and socioeconomic improvements of human living standards required further developments of advanced industries for energy production, particularly in coastal areas - which were vulnerable to the impact of tsunamis. Also, it was realized that the combination of social and economic factors in the development of coastal regions – without proper planning - made a number of developed and developing countries around the world particularly vulnerable. In the USA before licencing the sitting and construction of nuclear power plants, the U.S. Nuclear Regulatory Agency (NRC) had the responsibility for selecting safe coastal sites for locating such nuclear plants and for thorough evaluation of potential collateral damage that could be caused by a tsunami or another natural or man-made disaster.

As previously stated, NRC became very interested on the impact tsunamis could have on proposed or existing nuclear facilities and on coastal and offshore nuclear power plants and therefore contacted and consulted with the U.S. tsunami research community and scientists of the American Nuclear Society. As stated, and as early as in the 1970's, George Pararas-Caryannis was one of the people contacted asked to review environmental impact statements regarding the safety of nuclear plant sitting (San Onofre, California; Crystal River Florida, etc), of hurricane and hurricane surge effects, of earthquakes and of the impacts tsunamis could have particularly on the cooling systems from inundation and withdrawal of water during a tsunami. For the San Onofre nuclear plant there was particular concern on whether historical earthquakes and tsunamis had been adequately evaluated in licensing Unit 1 of the plant. NRC contracted the California –based engineering firm "Marine Advisors" to do the evaluation - which in turn subcontracted George Pararas-Carayannis to do historical studies of tsunamis in the Santa Barbara Channel and what a possible repeat of the two December 1812 earthquakes could have on the San Onofre plant. His study of Franciscan mission records of other historical accounts revealed lack of proper evaluation of the 1812 events in licensing the San Onofre nuclear plant. The 1981 San Bernardino earthquake added to these concerns. The review of the historical Franciscan Mission records and of newspaper articles for this event, provided given estimates of a 15 ft. tsunami at Gaviota, of 30-35 feet at Santa Barbara and determined that a tsunami of 15 feet or more had occurred in Ventura http://www.drgeorgepc.com/Tsunami1812SantaBarbara.html

Also, in 1974, the American Nuclear Society's Nuclear Power Engineering Committee, Working Group 2 asked him to participate with the drafting of the National Standard on Tsunami Guidelines at Power Reactor Sites (Pararas-Carayannis, 1974). As consultant to NRC, Pararas-Carayannis was also asked to review the tsunami site safety of the proposed Units 2 and 3 of the San Onofre nuclear plant, near San Clemente in California. Additionally he was asked to review such issues by the American Nuclear Society's National and International Environmental Standards for nuclear power plants' safety and for the proposed American National Standard (Pararas-Carayannis, 1979d).

9.3 Critical Assessment of Global and Regional Vulnerabilities and Strategies for Mitigating the Potential Impacts of Other Disasters on Nuclear Power Plants.

The critical assessment of the Mechanical and Civil Engineering Branch (EME) of NRC in selecting a safe site for the construction of a nuclear plant and in granting a permit required a detailed (often lasting as much as seven years) hydro meteorological design analysis which was developed to determine the extent of flood protection required for safety-related systems for a nuclear power plant or plants of specified type that might be constructed on the proposed site. The areas of review included the characteristics of an assumed probable maximum hurricane or other probable maximum windstorms and the techniques, methodologies, and parameters used in the determination of the design surge and/or seiche. Antecedent water levels, storm tracks, methods of analysis, coincident wind-generated wave action and wave run-up on safety-related structures, potential for wave oscillation at the natural periodicity, and the resultant design bases for surge and seiche flooding required also review.

Based on these requirements - and while George Pararas-Carayannis was with the U.S. Army Corps of Engineers' Coastal Engineering Research Center (CERC), in Washington D.C. - the NRC subcontracted with the CERC a study related to the licensing of the Crystal River nuclear plant in Florida. Pararas-Carayannis was charged this time with the responsibility of improving and calibrating a mathematical model of a mega-hurricane (a hypothetical design hurricane striking the plant at right angle) and to verify the model with actual historical hurricanes (Camille, Carol, Audrey etc.). As a result of this study completed in May of 1975 entitled "Verification Study of a Bathystrophic Storm Surge Model", the U.S. Army, Corps of Engineers Coastal Engineering Research Center, issued Technical Memorandum No. 50 (Pararas-Carayannis, George. 1975c). Subsequently the NRC required the Utilities Company to redesign the cooling system of the Crystal River plant and to build the cooling pumps at a higher elevation than Dames and Moore (Engineering Consultants to the Utility) had recommended.

9.4 Subsequent Concerns and Research on the Safety of Nuclear Power Plants

In subsequent years – particularly after the 2004 tsunamigenic earthquake in the Indian Ocean of that of 2011 in Japan, numerous other scientists in the USA and internationally got involved with safety and reliability issues of nuclear power plants. Robert T. Sewell for example, a member of Tsunami Society specialized in the development of a probabilistic tsunami hazard assessment (PTHA) methodology and hazard analysis with special emphasis on the safety and evaluations of nuclear power plants and published some of his work in the Society's journal SCIENCE OF TSUNAMI HAZARDS. Also Sewell served as external hazards specialist for the Swiss Nuclear Safety Inspectorate, participated in several missions for the International Atomic Energy Agency (IAEA) and UNESCO, and also served as a member of the ASME Joint Committee on Nuclear Risk Management (JCNRM).

Following the 2004 Indian Ocean tsunami, Robert Sewell performed a tsunami hazard study of a nuclear plant site in California, and worked with the Southwest Research Institute on the methodology development for tsunami risk assessment, including further advances in both PTHA and tsunami fragility assessment, in consideration of formal methods of uncertainty analysis. During the 2014 Tsunami Symposium in Costa Rica, he moderated with George Pararas-Carayannis a special long session on the tsunami safety of nuclear power plants - particularly in view of the 2011 destruction by tsunami of the Fukushima-Daichi plant in Japan. The TSI Symposium participants were particularly concerned about this great Japan Tsunami and Earthquake of 2011 and the collateral global damage that it caused. This collateral disaster could have been avoided if the designers of the plant had taken into consideration the impact of the 1896 and 1933 tsunamis along the same coastlines in Japan. The collateral damage should not have been a surprise. The TSI Symposium focused on this event and also on the tsunami safety of other nuclear power plants, as there are dozens of similar nuclear power plants in vulnerable coastal areas around the world – a number of them in the USA, UK, France, Germany, China, India and elsewhere – and drafted several recommendations for increased safety.

10. DEVELOPMENT OF OPERATIONAL AND EMERGENCY PREPAREDNESS

From the early days, the key element for tsunami hazard mitigation was judged to be an effective tsunami warning system. But regardless of how sophisticated a warning system may have been, it was recognized that all it could do was to issue a prompt warning to a central contact in each threatened region. The effectiveness of the system was judged by what Civil Defense Agencies needed to do when a warning was issued by PTWC or other regional system. Furthermore, it was recognized that these agencies needed to have an effective Operational and Emergency Preparedness Plan to act on the warning and disseminate it rapidly and effectively to the public. It was also recognized that this could only be achieved if there was an established operating plan designating infrastructural communications and responsibilities. Furthermore, it was understood that Civil Defense Agencies in each country participating in the Tsunami Warning System in the Pacific - and not the Tsunami Warning Centers - were ultimately responsible for establishing regional plans for evacuation or other preventative measures to be taken before a tsunami strike. Also understood was the need for local Civil Defense Agencies to establish training programs of their own people by holding frequent exercises and by educating the public on a continuous basis (Pararas Carayannis, 1988 a).

From the earliest dates, most of the countries that became members of the TWS begun developing such Operational and Emergency Preparedness Plans with help from ITIC and support from IOC via the ICG/Tsunami Program. However, there were many other member states of ICG/ITSU that had not developed or coordinated adequately their organizational infrastructure so they could deal effectively with an emergency situation. Obviously, international cooperation and assistance were required in assisting such countries with the formulation of a standard emergency operational plan, with the conduct of tsunami exercises, and with training of government officials. Thus, ITIC was called again to hold a workshop as an example of such international cooperation but, obviously, this was not sufficient. ITIC was directed to help member states of ICG/ITSU establish more frequent training programs of their own and of longer duration, particularly for developing countries or for countries that had not decided of what to do about planning for their tsunami hazard. ITIC was called again to assist with the preparation of manuals and exercise scenarios and to assist with training for operational and emergency preparedness. In later years, Laura Kong of ITIC and Atu Kaloumaira did a remarkable job on the development of regional strategies to mitigate tsunami risks for South Pacific islands (Kong & and Kaloumaira, 2004).

10.1 Visiting Scientists Training Programs and Applied Tsunami Research Coordination by ITIC and PTWC

In order to help member states with an effective Operational and Emergency Preparedness Plan to act on a warning and disseminate it rapidly and effectively to the public, 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, specific tsunami workshops were conducted by ITIC in South America with support of UN Organizations such as UNESCO, IOC, UNDP and UNDRO. Seminars and workshops were held in South America, Malta, Italy, Greece, Austria and elsewhere with financial support of UNDRO, UNESCO, and national agencies.

11. PREPARATION OF EDUCATIONAL MATERIALS IN SUPPORT OF PUBLIC EDUCATION AND AWARENESS OF TSUNAMI HAZARDS

From the early days, even before the establishment of the Tsunami Warning System and of Regional and National systems, it became clear that the best way of mitigating the impact of the tsunami hazard was the development of programs of public education and awareness. Because of the infrequency of tsunamis, it was recognized that the public needed to be constantly reminded of the potential hazard. It was also recognized that public informational activities needed be sponsored by governmental authorities on a regular and continuous basis to assure awareness and public response when a tsunami warning was issued and even when no warning had been given. Thus, the development of appropriate educational materials, such as brochures, pamphlets and audiovisual materials were necessary to implement a program of tsunami disaster mitigation. Such educational materials could be best developed with both national and international support. The preparation of educational materials for in several languages and for different age groups was identified as a needed primary goal for the success of tsunami warning services. Thus, the preparation of educational materials was repeatedly emphasized at the biannual meetings of the ICG/ITSU Group. ITIC and national agencies in IOC member countries began developing such educational programs.

Specifically, the ICG/ITSU Group 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.

11.1 Preparation of Educational Materials

ITIC was initially tasked with the responsibility of preparing educational materials and was the main contributor to the 1975 first edition of the brochure known as the "The Great Waves". The work begun in 1974. George Pararas-Carayannis, 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 added graphics and updated illustrations. Miscellaneous other educational materials were also published on the Internet and on different journals. For example, Patricia Lockrigde of NGDC in Boulder, Colorado published an educational article on tsunamis for mariners (Lockridge, 1989). George Pararas-Carayannis published numerous educational articles of the effects of tsunami on society (Pararas-Carayannis, 1983; 1986a) and accounts of historical tsunamis in his Internet website (Disaster Pages of Dr. George PC – http://www.drgeorgepc.com) - a site with many links for specific disasters which has many visitors every day.

11.1a Children's Book About Tsunamis

In later years, there were additional educational materials prepared by ITIC and subsequently translated by IOC in different languages and distributed to member states. One of these was a children's book entitled Tsunami Warning, authored by George Pararas-Carayannis, Patricia Wilson and Richard Sillcox and illustrated by Joe Hunt (Pararas-Carayannis et al., 1992). The booklet was the result of encouragement by the ICG/ITSU Group at its Thirteenth Session in Ensenada, Mexico (September, 1991). The illustrated book was designed to inform young persons about tsunamis and the dangers, which they present, and what should be done to save lives and property. Its preparation and hard copy printing were supported by the Intergovernmental Oceanographic Commission of UNESCO. A version of a similar Children's booklet in French was prepared by George Pararas-Carayannis with the assistance of Maurice Fournet in France, but also published in different languages. Additional efforts for the preparation of educational materials included the preparation of an article and a press kit describing UNESCO activities at the World Conference on Natural Disaster Reduction, in Yokohama, Japan held 23-27 May 1994 (Pararas-Carayannis, 1994).

11.2 Compilations of Tsunami Glossaries

At the 10th session of the ICG/ITSU group in Sidney, Canada in 1985 a recommendation was made by the Group 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. In response to this directive, the Director at the time of ITIC George Pararas-Carayannis, begun work and three years later had completed a draft of such a Glossary - which included definitions of primary and secondary terms that could be of importance for interdisciplinary studies of tsunami researchers, as well as for use by the scientific community, Civil Defense officials and the general public. The draft Glossary received a thorough review by a designated ICG/ITSU committee, which also suggested what terms were for use as primary or 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, 1989c), at the 1991 IUGG Tsunami Symposium at the University of Vienna, in Austria (Pararas-Carayannis, 1991a) and at the meeting of the International Coordination Group for the Tsunami Warning System in the Pacific held in 1991 in Ensenada, Mexico. 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, 1991 b & c; IOC, 1991a, b, c). Ten years later in 2001, a second, much shorter version of only the primary terms was published by IOC as a separate report with fine illustrations. Finally, in 2013, IOC published a final illustrated shorter version of a Tsunami Glossary, as UNESCO Technical Series Report #85.

11.3 Compilation of Sea Level Data

Systematic collection of sea level data was essential in evaluating tsunamis generated from earthquake along the Pacific Rim. Charles McCreery compiled such a listing (McCreery, 2004). Prior to that George Pararas-Carayannis and Eddie Bernard had completed a through review of the response of tide station in the Tsunami Warning System (Pararas-Carayannis G. and E. Bernard, 1979c).

12. PREPARATION OF WAVE REPORTING PROCEDURES FOR TIDE OBSERVERS IN THE TSUNAMI WANRING SYSTEM, MANUALS AND GUIDES

Based on recommendations of the IOC/ITSU Group, the Director at the time of ITIC George Pararas-Carayannis 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. ITIC and people at JIMAR, Harold Loomis and George Curtis prepared guidelines for the conduct of tsunami surveys (Loomis, 1981; Curtis, 1982) which were subsequently expanded and incorporated in 1998 by ITIC's Director George Pararas-Carayannis into the IOC manuals and guides #37 (Intergovernmental Oceanographic Commission (of UNESCO, 1998).

13. TSUNAMI SOCIETY'S SUPPORT OF THE TSUNAMI WARNING SYSTEMS THROUGH DISSEMINATION OF KNOWLEDGE, PROMOTION OF AWARENESS AND MITIGATION OF TSUNAMI HAZARDS

As described briefly in this report, pioneering tsunami research in the U.S. begun at the University of Hawaii following the devastating 1946 tsunami in the Aleutian Islands. Scientists at the Hawaii Institute of Geophysics, at the Pacific Tsunami Warning Center (PTWC), at the International Tsunami Information Center (ITIC), at the Hilo Tsunami Museum, at the USGS Volcano Observatory and at other universities in Hawaii, contributed significantly over the years towards the development of tsunami research, to improvements of the Tsunami Warning System in the Pacific and to tsunami preparedness around the world. Also, the Hawaii State Civil Defense always had a very effective program on tsunami preparedness and was designated as the best organized in the US. Other 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 these efforts and cooperated with scientists in Hawaii in many joint projects.

13. 1 Formation of the Tsunami Society

In 1981, William (Bill) Adams, Augustine (Gus) Furumoto and George Pararas-Carayannis founded the "Tsunami Society" which was incorporated and registered in the State of Hawaii as a professional scientific organization focusing on promoting awareness and mitigation of tsunami hazards globally by sponsorship of workshops, meetings and symposia, and by disseminating knowledge about tsunamis to scientists, officials, the media and the public through the publication of a journal named "Science of Tsunami Hazards", a home page, and other venues. Thus, the Tsunami Society primary objectives were to provide a focus for discussion and interactions among its members, government agencies and the public for the purpose of mitigating the adverse impact of tsunamis on humanity.

13.2 Mandate and Functions of Tsunami Society

To accomplish these objectives the Tsunami Society encouraged collaborative and multidisciplinary research related to the tsunami hazards for the purpose of promoting education, training, public awareness and implementation of early warning systems that could save lives around the world and safeguard property. The intent of the Society's officers and members was to promote the concept that tsunamis have a common adverse impact on mankind that transcends national boundaries and interests and, therefore, encouraged regional and international cooperation for research, education and preparedness. More specifically this became even more important after the tragic 2004 mega-tsunami disaster in the Indian Ocean and the subsequent 2010 Chilean, the 2011 Japan, the 2012 Canada and the 2013 Solomon Island tsunamis. – thus the Society greatly expanded its role by holding or co-sponsoring as in the past, several international symposia and training programs around the world (Canada, Austria, Australia, Scotland, New Zealand, Chile, Mexico, Panama, Colombia, Ecuador, Peru, Chile, Italy, Portugal, Puerto Rico, Russia, France, Algeria, Philippines, China, Thailand, India, Indonesia, Papua-New Guinea, French Polynesia, Saudi Arabia, Malta, Ukraine, Greece, Costa Rica, etc – some even before 2004).

Additionally, Tsunami Society promoted the setting up of facilities required for the undertaking of research on tsunamis, based on a holistic multidisciplinary approach that combines theoretical and applied sciences and mathematics, engineering, remote sensing methods, as well as social sciences, to the understanding of the tsunami phenomenon. Additionally, the Society coordinated and promoted 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. Also, the Society co-operated on an advisory capacity with other international scientific organizations, governments, foundations, industries, academic institutions and other professional groups concerned with the hazards of tsunamis, and acted as a focal point in assisting coordination between research institutions and universities around the world - which promote programs of theoretical and applied tsunami research. Furthermore, the Tsunami Society supported the organization of training programs;

symposiums, workshops, seminars and other meetings to study topics of interest related to tsunami studies and preparedness and conducted or actively participated in several international Tsunami Symposiums.

13.3 Publication of the international Journal "Science of Tsunami Hazards"

Immediately after its establishment in 1981, the Tsunami Society begun publishing a journal subsequently renamed Journal "SCIENCE OF TSUNAMI HAZARDS" (STH) – with papers of the ongoing tsunami research of the 1980's and 1990's. Thus the Tsunami Society played a key role in documenting the earlier tsunami research projects in the U.S. and internationally. Bill Adams served as the first president and other scientists at the University of Hawaii, PTWC and ITIC served as officers. Michael Blackford served as the Journal Publisher.

The editorial board initially included Dr. Antonio Baptista (Oregon Graduate Institute of Science and Technology), Professor George Carrier (Harvard University), Prof. George Curtis (University of Hawaii – Hilo), Dr. Zygmunt Kowalik (University of Alaska), Dr. Tad Murty (Baird and Associates Otttawa), Dr. Shighisa Nakamura (Kyoto University), Mr. Thomas Sokolowski (Alaska Tsunami Warning System), Dr. Costas Synolakis (University of California) and Prof. Stefano Tinti (University of Bologna, Italy).

James Lander, George Curtis and Barbara Keating of the University of Hawaii, served as Presidents of Tsunami Society and George Pararas-Carayannis as Vice-President, Gerard Fryer as Secretary, Vindell Hsu as Treasurer and Hernann Fritz as co-editor of the journal. Dan Walker served also as one of the officers. As editor of the journal for several years, Charles Mader did a remarkable job of organizing and archiving 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 in the 1990's 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. The name of the Society was changed in 2004 to Tsunami Society International, in view of the increased membership and contributions of scientists from around the world and the increased global distribution of its international, award-winning journal.

13.4 Change of Name to Tsunami Society International.

In 2008, when Barbara Keating retired from the University of Hawaii, George Pararas-Carayannis became President of the Tsunami Society, succeeding also Charles Mader as Editor of the STH journal with several other prominent scientists from around the world, agreeing to serve as officers and as members of journal's editorial board. Prof. Tad Murty continued as Vice-President.

The journal's editorial reviewing board included Dr. Charles MADER, Mader Consulting Co., Colorado, New Mexico, Hawaii, USA; Dr. Hermann FRITZ, Georgia Institute of Technology, USA; Prof. George CURTIS, University of Hawaii-Hilo, USA; Dr. Tad S. MURTY, University of Ottawa, CANADA; Dr. Zygmunt KOWALIK, University of Alaska, USA; Dr. Galen GISLER, NORWAY; Prof. Kam Tim CHAU, Hong Kong Polytechnic University, HONG KONG; Dr. Jochen BUNDSCHUH, (ICE) COSTA RICA, Royal Institute of Technology, SWEDEN; Dr. Yurii SHOKIN, Novosibirsk, RUSSIAN FEDERATION and of Dr. Radianta Triatmadja - Tsunami Research Group, Universitas Gadjah Mada, Yogyakarta, INDONESIA.

In subsequent years, as global membership increased, the Society now renamed "Tsunami Society International" (TSI), organized four more successful symposiums in 2010 in Toronto, Canada, in 2012 in Ispra, Italy, in 2014 in Costa Rica and in September 2016 the 7th International Tsunami Symposium at the European Commission's Joint Research Centre again at the European Commission's Research Centre in Ispra, Italy near Milano,

As of the publication of this summary (2018), the journal has completed thirty-seven year of continuous and uninterrupted publication and remains the only journal devoted exclusively to multidisciplinary papers on tsunami hazards. Numerous reports of research projects described in the present paper were published in the Journal and have been also archived at its website. 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, the older issues of STH have been archived at the U.S. Los Alamos Laboratory Library but can also be downloaded from the Society's website tsunamisociety.org .

In addition to the DOAJ database, STH is also included now in the EBSCO, ELSEVIER and SPRINGER publishing databases, which have given 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, Tsunami Society International participates presently 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 continues to provide a focus of continuous discussion and interaction 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, particularly because it is also an OPEN Access journal. 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 a medium (0.29), which is higher than some other reputable journals in the similar field of disasters in the world.

13.5 Awards of Tsunami Society International

Recognizing the original and outstanding contributions of tsunami scientists around the world, Tsunami Society International presents awards based on nominations with proper documentation. Although there is a plethora of international tsunami scientists who are doing outstanding work and truly deserve recognition, due to the lack of institutional financial support and because of limited resources, the Society cannot give such awards to scientists who cannot attend one of its symposia. However, since its establishment in 1981, TSI has given awards to many U.S. and international scientists and their significant contributions will be summarized in Part B of the forthcoming report. In summary, awards have been presented to scientists from Canada (Professor Tad S. Murty; Professor Ioan Nistor; Prof. Dan Palermo); USA (Dr. Charles Mader, Dr. Zygmunt Kowalik; Dr. Eddie Bernard; Mrs. Karen O'Loughlin; Dr. Barbara Keating; Mr. Thomas J. Sokolowski, Dr. George Pararas-Carayannis; Dr. Doak C. Cox; Mr. George D. Curtis; Prof. Augustine Furumoto, Dr. Daniel A. Walker, Mr. James F. Lander, Prof. Frank C. Lin, Dr. Robert Sewell); Ecuador (Prof. Theofilos Toulkeridis); Italy (Dr. Alessandro Annunziato of EC-JRC); Germany (Prof. Barbara Thielen-Willige), Japan (Prof. Tomoya Shibayama), Puerto Rico (Prof. Aurelio Mercado-Irizarry); Portugal (Prof. Maria Ana Baptista); Russia (Prof. Efim Pelinovsky; Dr. Andrey Marchuk, Prof. Boris Levin Wulfovich).

13.6 Recent Publications of International Scientists in the Society's Journal and other Academic Publications

After the 2004 mega-tsunami disaster in the Indian Ocean and the subsequent 2010 Chilean, the 2011 Japan, the 2012 Canada and the 2013 Solomon Island tsunamis, many scientists in countries impacted by these disasters, developed expertise and devoted their research efforts to these and other events, publishing numerous papers in many journals and in TSI's journal "Science of Tsunami Hazards". Their contributions were outstanding, significant and widely recognized. The following is a partial listing of countries whose scientists have published in the Society's Journal: Australia, Brunei, Canada, China, Ecuador; Fiji, France, Germany, Guam, Greece, Indonesia, Italy, India, Japan, Korea, Malaysia, Morocco, New Caledonia, New Zealand, Russia, Portugal, Scotland, Spain, Switzerland, Sri Lanka, Thailand, Turkey, UK, USA, Mexico, Norway. It is very difficult to mention all of the scientists that researched specific historical tsunami events but it important to mention some of their work. For example, the 1946 Aleutian tsunami was examined and subsequently re-examined by many researchers. The November 12, 1994 Mindoro Tsunami was examined by Synolakis and Inamura (Synolakis & Imamura, 1995). The extreme inundation flows generated by the July 12, 1993 Hokkaido-Nansei-Oki Mw = 7.8 tsunamigenic earthquake in Japan – which at that time resulted in the worst local tsunami-related death toll in fifty years, was studied by Vasily Titov and Costas Synolakis (Titov & Synolakis (1997).

A near field survey was conducted by Okal, Plafker, Synolakis and Borrero on Unimak and Sanak islands (Okal et al. 2003). Emil Okal, J. Borrero and Costas Synolakis also re-examined the 17 November 1865 earthquake in the Tonga-Kemadec region and the tsunami that - because of its directivity- greatly impacted Tonga (Okal, Borrero, & Synolakis, 2004). George Pararas-Carayannis, also evaluated the source mechanism of the tsunami generated by the September 29, 2009 earthquake and the impact it had in Samoa, in American Samoa, in Niuatoputapu and in Tonga – noting specifically that at the seismically active northern end of the Tonga Trench and Arc, there is greater obliquity of collision and a sharp change in direction towards the west. As shown in Figure 16 below the Kermadec-Tonga Arc is an intraoceanic arc, one of the longest on earth, extending for almost 2500 km from New Zealand to Samoa.

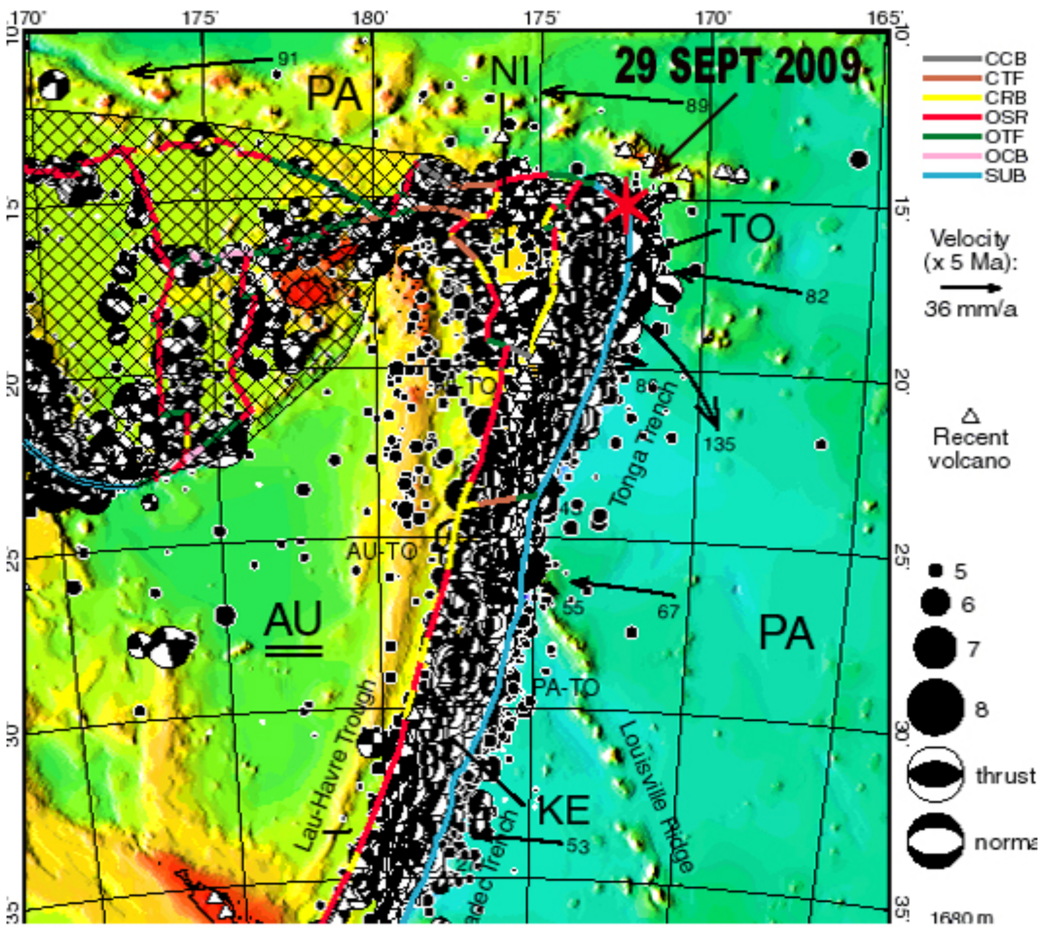

Figure 16.. The Tonga-Kermadec Trench and Arc. Seismotectonics, Kinematics and Plate Boundaries of the Tonga subplate seismic activity along the Tonga Trench and its northern boundary near the region where the 29 September Earthquake occurred. TO-Tonga plate, PA-Pacific plate. KE-Kermadec plate, AU-Australian plate (from: http://www.drgeorgepc.com/Tsunami2009Samoa.html - modified graphic after Bird, P. (2003) Figure 11).

He also noted that this earthquake was particularly unusual in the sense that it did not occur on the inter-plate thrust fault within the subducting Pacific plate but further out on the outer-rise region – thus concluding that outer-rise earthquakes are caused by extreme stresses that result in bending within the subducting oceanic plate itself before it enters the subduction zone and thus can generate significant tsunamis (Fig. 17) (Pararas-Carayannis, 2009; http://www.drgeorgepc.com/Tsunami2009Samoa.html)

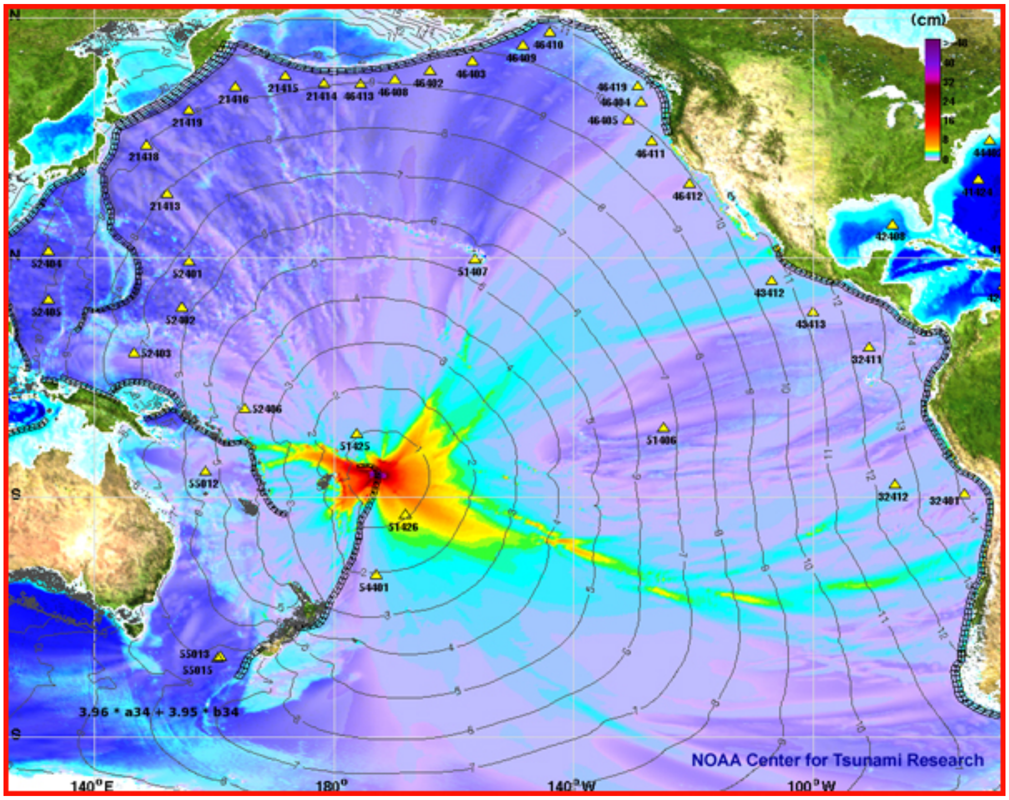

Figure 17. The 29 September 2009 tsunami travel time chart. Location of DART buoys ((from: http://www.drgeorgepc.com/Tsunami2009Samoa.html Source: NOAA Center for Tsunami Research).

Costas Synolakis, C.E, Bardet, J.P, Borrero, J., Davies, H., Okal, E., Silver, E., Sweet, J., & Tappin, D., 2002, examined the1998 tsunami in Papua New-Guinea and concluded that it was caused by an earthquake which generated a slump (Synolakis et. al, 2002; Okal & Synolakis 2002). An extention of the study of this 1998 earthquake and tsunami by P.J. Lynett, J.C. Borrero, P.L. Liu and C. Synolakis, also reviewed field evidence and made numerical simulations in order to confirm the mechanism of generation (Lynett et.al., 2003).

CONCLUSIONS

The study of Tsunami Hazards is a relatively new interdisciplinary field of science. As mentioned, early tsunami research on tsunamis was primarily conducted in Hawaii, in Japan and in Russia after World War II, but intensified after the destructive 1946 tsunami from the Aleutian Islands, which hit without warning Hawaii and coastal areas in the Pacific. The preparation of this brief historical review (Part A) was extremely difficult and not necessarily presented in the right chronological order. The author recognizes that there have been many omissions in describing other earlier pioneering inter-disciplinary research in all aspects of mathematical, geophysical and marine sciences, which preceded the development of "Tsunami Science". A second paper under preparation (Part B), will expand on summarizing the numerous and significant contributions in applied and theoretical research by international scientists around the world, which also helped in the understanding of the tsunami phenomenon and the development of the Science of Tsunami Hazards.

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