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COMET AND ASTEROID HAZARDS: THREAT AND MITIGATION

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ABSTRACT

I discuss the magnitude of threat posed by comets or asteroids that might collide with the Earth. While the probability of collision is small, the effects could be devastating, suggesting that it should be carefully considered in relation to natural disasters. It is one of the few natural disasters that could be averted by technical means. Although many more complex schemes are possible, the most cost-effective and the only currently-available means of disruption (deflection or pulverization) is a nuclear explosive.

I discuss optimal tactics for terminal intercept, which can be extended to remote-interdiction scenarios as well. The optimal mass ratio of an interceptor rocket carrying a nuclear explosive depends mainly on the ratio of the exhaust velocity to the object closing velocity. Nuclear explosives can be employed in three different modes depending on their location at detonation: (1) buried below the object's surface by penetrating vehicle; (2) detonated at the object's surface; or (3) detonated some distance above the surface.

I show results of a model for gravitationally bound objects and obtain the maximum non-fracturing deflection speed for a variety of object sizes and structures. For a single engagement, I conclude that the non-fracturing deflection speed obtainable with a stand-off device is about four times the speed obtainable with a surface-burst device. Furthermore, the non-fracturing deflection speed is somewhat dependent on the number of competent components of the object.

Generalizations indicate: (1) asteroids more than 3 km in diameter can be most efficiently deflected with a surface burst; (2) asteroids as small as $\frac{1}{2}$ km can be effectively deflected with a stand-off device; (3) smaller asteroids are best pulverized.

INTRODUCTION

The current understanding of the potential hazards owing to a collision of the Earth with a comet or asteroid is substantial but clearly incomplete. The estimate of the threat is constantly changing as the scientific community learns more about these objects. From the stand point of defense against collision, it is as important to understand the composition and structure of these objects as it is to measure their orbital parameters. Several spacecraft are now launched or under construction to acquire physical information on the makeup of comets and asteroids.

Similarly the dynamics of the terminal intercept problem need to be explored in greater depth by numerical simulation. This paper expounds on several possibilities for deflection mechanisms, but shows the only realistic methods, within the scope of current or near future technology, involve the use of nuclear explosives.

HAZARDS

Since Alvarez[1] announced evidence for a collision with an asteroid as the cause of the cretaceous-tertiary extinction, there has been a heightened awareness that our planet is and always has been in a state of merciless cosmic bombardment. More realistic, and on human time scales, is the possibility of a strike from an interplanetary body with radius on the order of 100 m. If an asteroid, such an object would likely have a relative velocity of about 25 $\text{km} \cdot \text{sec}^{-1}$, which would give it a kinetic energy of about 1,000 megatons. In a populated area, the damage would be catastrophic. If it were a comet, the relative velocity would be more like 50 $\text{km} \cdot \text{sec}^{-1}$ and the energy would quadruple. The Tunguska Event[2] (1908) offers sobering evidence that such potentially catastrophic collisions are not so infrequent that they can be ignored. The Tunguska event (a meteoric areal explosion) was about 20 megatons and could be expected every few hundred years. It leveled about 2,000 km^2 of forest — about the size of Los Angeles — but resulted in only two deaths. Had nomadic Siberians been in the area at the time, the event would be more than a footnote in astronomical history. Recent estimates[3] indicate that a 20-kiloton (Hiroshima-size) event should occur every year. This ought to be conspicuous, but apparently objects of this size tend to break up while penetrating the atmosphere[4], dissipating much of their energy as smaller fragments. That larger cataclysms are not generally recorded in the archives of natural disaster seems somewhat of a mystery. Perhaps it can be attributed to the fact that until the 20th century, very little of the Earth's surface was populated.[5]

Objects known to have impacted the Earth can be classified into three main groups: (1) Earth-orbit-crossing asteroids; (2) long-period comets, and (3) periodic comets.[6] Astronomers estimate a population of about 1,500±500 Earth-orbit-crossing asteroids with diameter greater than 1 km, of which about 250 have been catalogued. Some 700 long period comets have been catalogued and most cross the Earth's orbit. Their Earth-collision rate as a function of magnitude has been worked out, but the relation between magnitude and actual size is not well known. Periodic comets are the population with period less than 200 years, 95% of which have lost their coma and are as inconspicuous as asteroids of the same size The late, great, Gene Shoemaker has dubbed these *stealth comets.* Only 25 of the larger stealth comets have been seen and 26 active Earth-orbit-crossing comets have been catalogued, but astronomers estimate there are about 1,500 with diameter greater than 1 km.

The distribution of these main groups is such that about 60% of craters larger than 10 km have resulted from Earth-orbit-crossing asteroids; about 20% have been caused by long-period comets, and about 20% have been caused by periodic comets[6].

Objects of size 1 km or larger will have a devastating effect on our planet. But, as evidenced by Tunguska, smaller object can cause severe local damage, and such objects impact more frequently. How frequently? A object with a million megatons of high-explosive equivalent yield, sufficient for global catastrophe might impact every million years. This is not to imply any regularity of such objects, one could strike the Earth tomorrow and another the next day. It is just on average that one such impact might occur ever million years. Starting from this point, the impact probability decreases inversely as the 2/3-power of the object's mass to the 1,000-yearly event, which would be 50 to 100 megatons. The impact probability then further decreases inversely as the object's mass to the year event, which as mentioned above, would have energy of about 20 kilotons. Objects smaller than 10 m generally never reach the Earth's surface, depositing all there energy in the atmosphere. The exception is nickel-iron objects, which can impact with initial sizes as small as a meter[7].

David Morrison, on several previous occasions, has asserted that the risk of being killed as a result of asteroid impact is somewhat greater than the risk of being killed in an airplane crash.[8] Since the time of those estimates, the astronomical community has found more objects posing a threat to our planet, particularly comets and the damage potential of tsunamis created by impacts has become more thoroughly understood.[9] Furthermore, air safety has improved. Now it would be reasonable to estimate that the risk of being killed as a result of Earth-orbit-crossing object impact is more than twice the risk of being killed in an airplane crash.

HAZARD MITIGATION

The first serious study of a defense against asteroid collision[10] was conducted as an interdepartmental student project in systems engineering at the Massachusetts Institute of Technology. Remarkably, the study was conducted in the spring of 1967, a dozen years before the Alvarez discovery. The hypothesis was a predicted 1968 collision with Icarus, a kilometer-scale Apollo asteroid. The solution agreed upon was to deploy six Saturn V rockets carrying 100-megaton warheads to deflect or pulverize the asteroid.

In 1981, NASA and JPL sponsored a workshop[11] to evaluate the rate and consequences of collisions with both asteroids and comets. The workshop also considered requirements for a mission capable of deflecting an asteroid from Earth collision, and concluded that it was probably within technological means. It seemed unlikely, however, that an object requiring deflection would be detected over a period of time for which the technology was relevant.

In 1984, Hyde[12] further explored using nuclear explosives to counter a threatening object. In 1990, Wood, Hyde, and Ishikawa[13] showed that defense against small objects could be accomplished with non-nuclear interceptors, largely using the kinetic energy of the relative velocities of the interceptor and the oncoming object. The subject has been more deeply examined at: (1) The Near-Earth-Object Interception Workshop, January 14-16, 1992 at Los Alamos, New Mexico[14]; (2) the Conference on Hazards Due to Comets and Asteroids at Tucson, Arizona, January 7-12, 1993[15]; (3) Erice International Seminar on Planetary Emergencies 17th Workshop: The Collision of an Asteroid or Comet with the Earth at Ettore Majorana Centro di Cultura Scientifica, Erice, Sicily, April 28 - May 4, 1993[16]; (4) International Conference on Problems of Earth Protection Against the Impact with Near Earth Objects (Space Protection of the Earth – 1994), September 26-30, 1994 at Snezhinsk, Russia; (5) The United Nations Conference on Near-Earth Objects, April 24-26, 1995[17]; (6) International Conference on Problems of Earth Protection Against the Impact with Near Earth Objects (Space Protection of the Earth – 1996), August 12-17, 1996 at Snezhinsk, Russia. (7) The Collision of an Asteroid or Comet with the Earth as part of The 23rd International Seminar on Planetary Emergencies at Ettore Majorana Centro di Cultura Scientifica, Erice, Sicily, August 19-24, 1998.

The problem of preventing a collision with a comet or asteroid can be considered two domains: (1) actions to be taken if the collision can be predicted several orbital periods in advance, and can be averted by imparting a small change in velocity (most effectively at perihelion) and (2) actions to be taken when the object is less than an astronomical unit (AU) away, collision is imminent, and deflection or disruption must be accomplished as the object closes on Earth. I call the first domain of actions, "*remote interdiction*" and the second domain of actions "*terminal interception.*"

If all of the Earth-threatening asteroids and periodic comets were known, the orbits could be calculated and the process of deflection could be carried out in a leisurely manner. Remote interdiction would be the option of choice.

Asteroids and comets in the 100-m size range are exceedingly difficult to detect unless they are very close. Active comets in this size range are more conspicuous owing to their coma, but inactive *stealth* comets are at the limits of technology to detect. Comets move a lot faster and can be in retrograde orbits or out of the plane of the ecliptic. In any case, it seems likely we will have little time to respond to a potential collision. It therefore appears that terminal interception — disruption or deflection at relatively close range —is the most important issue.

Many schemes have been devised to deflect or pulverize comets and asteroids bent on colliding with our fair planet[18,19,20,21,22]. Reaction devices have been proposed that require landing on the object quite some time before the impending collision and setting up a rather elaborate propulsion power plant. These include very-low-specific-impulse devices such as mass drivers, which are essentially electromagnetic bucket brigades that scoop up material from the object and expel it into space with physics reminiscent of a conveyor belt. They also include high-specific-impulse devices such as nuclear-reactor rocket engines that use volatiles from the object as a propellant.[23] Albeit with exceedingly low thrust, solar sails[24];[25];[26] have also been proposed to gently drag the threatening object off its course. Beamed energy has been suggested in the form of high-power laser or microwave sources to heat and blow-off material from the object's surface, thereby providing a high-specific-impulse rocket with a remote power source. Solar collectors have been designed to focus the sun's radiation onto the object and thereby produce a modest vapor blow-off during a protracted encounter[26], producing a gradual acceleration and deflection. Kinetic energy devices seem quite viable for both deflection and pulverization[27,28,29,30,31] because of the enormous energies involved in orbital collisions.

Exploration of the myriad alternatives is a wonderful stimulus to the imagination, makes an for an excellent set of exercises for undergraduates, and is fine grist for the science fiction mill. We would like to find solutions other than nuclear explosives. Clearly, the arms-control, safety, and nonproliferation implications are horrendous. But a practical technology beyond nuclear explosives has yet to emerge. The most nearly competitive technology is the kinetic energy device. The specific energy of an interceptor spacecraft at typical orbital speeds is several hundred times that of high explosive. However, the specific energy of a nuclear explosive is several million times that of high explosive. The kinetic energy device to deflect a kilometer-size object is an unimaginably large spacecraft[26,28]. At this time, and probably for decades to come, the only thing we have is a nuclear explosive.

TERMINAL INTERCEPT, TACTICS, OPTIMIZATION

The final velocity of an interceptor missile relative to the Earth, or the orbit in which it is stationed, is given by,

$$V = gI_{sp} \ln \frac{M_i}{M_f}, \tag{1}$$

where M_i and M_f are the initial and final mass of the interceptor, g is the gravitational constant, and I_{sp} is the rocket specific impulse. If the intercept gives the object a transverse velocity component $v_\perp$ then the threatening object will miss its target point by a distance

$$\varepsilon = R_l \frac{v_\perp}{v} \left(\frac{V}{v+V} \right), \tag{2}$$

where R_l is the range when the interceptor is launched and v is the speed at which the object is closing on the Earth and I have neglected the effect of the Earth's gravitational focussing and used a linear approximation to Keplerian motion. The nuclear explosive will blast a crater on the side of the object. The momentum of the ejecta would be balanced by the transverse momentum imparted to the object. From Glasstone's empirical fits[32], the mass of material in the crater produced by a large explosion is $M_e = \alpha^2 E^\beta$, where α and β depend on the location of the explosion, the object's composition, strength, and density, and a myriad of other parameters. Clearly the *crater constant* α and the *crater exponent* β will vary depending on whether we are considering an object composed of nickel-iron, stony-nickel-iron, stone, chondrite, ice, or dirty snow. For almost every situation involving a surface explosion, however, we find $\beta \simeq 0.9$. This has now been extensively verified by numerical simulations[33]

Only a fraction of the nuclear explosive's energy is converted to kinetic energy of the ejected or "blow-off" material. Let this fraction be equal to $\frac{1}{2}\delta^2$ for algebraic convenience. Most of the weight, after the rocket fuel is expended, would be the nuclear explosive, which produces a yield of $E = \varphi M_f$, where φ is the yield-to-weight ratio. Despite the many parameters that come into the problem, the optimal mass ratio depends only on the quotient of the *closing velocity* and the *exhaust velocity* (gI_{sp}). The *crater exponent* is well established at 0.9. A substantial advantage accrues to a higher-specific-impulse rocket[28,30]. The maximum displacement of the impact location on Earth is

$$\varepsilon = \frac{\alpha \delta R_l}{M_a v} \frac{v_x Q (\varphi M_i e^{-Q})^{\frac{\beta+1}{2}}}{v_x Q + v}, \tag{3}$$

where

$$Q = -\frac{v}{2gI_{sp}} + \frac{1}{2}\sqrt{\frac{8v}{(1+\beta)gI_{sp}} + \left(\frac{v}{gI_{sp}}\right)^2}. \tag{4}$$

For a surface burst, Glasstone uses $\beta = 0.9$, but takes $\alpha \simeq 1.6\times10^{-4}$ $\mathrm{gm}^{\frac{1}{2}(1-\beta)} \cdot \mathrm{cm}^{-\beta} \cdot \mathrm{sec}^{\beta}$. He describes the material as dry soil. Medium strength rock would be more consistent with $\alpha \simeq 10^{-4}$ $\mathrm{gm}^{\frac{1}{2}(1-\beta)} \cdot \mathrm{cm}^{-\beta} \cdot \mathrm{sec}^{\beta}$, and, in the 20-kt range, would roughly agree with Cooper[34]. If about 5% of the nuclear explosive energy goes into kinetic energy of the blow-off, then $\delta = 1/\sqrt{10} \simeq 0.316$. Equation (3) can be rearranged to give the required initial mass of the interceptor,

$$M_i = \frac{e^Q}{\varphi}\left[\frac{M_a v \varepsilon}{\alpha \delta R_l}\left(1 + \frac{v}{v_x Q}\right)\right]^{\frac{2}{\beta+1}}, \tag{5}$$

It is generally known that the yield of nuclear warheads can be a few kilotons per kilogram if they weigh more than about a hundred kilograms. For the purpose of these estimates, we will take a conservative value of $\varphi = 1$ kiloton $\cdot$ kilogram^{-1}. Figure 1 shows the initial mass of the interceptor required to deflect an object by 10 megameters (Mm), as a function of the object's diameter d and its range R_l when the interceptor is launched. Figure 1 assumes an object density of $\rho = 3.4$ gm $\cdot$ cm^{-3}, an object velocity of $v = 25$ km $\cdot$ sec^{-1}. The deflection is conservative for missing the planet entirely ($R_\odot = 6.378$ Mm), partially compensating for the neglect of gravitational focusing. From the graph, it is clear that threatening objects as large as a kilometer can be deflected, even if the are only one astronomical unit away when the interceptor is launched. A Russian *Energia* rocket could easily boost the 100-ton interceptor into Earth orbit.

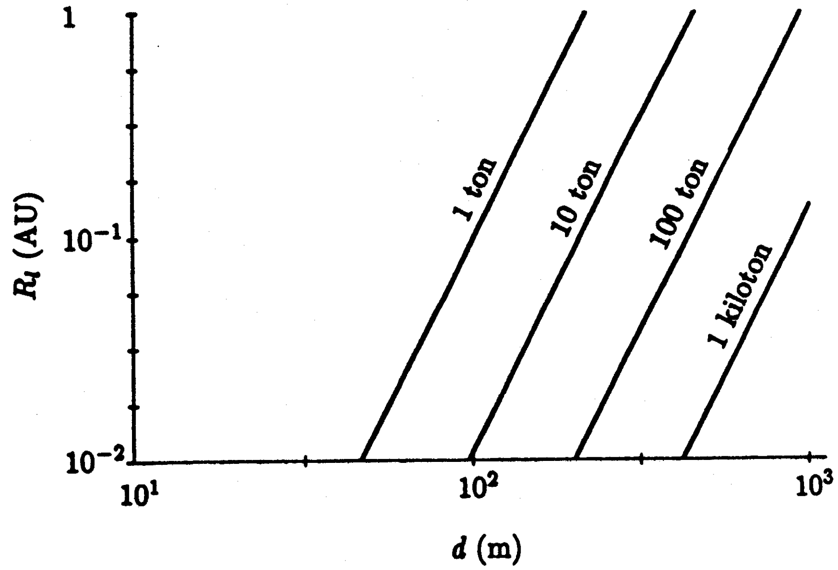

Figure 1. Initial masses of optimally designed interceptor rockets to obtain 10-Mm deflection.

MODES OF ENGAGEMENT

There are three qualitatively different ways in which a nuclear-explosive-carrying interceptor can engage a comet or asteroid, either for the purpose of deflection or pulverization. The engagement can deploy (1) a surface-burst, which is detonated at or very near the surface of the object; (2) a stand-off device, which is detonated at considerable distance from the surface; or (3) a penetrator device, which buries the nuclear explosive at an optimum depth. These modes have been discussed extensively in prior publications, I will present here a brief description of what I believe we have learned.

Surface-Burst Device

The optimization calculations of the previous section, which led to Fig. 1, were based on a surface-burst engagement. The surface burst is highly efficient for transferring momentum to the target object. If the same optimization procedure is applied to the kinetic energy device, the nuclear-explosive and interceptor system can be shown to be three orders of magnitude lighter. A problem with the surface burst is that it creates a crater to provide blow-off material. This introduces a great deal of stress and a fairly high probability of fracture. It is also somewhat difficult to time the surface-burst detonation at high rates of closure. If the relative velocity of the interceptor is 50 $\text{km} \cdot \text{s}^{-1}$ and the acceptable error in altitude of the detonation is 10 cm, as it might be for a typical surface explosion, then the timing jitter must be less than 2 μs.

Stand-Off Device

The fracture problem can be much mitigated by detonating the nuclear explosive some distance from the approaching object. Rather than forming a crater, the neutrons, x-rays, γ-rays, and some highly ionized debris from the nuclear explosion will blow-off a thin layer of the object's surface. This will spread the impulse over a larger area and lessen the shear stress to which the object is subjected. Of these four energy transfer mechanisms, by far the most effective (at reasonable heights of burst) is neutron energy deposition, suggesting that primarily-fusion explosives would be most effective[35].

Complete description requires computer simulations. However some general statements can be made. At an optimal height of burst, I find about 2 to 8% of the explosive's energy is coupled to the object's surface, again depending on the object's actual composition and the neutron spectrum and total neutron energy output of the explosive. Most of the energy is deposited within 10 cm of the surface. The blow-off fraction will be about a factor of 35 times smaller than the surface burst and the initial mass of the interceptor would have to be about 40 times as large.

Penetrator Device

A greater momentum can be imparted for the same yield if the detonation is below the surface. The relative velocity will provide adequate kinetic energy the bury the nuclear explosive at significant depths. In order to penetrate into the object, the nuclear explosive must be fitted with a weighty billet: a cylinder of material that will erode during penetration. The billet will add weight to the package that must be delivered. Analytic studies have shown that a penetrator has no value in enhancing deflection, but may be of great value if we choose to pulverize the object[36]. Surface and subsurface detonations make a crater that is small compared to the characteristic dimension of the object. The linear momentum impulse will be imparted along a line connecting that crater and the center of mass — with corrections for local geology and topography. An aspheric object will also receive some angular momentum, depending on the location of the crater and the object's inertial tensor. The size of the impulse will depend on material properties, geology, and topography. Thus, it will be necessary to characterize the geology and mechanical properties of the object when using the *cratering* deflection techniques. Such characterization might be accomplished by a vanguard spacecraft. Stand-off deflection is much less sensitive to these details. In general, linear momentum will be imparted along the line connecting the detonation point with the center of mass — a large lever arm. Little angular momentum will be imparted, and this will depend on relative projected areas of various topographical features compared with components of the inertial tensor. Thus, besides its inherent fracture-mitigation virtues, the stand-off deflector demands substantially less information about the object it is deflecting.

MULTICOMPONENT GRAVITATIONALLY-BOUND OBJECTS

Energetically, it is always preferable to deflect the object, particularly when it can be intercepted early, perhaps several orbital periods before it would impact our planet. More friable objects, however, might be susceptible to fracture, which may make the problem of deflection more difficult as several resulting objects would have to be deflected or pulverized by nuclear explosives, probably delivered by subsequent interception vehicles.

Model for Asteroid Fracture

The model of an asteroid as a agglomeration of competent rocks bound together by mutual gravitational attraction is surely a great simplification. We have little knowledge of how asteroids are held together. There are certainly other cohesive forces between components, but the model may be adequate for many objects, particularly the larger ones.

We wish to ascertain under what conditions the asteroid will: (1) hold together as a single body, but change its trajectory; (2) fracture into dangerous shards, some of which are on nearly the original trajectory; or (3) be pulverized into harmless smithereens that will burn-out in the Earth's atmosphere if their departure from the original trajectory is insufficient to miss the Earth entirely.

For these simulations, I model the rocks or snowballs comprising the asteroid or comet as uniform spheres, which interact gravitationally except when they touch. The touching, or collision, of two rocks is handled as a scattering, that is, the velocities are suddenly changed in such a way that momentum is conserved. The scattering approximation, as well as the lack of cohesive strength between the component rocks, favors shattering the asteroid over moving it as a unit. Thus we are bounding the problem from the conservative end. The objects are modeled as more friable than they probably are. The depiction of comets as "flying rubble piles" has enjoyed increasing support[37,30,38,39,40,41] and comets with multiple nuclei, probably owing to tidal disruption, are not uncommon[42,43]. Asteroids may well be similar agglomerations.

Sketch of the Simulation Algorithm

During the calculation, the spherical components interact gravitationally except when they touch. The touching, or collision, of two components is handled as a non-adhesive frictionless scattering, that is, the velocities are suddenly changed in such a way that momentum is conserved, but some of the kinetic energy may be converted to heat. Because the components are frictionless, no spin is imparted in a collision. The simulation is a detailed calculation of the gravitational interaction and collisions of the components — it is not a hydrodynamic calculation.

A further simplification, which greatly accelerates computation, is to assume the radius and density of each component to be the same.

As long as all the components remain separated by at least two radii, the motion is found by straightforward integration. In the simulation, a collision can only alter the normal component of the relative velocity. $1 \leq \delta \leq 2$.

We have little knowledge of how components of this sort might lose kinetic energy in collisions. For this calculation, the details are not very important. It can be shown that for completely random impact parameters, the selection of $\delta = 1$ causes the average collision between components to lose half its relative kinetic energy to heat. This seems realistic. Because the gravitational orbital dynamics favors grazing collisions over random impact parameters, $\delta = 1$ will result in slightly less than half energy loss on average.

Fragmentation Studies

I have performed a large number of calculations with this model, and it is possible to give only a few to provide some flavor for the behavior of these objects[44]. Table 1 shows the maximum velocity that can be imparted to gravitationally bound asteroids while maintaining their overall integrity. The comparison is for surface detonation and stand-off detonation with 13- and 135-component asteroids. Component density is 3 $\mathrm{gm} \cdot \mathrm{sec}^{-1}$. For the stand-off detonation, the nuclear explosive is placed $\sqrt{2} \times$ the asteroid radius from the asteroid surface. For the surface burst, a single component is accelerated into the body of the asteroid. The single component's crater parameters correspond to medium strength rock: $\beta = 0.9$, $\alpha = 10^{-4}\ \mathrm{gm}^{\frac{1}{2}(1-\beta)} \cdot \mathrm{cm}^{-\beta} \cdot \mathrm{sec}^{\beta}$, and δ=0.316. The stand-off detonation corresponds to $\beta = 0.97$, $\alpha = 1.5 \times 10^{-6}\ \mathrm{gm}^{\frac{1}{2}(1-\beta)} \cdot \mathrm{cm}^{-\beta} \cdot \mathrm{sec}^{\beta}$, and δ=0.3.

Table 1. maximum non-fracturing deflection speeds

Asteroid Diameter	13 Components				135 Components			
	Stand-Off		**Surface**		**Stand-Off**		**Surface**	
(km)	(cm/s)	(kilotons)	(cm/s)	(kilotons)	(cm/s)	(kilotons)	(cm/s)	(kilotons)
20.	1000	9×10^8	256.	3×10^7	477.	5×10^8	118.	1×10^7
10.	500.	5×10^7	129.	1×10^6	239.	3×10^7	58.9	7×10^5
6.	300.	6×10^6	76.9	2×10^5	143.	3×10^6	35.3	8×10^4
3.	150.	4×10^5	38.5	9×10^3	71.5	2×10^5	17.7	4×10^3
2.	100.	7×10^4	25.6	2×10^3	47.7	4×10^4	11.8	8×10^2
1.	50.0	4×10^3	12.8	9×10^1	23.9	2×10^3	5.89	4×10^1
0.6	30.0	6×10^2	7.69	1×10^1	14.3	3×10^2	3.53	5×10^0
0.3	15.0	3×10^1	3.85	5×10^{-1}	7.15	2×10^1	1.77	3×10^{-1}

Implications of Table 1

The calculations presented in Table 1 are, of course, for a single engagement. Multiple engagements will impart the vector sum of the velocity increments from each explosion. However, when approaching the level of incipient fracture, the time interval between successive explosions must be great enough to allow the asteroid to settle down — to convert gravitational kinetic energy from the disturbance into heat energy.

From Table 1 we could conclude that, for a single engagement, the non-fracturing deflection speed obtainable with a stand-off device is about four times the speed obtainable with a surface-burst device. We also see that the non-fracturing deflection speed depends on the number of components, the speed for a 13 component object being about twice that for a 135 component object. The calculations given in the table lead us to the following tentative conclusions: (1) asteroids more than 3 km in diameter can be most efficiently deflected using a surface burst; (2) asteroids as small as $\frac{1}{2}$ km can be effectively deflected using a stand-off device; (3) smaller asteroids are best pulverized.

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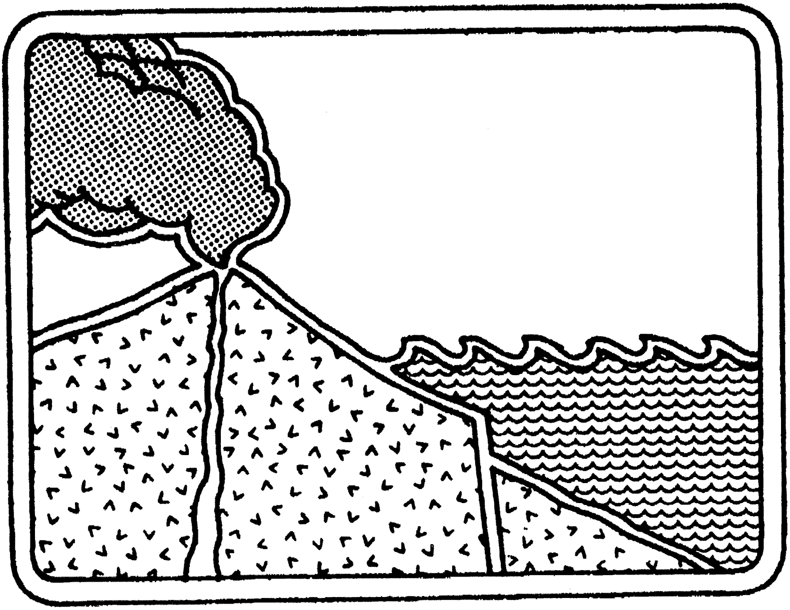

ASTEROID IMPACTS:
THE EXTRA HAZARD DUE TO TSUNAMI

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ABSTRACT

This paper provides an introduction to the consequences of an asteroid colliding with the Earth above an ocean. A method of estimating the risk to coastal regions from tsunami generated by such impacts is presented. This risk is compared with the risk of being within the area of direct devastation from an asteroid impact. An advantage of this approach is that uncertainty about the frequency of asteroid impacts does not affect the assessment.

This tentative analysis suggests that the risk from asteroid tsunami has been substantially overstated - particularly in popular books about asteroid impacts with Earth. For typical coastal regions the risk of dying from an asteroid-generated tsunami is probably no greater than that of dying from the indirect effects (for example, global starvation) of a large asteroid striking the Earth. For some coastal regions with unusual vulnerability to tsunami the risk of dying from asteroid-generated tsunami may be several times greater than that of dying from other asteroid-related causes. The tsunami risk from asteroids 200m in diameter or smaller is likely to be very low.

INTRODUCTION

This paper provides an introduction to the topic of tsunami generated by asteroid impacts. It is intended for a general audience and is based on a World Wide Web page created by the author (Paine 1999). A method of estimating the risk to coastal regions from tsunami generated by such impacts is presented. This risk is compared with the risk of being caught within the area of direct devastation from an asteroid impact.

NATURE OF TSUNAMI

The waves created by a sudden disturbance in the ocean are known as tsunami. Typical causes are earthquakes and underwater landslides. Tsunami travel at high speed across the deep ocean - typically 500km/h or more. In deep water the tsunami height might not be great but the height can increase dramatically when they reach the shoreline because the wave slows in shallow water and the energy is concentrated. In addition to the inherent increase in the height of the wave from this shoaling effect, the momentum of the wave might cause it to reach a considerable height as it travels up sloping land. It is typical for multiple waves to result from one tsunami-generating event and these could be several hours apart when they reach a distant shore.

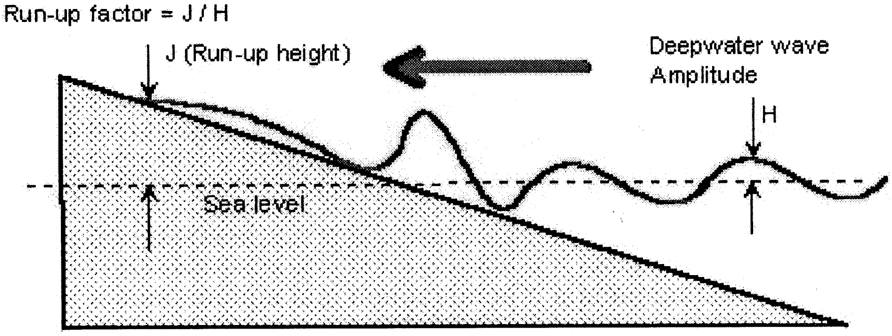

Figure 1: Illustration of Tsunami Terms (Magnified Vertical Scale)

For the purpose of the analysis, several tsunami terms need to be defined: "Run-up height" is the vertical height above sea level of the tsunami at its furthest point inland. "Run-up factor" is the run-up height divided by the deepwater wave amplitude. In effect, "amplitude" is the maximum height of the wave above sea level when in deep water (see Figure 1). This is not the same as the "double amplitude" which is the vertical distance between the crest and the trough and is often used to describe the height of a wave.

The run-up factor can vary considerably, depending on local topography and the direction of travel of the wave. Crawford and Mader (1998) estimate the typical run-up factor for coastal locations is only 2 to 3. Hills and Goda (1998) note that earthquake-generated tsunami in Japan have an average run-up factor of 10 but sometimes reach 25. In Hawaii run-up factors of 40 have been observed for earthquake-generated tsunami.

Recent research suggests that the Australian coastline is vulnerable to tsunami - although not necessarily due to asteroid impacts (Nott & Bryant 1999 and Rynn & Davidson 1999). There is also evidence of substantial variations in run-up factor for tsunami along the Australian coast . Along a 40km stretch of coastline the run-up height from one ancient tsunami event varied by more than 40 (based on Young et al 1996). The effects are complicated by features such as estuaries, harbours, cliffs and reefs. The topography and features of the continental shelf, the shoreline, an estuary/harbour and the land are all very important is considering the damaging effects of tsunami. Some coastal areas could be vulnerable to relatively small tsunami. Until recently there appears to have very little assessment of this risk except in areas prone to earthquake-generated tsunami such as Japan and Hawaii.

The urgency for increased research on tsunami is reinforced by the devastating tsunami which struck northern New Guinea in July 1998

ASTEROID IMPACTS WITH THE EARTH

Stony asteroids with a diameter less than about 100 metres generally do not reach the Earth's surface. These objects usually explode several kilometres above the surface (an "airburst"). This was probably the case with the "Tunguska" Siberian event in 1908. The kinetic energy involved is substantial - a typical impact by a 50m object is equivalent to about 10 megatons (Mt) of TNT and that of a 100m object is equivalent to about 75 Mt. The actual kinetic energy depends on several factors such as speed and density and can vary by a factor of more than 10. These explosions are equivalent in energy to large thermonuclear explosions and they can cause devastation over thousands of square kilometres. In the case of Tunguska the area of destruction was about 2,000 sq km or a circle of radius 25km.. Fortunately the region was sparsely populated and had little effect on humans (nowadays it might be mistaken for a hostile nuclear explosion).

Estimates of asteroid/comet impact frequency may vary by a factor of ten - "Events like Tunguska occur with uncertain frequency, possibly once every 50 years, if the interpretation of the Spacewatch data is correct, or at most once every 300 to 500 years" (Steel 1995). Subject to this uncertainty, the probability of an impact at a given location, P(L), can be estimated from

$$P(L) = P(D)\ A_D / A_E \qquad (1)$$

where:
P(D) is the probability of an impact by an asteroid of diameter D somewhere on the Earth,
A_D is the area of destruction due to the impact and
A_E is the total area of the Earth's surface (including ocean).

Applying this to the Tunguska event, and assuming an impact frequency of one per century: P(annual)= 0.01, A_D=2000, A_E=5.1×10^8. Therefore the *annual* probability of a given location being within the devastation area is 4×10^{-8} or 1 in 25 million.

Steel (1995) provides the following formula for estimating the area of destruction, based on nuclear weapons tests:

$$A = 400\ (\text{Kinetic Energy})^{0.67} \qquad (2)$$

Using this formula the following table sets out the typical values for stony asteroid up to 200m diameter (assuming velocity=20km/s, density=3 g/cc). Values for asteroids 500m and 1km in diameter are based on Morrison and Chapman (1995). The values are subject to considerable uncertainty and may vary by a factor of ten or more.

Table 1
Risk of Direct Impact for a Given Location

Diameter	Kinetic Energy Mt TNT	Area Devastated sq km	Average. interval between impacts (years)		
			Earth	**Point (Town)**	**Inhabited Region # (Potential fatalities)**
50 m	10	1900	100	30 million	900 (1 million)
100 m	75	7200	1000	70 million	8000 (3 million)
200 m	600	29 000	5000	90 million	30 000 (14 million)
500 m	10 000	190 000	40 000	100 million	180 000 (30 million)
1 km	75 000	740 000	100 000	70 million	290 000 (60 million)
2 km	1 million	Global effects	1 million	-	1 million (1.5 billion)
All*			90	12 million	800

*All = $1/(1/T_{50} + 1/T_{100} + 1/T_{200} + 1/T_{500} + 1/T_{1000})$ on the basis that probabilities are independent and span the range of asteroid sizes.

Assuming 9% of Earth's surface area is inhabited but taking into account boundary effects from the area of devastation - see Paine 1999.

An impact by a 2km diameter stony asteroid is thought to be at the threshold of a global catastrophe. It has been estimated that one quarter of the world's population could die from starvation and other indirect effects due to such an impact (Morrison and Chapman 1995).

Iron asteroids are more likely to reach the ground intact. They comprise perhaps 5% of the smaller asteroids and are disregarded in the analysis.

TSUNAMI GENERATED BY IMPACTS

Although, for a given location on the Earth's surface, the risk of a "direct" hit from an asteroid is slight, researchers realized that an ocean impact had the potential to be much more destructive due to the additional hazard of tsunami. An airburst explosion is a three dimensional event and energy decreases according to the square of the distance but a radiating ocean wave is a two-dimensional phenomenon and, in theory, energy decreases in proportion to distance. Since the early 1990s some advanced computer simulations have been conducted to estimate the effects of asteroid impacts above deep oceans.

At this stage there are considerable differences in asteroid/tsunami predictions between the researchers. For a review of the methods see Ward & Asphaug (1999).

The main items of contention appears to be:

- the initial size of the wave - based on analysis of the size and shape of the "crater" and the manner in which it collapses, and
- the rate at which a tsunami from an asteroid impact dissipates as it travels.

Crawford & Mader (1998) explain that, for an impact to produce a coherently propagating wave (one that does not dissipate substantial energy when it travels over great distances) the "cavity" must be 3 to 5 times broader than the depth of the ocean. Using a rule-of-thumb (derived from simulations) that the cavity diameter is 20 times the asteroid diameter then, for a typical ocean depth of 4km, the impactor must be at least 1 km in diameter to produce a coherent wave. On this basis, for asteroids smaller than about 1km, the wave will dissipate considerably as it travels over thousands of kilometres of ocean.

Table 2
Estimated Deepwater Wave Height (Above Sea Level) at a Point 1,000km from an Asteroid Impact - Selected Research Results

Asteroid Diameter (m)	Hills & Goda (1998)	Crawford & Mader (1998)
200m	5m	Negligible
500m	11m	<2m
1000m	35m	6m

Ward & Asphaug (1999) predict a similar tsunami height to that of Hills & Goda for a 250m diameter asteroid. There have been no detected asteroid impacts into an ocean on Earth so it is difficult to verify the models. However, the CTH computer code used by Crawford and Mader successfully predicted the consequences of the impact of Comet Shoemaker-Levy 9 with Jupiter. In the (fortunate) absence of experimental evidence on the Earth, the conservative results produced by Crawford & Mader have been used in the following analysis. In other words, it is assumed that asteroid impacts will generally produce non-coherent waves which dissipate quickly. There may be cases where an asteroid impact produces coherent waves but this would be due to a combination of unusual conditions, such as shallow water, rather than the norm.

In the case of asteroids 200m and larger there is likely to be an impact into the ocean. For objects under this diameter an airburst is likely and there is a corresponding reduction in the size of the predicted deepwater wave due to energy dissipation in the atmosphere. Speed, trajectory, density and strength of the object can affect the nature of the explosion. There does not appear to be an empirical formula available to deal with these smaller objects and it is possible that the smaller asteroids produce no appreciable waves. On the other hand, in the case of serious tsunami generated by earthquakes the energy involved is estimated to be equivalent to about 2 Megatons of TNT (Yabushita 1998). The impact by a 100m asteroid typically involves kinetic energy of about 75Mt so it would only involve the conversion of about 3% of this energy to ocean wave energy in order to produce a serious tsunami. However, the tsunami would probably quickly dissipate, compared with an earthquake-generated tsunami.

On balance, the following conservative values have been used for risk assessment. These are based on extrapolation of Crawford and Mader data (see Appendix). Note that, compared with Table 2, the range has been reduced to 100km to obtain reasonable values for the smaller asteroids.

Table 3
Estimated deepwater wave height (above sea level)
at a point 100km from asteroid impact

Asteroid Diameter (m)	Deepwater Wave Height (m)
50	0.12
100	0.7
200	3
500	22
1000	70

ESTIMATED RISK TO COASTAL LOCATIONS

Taking the New Guinea experience as a reference level, it is assumed that a tsunami with a 10m will be of concern to low-lying coastal areas. The risk is estimated in the following steps:

a) Determine the run-up factor W for the location in question.

b) Determine the critical deepwater wave height that will produce a tsunami with a run-up height of 10m (H = 10 / W).

c) For each size of asteroid, determine the distance over which a deepwater wave will need to travel before it has reduced in size to the critical height determined in step (b). This will be the "danger radius" for this combination of run-up factor and asteroid size.

d) Determine the area of a semi-circular area of ocean with a radius equal to the distance derived in step (c).

e) Calculate the probability of an impact within the area derived in step (d).

In the absence of better data the following estimates of danger radius have been derived by extrapolation of the Crawford and Mader data (see Appendix). This should be regarded as tentative.

Table 4
Danger radius - Estimated radius from impact for a tsunami 10m or higher at the shore (deepwater wave height in metres is 10/run-up factor)

Stony Asteroid Diameter (m)	**Tsunami Run-up Factor**			
	5	**10**	**2**	**40**
	Distance from impact (km)			
50	10	20	4	60
100	40	70	13	230
200	140	250	46	820
500	800	1400	250	4400
1,000	2800	5000	900	16 000

It is noted that, irrespective of run-up factor, the radius derived for a 50m asteroid is similar to radius of direct devastation for the Tunguska event.

For most coastal locations the surface area of ocean which poses a tsunami threat is a semi-circle with a radius R equivalent to the danger radius. This radius is, however, limited by the size of the ocean. An area corresponding to 30% of the surface area of the Earth has been used for this limit (the approximate size of the Pacific Ocean). Applying equation (1) to the resulting semi-circular areas provides the following estimates of average intervals between events:

Table 5
Estimated Interval Between Major Tsunami Events
(Tsunami Run-up Height 10m or Greater)

Stony Asteroid Diameter (m)	**Tsunami Run-up Factor**			
	5	10	20	40
	Average interval between tsunami events (years) for a single location on the shore of a deep ocean.			
50	-	81 million	20 million	9 million
100	-	66 million	19 million	6 million
200	83 million	26 million	8 million	2 million
500	20 million	7 million	2 million	670 000
1000	4 million	1.3 million	400 000	330 000
All	3 million	1million	300 000	190 000

In all cases it appears that risk of serious tsunami from asteroids 200m diameter and smaller is much less than for larger objects.

For a given coastal location the predicted average interval between major tsunami events (bottom row from Table 5) can be compared with the average interval between "direct" impacts of 12 million years (from Table 1) to derive the relative risk for that location compared with an inland location (that is, a location which is not vulnerable to a 10m tsunami). This relative risk is independent of the actual rate of impacts.

Table 6 Relative risk of coastal location compared to inland location

Tsunami Run-up Factor	Relative Risk
0 (inland)	1
5	4
10	11
20	46
40	74

This tentative analysis suggests that the risk to a low-lying coastal area from tsunami generated by asteroids is greater than the risk from a "direct" impact by such objects. The average interval between such tsunami events is estimated to range from about 190 000 years for a location with a run-up factor of 40 to about 3 million years for a location with a run-up factor of 5.

DISCUSSION

Comparison with the risk analysis by others

Ward and Asphaug (1999) set out a comprehensive method of determining the impact tsunami risk. The analysis is based on methods they have developed for assessing earthquake risk. Probabilities are derived for a range of tsunami sizes striking a given coastline within a 1000 year period. In that paper tsunami height is measured just before the wave reaches the shore rather than run-up height. They assess the tsunami risk for a generic coastline and for the coastal cities San Francisco, New York, Tokyo, Hilo Harbour (Hawaii), Perth and Sydney.

The risks derived from Table 5 above are considerably less than the risks from an asteroid-generated tsunami derived by Ward and Asphaug. For example, they estimate the risk of a 10m tsunami inundating a generic coastline (with a semi-circular "target area" of ocean having a radius of 6,000km) is 1.1% in 1000 years - equivalent to one event every 91 000 years and about ten times the risk estimated in Table 5. The main differences are likely to arise from assumptions about initial wave size and dissipation.

Comparison with other asteroid impact risks

Table 6 compares the risk of being caught in a region of direct devastation (within the "blast area") with that of being within an area inundated by an asteroid-generated tsunami. In the case of an impact by a large asteroid (diameter 2km or more) is has been estimated that 25% of the human population of the Earth would die. This extreme event is thought to occur with an average interval of 1 million years. The annual risk of dying from such an event is therefore about 1 in 4 million, which is similar to the tsunami risk for a location with a run-up factor of 5 (1 in 3 million).

CONCLUSION

This tentative analysis suggests that the risk from asteroid tsunami has been substantially overstated - particularly in popular books about asteroid impacts with Earth. For typical coastal regions the risk of dying from an asteroid-generated tsunami is probably no greater than that of dying from the global effects of a large asteroid striking the Earth.

For some coastal regions with unusual vulnerability to tsunami the risk of dying from asteroid-generated tsunami may be several times greater that of dying from other asteroid-related causes. For these highly vulnerable areas the typical interval between asteroid tsunami events is likely to be about 200 000 years - assuming that impacts are randomly distributed in time. It appears that there is a very low tsunami risk from asteroids 200m in diameter or less.

There is considerable uncertainty about most of the "input values" used in these estimates. Also it is possible that impacts are not randomly distributed in time (Steel et al, 1995) and the Earth may be subjected to a barrage of small asteroids (or comet fragments) from time to time. Until we better understand the impact threat, there is no cause for complacency over the long intervals derived above. Finally, it is stressed that the run-up factor is not the sole issue in determining the destruction caused by a tsunami.

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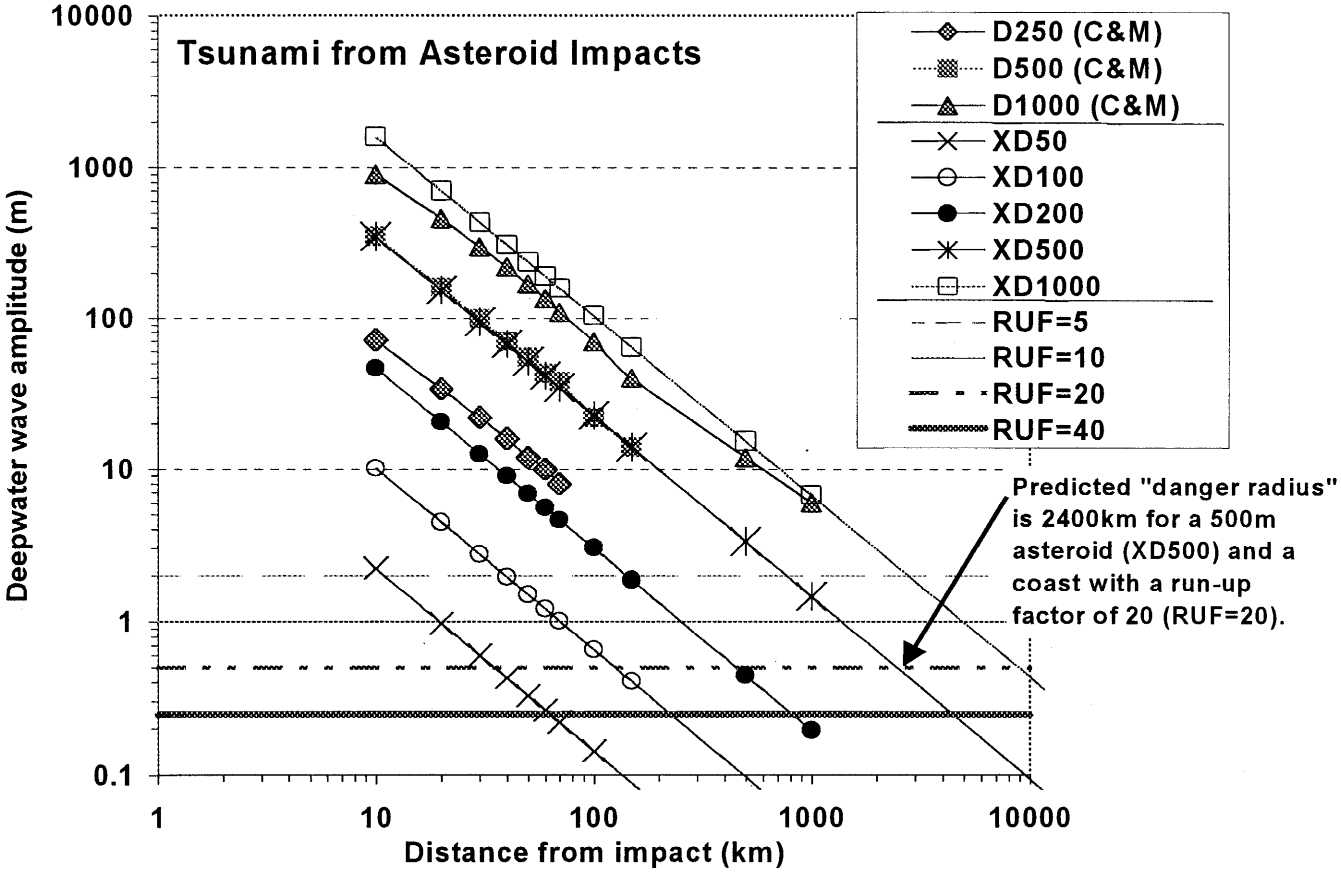
APPENDIX

Extrapolation of Crawford & Mader Data

The graph overleaf shows deepwater wave height (metres above sea level) by distance from impact (kilometres) for a range of asteroid diameters. It is a log-log plot of the extrapolations (X) used to derive Table 4, superimposed on the data (C&M) from Crawford & Mader (their Table 1 on page 28). It can be seen that the extrapolations are *speculative* for both smaller asteroid sizes and large distances, since the Crawford and Mader data do not go below an asteroid diameter of 250m and do not go beyond a radius of 1000km (and then only for the 1km asteroid). Strictly the extrapolations for the 50m and 100m asteroids do not take into account airburst effects but since the contribution of these impacts to overall tsunami risk turns out to be very low this will have negligible effect on the risk estimates. As a consequence of the uncertainties the risk estimates derived in this paper should be regarded as ballpark only.

The horizontal lines show the deepwater wave heights that would produce a tsunami with a run-up height of 10m for a range of run-up factors (RUF 5, 10, 20 & 40). An estimate of "danger radius" can be derived from the intercept of these lines with the asteroid lines. For example, the horizontal dot-dash line shows a deepwater wave height of 0.5m. This would produce a 10m tsunami at a location with a run-up factor of 20. This line intercepts the extrapolated line for a 500m asteroid at a "distance from impact" of about 2400km. It is therefore predicted that an impact by a 500m diameter asteroid anywhere within a radius of 2400km would produce a tsunami 10m or higher at a location with a run-up factor of 20 (this is an unusually high factor).



Predicted "danger radius" is 2400km for a 500m asteroid (XD500) and a coast with a run-up factor of 20 (RUF=20).

Figure 2: Prediction of the range of impact tsunami by extrapolation of the data ("C&M") provided by Crawford and Mader (1998). A tsunami run-up height of 10m is assumed for the run-up factor (RUF) intercepts.

TSUNAMIS ON THE COASTLINES OF INDIA

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ABSTRACT

Even though earthquakes occur frequently in India and in the surrounding waters, tsunami events are rare. No matter how rare they may be, they cannot be totally ignored in terms of public safety as well as safety of the coastal infrastructure.

1 INTRODUCTION

Although the majority of the reported tsunamis are from the littoral countries of the Pacific Ocean, there are a few cases of tsunamis in the Indian Ocean. The approximate length of the Indian coast is about 6000 km. The coasts run from north to south and have two arms in the east and west with a tapering end at Kanyakumari. The tsunamigenic earthquakes occur mostly at the following three locations. 1) The Arabian Sea, 2) Area about 400 – 500 km south or Sri Lanka (Ceylon), 3) The Arabian Sea about 70 to 100 km south of Pakistan coast—off Karachi and Baluchistan (Figure 1). The oldest record of tsunami is available from November 326 BC earthquake near the Indus delta /Kutch region. Alexander the Great (Table 1) was returning to Greece after his conquest and wanted to go back by a sea route. But a tsunami due to an earthquake of large magnitude destroyed the mighty Macedonian fleet (Lisitzin, 1974).

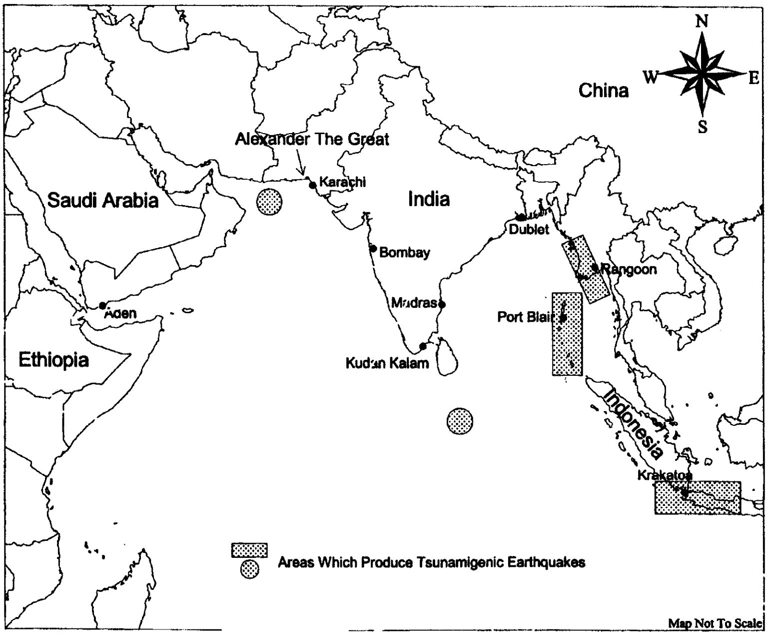


Figure 1 -Tsunamis on the Coastlines of India

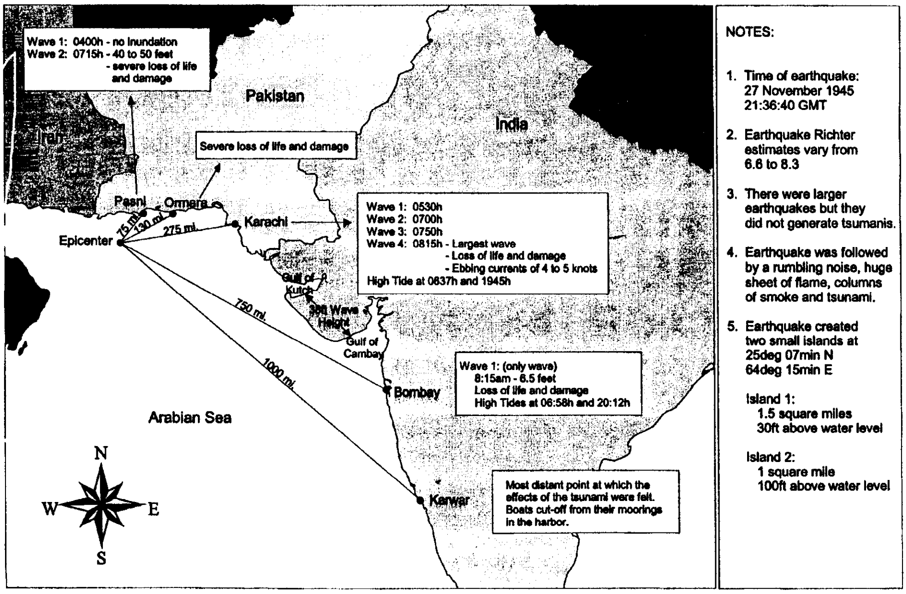
Figure 1

Tsunami-Genic Areas in the Northern Part of the Indian Ocean

The earliest record of tsunami is reported to be of 1.5 meters at Chennai (formerly Madras) which was created by the 27th August 1883 Krakatoa volcanic explosion in Indonesia. An earthquake of magnitude 8.25 occurred about 70 km south of Karachi (Pakistan) at 24.5 N and 63.0 E on 28th November 1945 (Figure 2). This created a large tsunami of about 11.0 to 11.5 meters height on the coast of India in Kutch region (Pendse 1945). An earthquake of magnitude 8.1 occurred in the Andaman Sea at 12.9 N and

92.5 E on 26th June 1941 and a tsunami hit the east coast of India. As per non-scientific/journalistic sources the height of the tsunami was of the order of 0.75 to 1.25 m. At that time no tide gauge was in operation.

November 1945 Earthquake



NOTES:

1. Time of earthquake: 27 November 1945 21:36:40 GMT
2. Earthquake Richter estimates vary from 6.6 to 8.3
3. There were larger earthquakes but they did not generate tsunamis.
4. Earthquake was followed by a rumbling noise, huge sheet of flame, columns of smoke and tsunami.
5. Earthquake created two small islands at 25deg 07min N 64deg 15min E

   Island 1:
   1.5 square miles
   30ft above water level

   Island 2:
   1 square mile
   100ft above water level

Figure 2

Figure 2

Tsunami of November 1945 in the Arabian Sea

Table 1

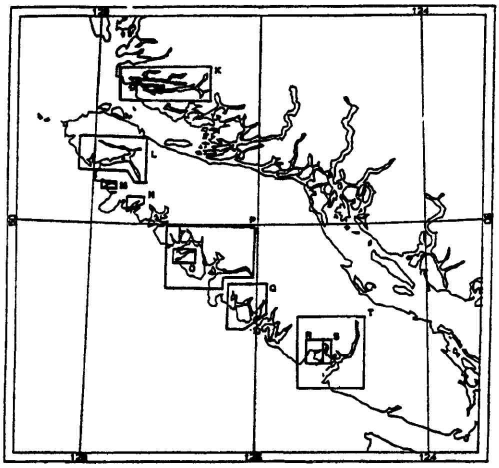
A Partial List of Tsunamis in the North Indian Ocean

Date	Remarks
326 B.C.	Alexander the Great
Between 1st April and 9th May 1008	Tsunami on the Iranian coast from a local earthquake
August 27th 1883	Krakatoa 1.5 m tsunami at Madras, 0.6 m at Nagapattinam, 0.2 m at Arden
1884	Earthquake in the western part of the Bay of Bengal. Tsunamis at Port Blair, Dublet (mouth of Hooghly River)
26th June 1941	8.1 quake in the Andaman Sea at 12.9°N, 92.5°E. Tsunamis on the east coast of India with amplitudes from 0.75 to 1.25 m
27th November 1945	8.25 quake 70 km south of Karachi at 24.5°N, 63.0°E Tsunami amplitude at Kutch was 11.0 to 11.5 m.

However, the heights are reported to be estimates. Mathematical calculations suggest that the height could be of the order of 1.0 meter or so. There are a few more cases of earthquakes of magnitude less than 8.0 which have given rise to some smaller tsunamis (Bapat et al (1983) have reported a few more earthquakes on the coast of Myanmar (formerly Burma).

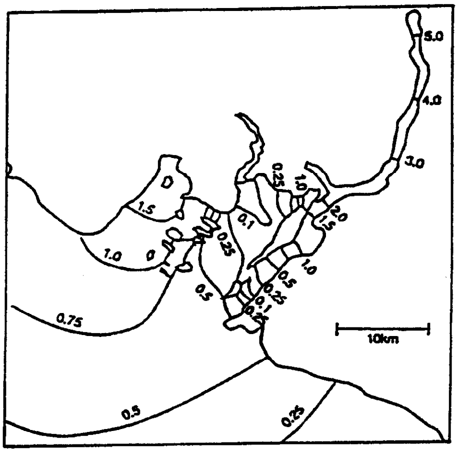
2 DISCUSSION OF RESULTS

Figure 2 shows the pertinent details about the tsunami generated by the November 1945 earthquake in the Arabian Sea. The significant amplification of the tsunami in the Gulfs of Kutch and Cambay is evident. We plan to develop a mathematical model to simulate this amplification. Meanwhile, we refer to a similar resonance amplification (Henry and Murty, 1995) in the Alberni Inlet on the Pacific Coast of Canada (Figures 3, 4 and 5).



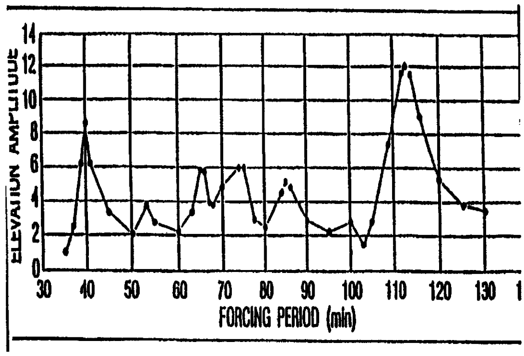
Vancouver Island on the Pacific Coast of Canada.
Inset: Alberni Inlet

Figure 3



Tsunami amplitude (m) at Port Alberni located at the head of the Alberni Inlet at forcing period of 85 min

Figure 4



Maximum Tsunami Amplitude Versus Forcing Period (Minutes)
Local Resonant Amplification

Figure 5

As can be seen, resonance amplification can occur for various periods depending upon the frequencies of normal modes of the waterbody. A tsunami with an amplitude of 0.5 m in the ocean can amplify to 5.0 m at the head of the inlet, whereas a tsunami with a period of about 113 m can amplify to over 12 m. We plan to use a numerical model to compute the normal modes and resonance amplification in the Gulfs of Kutch and Cambay.

3 A POSSIBLE TSUNAMI WARNING SYSTEM FOR THE INDIAN OCEAN

Otto and Murty (1996) discussed a possible tsunami warning system for the Indian Ocean and they developed travel time charts for various locations around the Indian Ocean rim. Two examples are shown in Figures 6 and 7. Here the travel times are in hours.

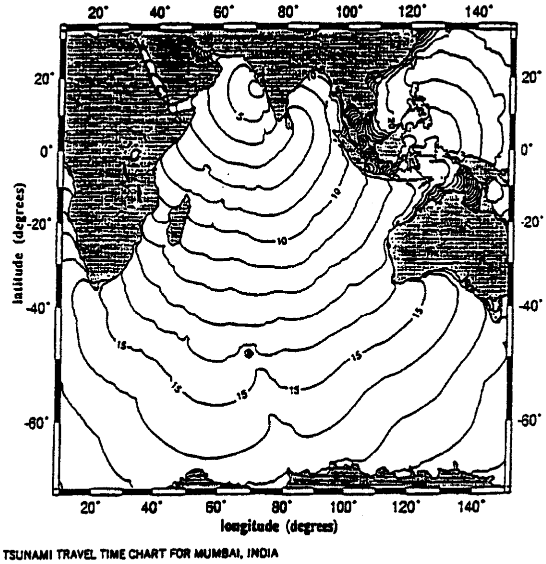


Figure 6

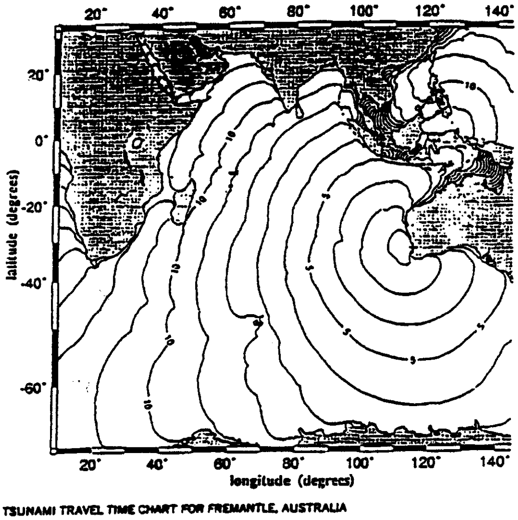


Figure 7

4 CONCLUSIONS

Tsunami events are rare on the coastlines of India. Nevertheless, the tsunami threat cannot be ignored in view of public safety and possible damage to coastal infrastructure. A tsunami warning system can be developed somewhat similar to the Pacific tsunami warning system.

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DESTRUCTIVE TSUNAMIS AND TSUNAMI WARMING IN CENTRAL AMERICA

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ABSTRACT

The Central American Coasts have been hit by nine destructive tsunamis during the last two centuries. Seven of these tsunamis are from the Pacific and two from the Caribbean. Reported damages range from coastal and ship damage to destruction of small towns. Almost 500 people have been killed by these tsunamis. The Pacific coast of Central America has higher tsunami hazard than the Caribbean Coast. Tectonic environments that generate tsunamigenic earthquakes are the Middle American Trench, the Polochic-Motagua Fault System and the North Panama Deformed Belt (NPDB).

A Tsunami Warning System for Central America has been designed (Fernandez, 1998). This system uses earthquake magnitude as the trigger for tsunami warning. Three institutions are involved in this system: The Instituto de Estudios Territoriales de Nicaragua (INETER), The Central American Seismological Center (CASC) and the National Emergency Office (NEO) of each country. CASC locates the earthquake and determines the magnitude and sends the seismic information to INETER. This institution evaluates the seismic information and decides if the earthquake has potential to generate a tsunami. In the event of a tsunamigenic earthquake INETER issues a tsunami warning which is sent to the National Emergency Office (NEO). NEO actives the local emergency plan and takes actions to protect coastal residents.

Introduction

The Middle American Trench, located in front of the Pacific Coast of Central America, is the tectonic boundary between the Cocos and Caribbean plates (Fig. 1); along this trench the Pacific Plate subducts under Caribbean Plate, generating high seismic activity, large earthquakes and tsunamis. Also the Polochic-Motagua Fault System (the tectonic boundary between Caribbean and North American plates) and the North Panama Deformed Belt (a convergent margin within the Caribbean Plate) generate tsunamigenic earthquakes. Even though large tsunamis are not common in this area, three important tsunamis with heights larger than 5 meters have threatened islands and coastal villages, destroyed property and killed people. A recent investigation indicates that 49 tsunamis have hit the Central American Coasts in the period 1539-1998 (Molina, 1997; Fernandez et al., submitted to Natural Hazards), both Caribbean and Pacific, resulting in 455 deaths.

The purpose of this article is to summarize the information concerning the destructive tsunamis of Central America and to outline procedures to warn coastal settlements of the approach of possible tsunamis that could affect coastal areas of Central America.

The warning plan is addressed to the seismological staff of the Central America Seismological Center (CASC), the Instituto de Estudios Territoriales de Nicaragua (INETER), and to all personnel of the seismological laboratories of Central America who are in charge of the seismic monitoring in the region. Detailed actions to be taken by individuals and communities in case of tsunami must be part of a local plan prepared by the National Emergency Office of each country and because of that, they are not included here. This work is part of a plan carried out by the Centro para la Prevencion de Desastres Naturales en America Central (CEPREDENAC) to mitigate natural disasters in the region.

Destructive tsunamis in Central America

Nine destructive tsunamis, two from the Caribbean side and seven from the Pacific have hit the Central American Coasts. Seven of these tsunamis are local, one regional and one distant. The regional tsunami originated in Ecuador and the distant one in the Aleutian Islands. The most important characteristics of these tsunamis are given in table 1.

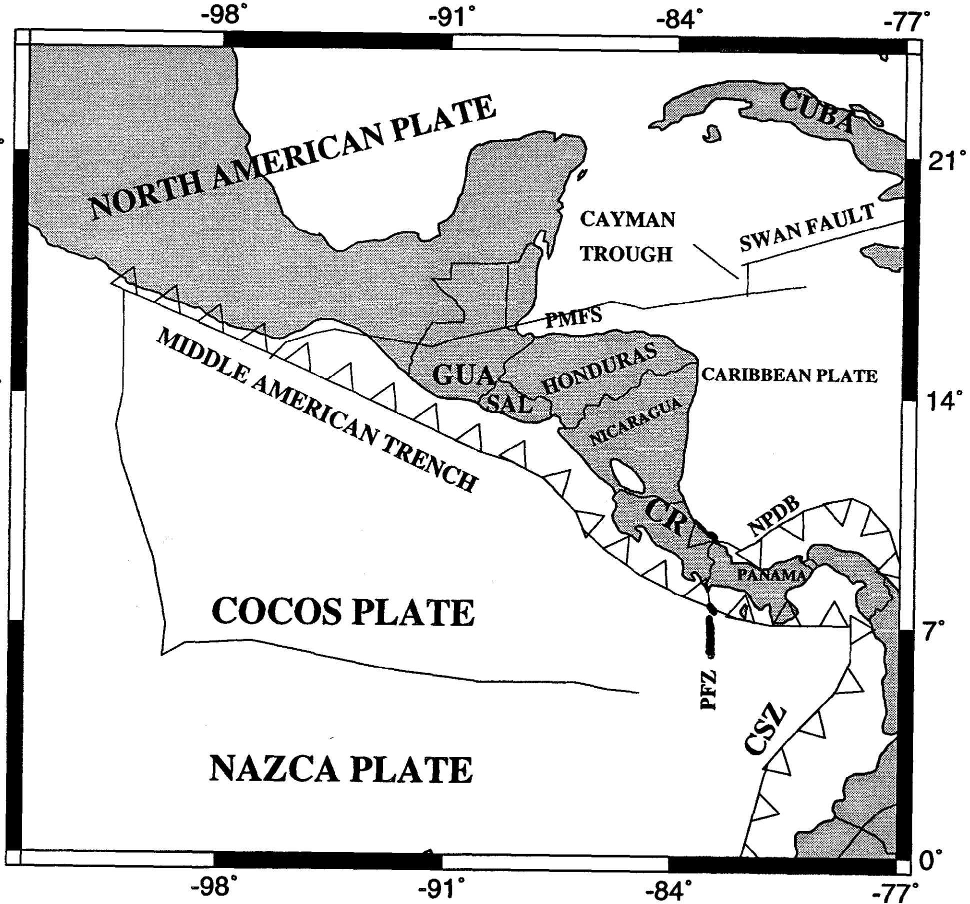

FIG. 1 THE MOST IMPORTANT TECTONIC FEATURES OF CENTRAL AMERICA. CENTRAL AMERICA IS PART OF THE CARIBBEAN PLATE. THIS PLATE IS BOUNDARED BY NORTH AMERICAN, SOUTH AMERICAN, COCOS AND NAZCA PLATES. PFZ: PANAMA FRACTURE ZONE, NPDB: NORTH PANAMA DEFORMED BELT, CSZ: COLOMBIA SUBDUCTION ZONE, PMFS: POLOCHIC-MOTAGUA FAULT SYSTEM. GUA: GUATEMALA, SAL: EL SALVADOR CR: COSTA RICA.

Table 1 Destructive tsunamis of Central America.

#	Date	Ms	Location	H(m)	M	Type	CO	TE
1	1854-0805	7.3	Golfo Dulce, CR		1.5	Local	P	CO-CA
2	1856-0804	7-8.0	Honduras Gulf	5	2	Local	C	NA-CA
3	1882-0907	7.9	San Blas, PAN	3	1	Local	C	NPDB
4	1902-0226	7.0	P. Coast GUA/SAL		2	Local	P	CO-CA
5	1906-0131	8.1	ECUA, PAN, CR	2-5		Regional	P	NZ-SU
6	1913-1002	6.7	Azuero, PAN			Local	P	A Fault
7	1957-0310	8.1	Acajutla, SAL	> 2		Distant	P	PA-NO
8	1976-0711	7.0	Darien, PAN			Local	P	NZ-CA
9	1992-0902	7.2	Nicaragua Coasts	9.5	2.5	Local	P	CO-CA

Ms: Earthquake magnitude, H: Height, m: meters, M: Tsunami Magnitude, CO: coast, P: Pacific, C: Caribbean, A: Azuero, CR: Costa Rica, PAN: Panama, GUA: Guatemala, SAL: El Salvador, ECUA: Ecuador and TE: the tectonic environment where the earthquake took place. CO-CA: Cocos-Caribbean, NA-CA: North America-Caribbean, NPDB: North Panama Deformed Belt, NZ-SU: Nazca-South American, PA-NA: Pacific-North American.

Tsunamis on the Caribbean Coast due to earthquakes originated either in the North Panama Deformed Belt (NPDB) and the Polochic-Motagua Fault System. Tsunamis on the Pacific are uniformly distributed along the all coast. They are due to subduction earthquakes of the Cocos-Caribbean tectonic environment. The Nicaragua-Guatemala coastal segment is the most dangerous tsunamigenic zone of the Pacific Coast since the largest tsunamis of the Pacific have occurred there.

Table 2 Reported damage and effects of the tsunamis

#	Date	Damage and effects
1	1854-0805	The village of Golfo Dulce was flooded by the sea and destroyed (Soloviev & Go, 1984).
2	1856-0804	The maximum amplitude of the tsunami was 5 meters. There are reports of damage at Omoa, Cortez, Atlantida, Trujillo and Criba Lagoon. There are accounts of the complete ruin of Omoa, destruction of entire villages and rivers changing directions. (Iida et al., 1967; Sutch, 1981; Cruz & Wyss, 1983; Soloviev & Go, 1984).
3	1882-0907	This tsunami hit the San Archipielago located northeastern Panama, with waves 3.0 m high or more. According to the historical reports, between 75 and 100 died, most of them drowned. The tide ran out a great distance, and on its return, swept away the villages built on the beaches of different islands of the archipelago and on the mainland. People at the vessel Honduras felt the seaquake. (Iida, et al., 1967; Grases, 1974; Soloviev & Go, 1984; Mendoza & Nishenko, 1989; Grases, 1990; Camacho & Viquez, 1993b).
4	1902-0226	The coast of El Salvador from Garita Pamera to Barra de la Paz and beyond (a distance of about 120 km.) was flooded. There was extensive damage to the property. The sea bottom was exposed for a considerable distance. A large wave reached the coast killing 100 persons in Barra de Santiago and 85 more

		in Barra del Paz. Homes and trees were washed out to sea. Three waves were observed. (Iida et al., 1967; Soloviev & Go, 1984; Ambraseys & Adams, 1996).
5	1906-0131	The wave generated by the earthquake was 2.5-5 meters high. The tsunami was observed along the entire coast of Central America, in Mexico and California. A beach 2 km long dried up in Potrero Bay, then the water rushed onshore, tossing up boats (Iida et al., 1967; Hatori, 1968; Soloviev & Go, 1984).
6	1913-1002	The Sea level increased suddenly and some rivers rose up flooding areas inland. Pedasi Village disappeared. (Viquez & Camacho, 1993; Ambraseys & Adams, 1996).
7	1957-0310	A sea wave of several meters high damaged part of the Acajutla Harbor (El Salvador). Loss of lives. The earthquake took place in Aleutians Islands (Alvarez, 1979, Guinea, 1995).
8	1976-0711	Moderate damage in the province of Darien (Panama), especially in the coastal villages of Jaque and La Palma. In Jaque people died. (Grases, 1990).
9	1992-0902	This is the largest tsunami of Central America. A sea waves of 9.5 m high flooded the whole Pacific Coast of Nicaragua and part of the Costarrican Coast. The horizontal extent of the inundation was of the order of few hundred meters. There were about 170 casualties. The largest run-up occurred in the central part of the Nicaragua coast. Damage to small harbors and boats in Costa Rica where the maximum amplitude of the wave was 4 meters. (Baptista et al., 1993; Ide et al. 1993; Imamura et al., 1993; Fernandez, et al., 1993; Sakate, 1994; Ambraseys & Adams, 1996).

The most affected areas on the Caribbean side are the Honduras Gulf and the coasts of Panama and Costa Rica. Towns extensively damaged by tsunamis on the Caribbean Coast are Omoa, Trujillo, Cortes and San Blas (Fig. 2). The San Blas tsunami is the most tragic tsunami of the Caribbean, which killed 100 people.

Almost all of the countries of Central America have been hit by destructive tsunamis from the Pacific Side (Fig. 2). Towns on this coast severely damaged by tsunamis are Pedasi (Panama), Golfo Dulce (Costa Rica), Corinto (Nicaragua), Acajutla (El Salvador), Barra de la Paz (El Salvador) and Barra de Palmera (El Salvador). The largest tsunamis on this coast are the Ahuachapan Tsunami that in 1902 killed 185 people in El Salvador, and the Nicaraguan Tsunami that destroyed Corinto, killing 170 people. The Nicaraguan Tsunami is the largest of Central America; its maximum amplitude was 9.5 meters in the Nicaragua Coasts. There are 355 deaths reported as consequence of the destructive tsunamis of the Pacific. However this amount might be more because three tsunamis (Golfo Dulce Costa Rica, 1854; Pedasi Village, Panama, 1913 and Acajutla, El Salvador, 1957) caused extensive damage but no casualties were reported.

Regional tsunamis from other places in the Pacific Basin have also hit the coasts of Central America. In 1957 an earthquake from the Aleutian Islands generated a tsunami that reached the coasts of El Salvador and caused extensive damage to coastal villages and killed people. The 8.5 magnitude Chile Earthquake in 1960 hit some coasts of Guatemala and Salvador (Molina, 1997), but neither damage nor deaths were reported at that occasion. Also the Tumaco (Ecuador) Tsunami was observed along the entire coast of Central America.

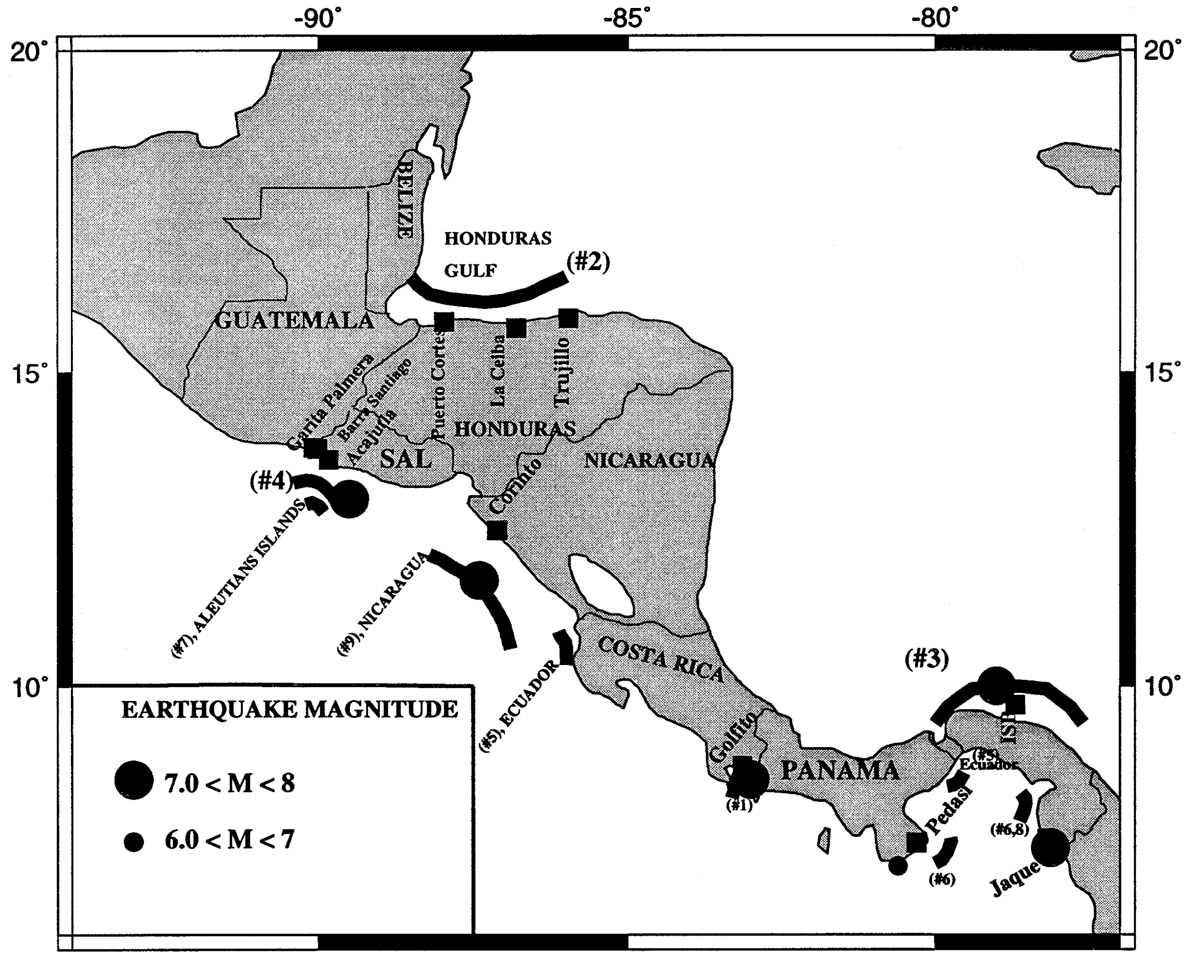

FIG. 2 TSUNAMIGENIC EARTHQUAKES, AND TSUNAMI AFFECTED AREAS. BLACK SQUARES ARE POPULATION CENTERS. THE NUMBER OF THE TSUNAMI (TABLE 2) HAVE BEEN ATTACHED TO THE HEAVY LINE REPRESENTING THE TSUNAMI AFFECTED AREA. CIRCLES ARE TSUNAMIGENIC EARTHQUAKES. ISB: SAN BLAS ISLANDS.

The Central America Tsunami Warning System (CATWS)

An efficient Tsunami-Hazard Mitigation Plan should take into account three basic elements: hazard assessment, warning and education (Bernard in Hebenstreit, 1997). Without a hazard assessment plan and an educated-response to tsunami hazard, any tsunami warning would be inefficient. Therefore, the proposal to establish a Tsunami Warning System in Central America would include the conceptual model (three elements) of Bernard in: Hebenstreit (1997) and follow its recommendations.

Tsunami Hazard Assessment

Knowing that Central America is a tsunamigenic zone, all countries in the region should be interested in a highly efficient hazard mitigation plan. Even with existing interest and good intentions to develop such a plan, another ingredient is necessary, cooperation. Good cooperation between countries is an indispensable requirement for the CATWS to be successful. First empirical estimation of tsunami hazard of Central America have already been done based on data from earlier tsunamis (Fernandez et al., submitted to Natural Hazards). Now, it is necessary to produce maps of inundation using tsunami inundation numerical model. Due to the lack of experience in this matter, the first task regarding tsunami hazard assessment should be to establish a group of scientist and institutions to produce tsunami inundation maps for coastal localities, starting with the most important ports.

The Warning System

An appropriate warning system is required to alert the population that danger in imminent. This warning system will start in 2000. There are three institutions involved in the issuance of a tsunami warning in Central America, the Institute of Territorial Surveys of Nicaragua (INETER), the Central American Seismological Center (CASC), and the National Emergency Office of each country of Central America (Fernandez, 1998). The three institutions should operate 24-hr/day.

The Institute of Territorial Surveys of Nicaragua (INETER)

INETER would be the sole institution responsible for the issuance of a tsunami warning in Central America. After evaluating seismic information, this institution should decide if a warning should be declared. After the Nicaraguan Tsunami on September 01, 1992, INETER became the institution responsible for building up and maintaining the seismic and mareographic monitoring system and for developing the scientific studies necessary for the establishment of a tsunami warning system in Nicaragua. Due to the experience gained on issuing tsunami warning after the Nicaraguan Tsunami (1992), this institution was chosen to manage the issuance of tsunami warning in the region.

The Central American Seismological Center (CASC, Alvarenga et al., 1998)

This center is located at the Geology Department of the University of Costa Rica and was opened in August 1998. The purpose of this center is to store the most important data from seismic stations from Central America and collect data from all the seismic station in semi-real-time in order to issue daily bulletins. The data center has two functions: (I) automatically collect data for large events (Ms > 4) from all regional stations with modem or Internet connection and determine a preliminary location and magnitude in near real-time, and (ii) be a permanent archive for seismic data in Central America.

The near real-time system is based on the network data collection system SEISNET and connects to IRIS or SEILOG systems in the region using Internet or Modem. The SEILOG gives P- and S-triggers times for each channel as well as duration of the event. Based on this information a preliminary hypocenter and magnitude are calculated.

Each country of the region has a seismic network, except Costa Rica that has two. There are 138 short-period seismic stations in Central America, most of them with analog transmitting system. Data are sent from the field to the recording center by radio or telephone. In addition there are eight permanent broadband or extended short-period stations; each country has at least one broadband station. The processing is done with the SEISAN on Sun workstations.

CASC is responsible for processing the Central American Seismic activity. In the event of a tsunamigenic earthquake, the operator in turn should locate the earthquake as fast as possible and send a seismic bulletin to INETER, indicating the magnitude and the location of the earthquake.

The National Emergency Office (NEO)

The National Emergency Office of each country is the institution in charge of activating Local Emergency Plans at coastal settlements that can be hit by tsunami. After receiving the tsunami warning from INETER, the National Emergency Office should take practical actions to protect coastal residents against the tsunami. Each country of the area has a National Emergency Office and this is very useful for the purpose of the warning system because that office has an emergency plan even in small towns. This plan should take into consideration the effects of the tsunamis. Each one of these offices should have efficient communication with INETER and CASC in order to take faster actions after the potential tsunamigenic earthquake.

The Magnitude of the Earthquakes

One of the most important aspects of tsunami warning is to very quickly determine a reliable Mw. Surface waves, that in general are the best data to use, could be used to calculate Mw if waveforms from the all broadband stations are collected immediately after the earthquake. But this is quite difficult now due to the inefficient communication between the seismic laboratories of Central America and the CASC. On the other hand, calculating the Mw with surface waves with a single station could be a problem if the distance to the station is short, as the surface waves can not be recorded. Recent studies using Central America Broadband data (Vega, 1998) show that a reliable Mw can be determined from P and/or S-Waves. This is a simple approach that can be used as soon as a few seconds of P-Waves are available and a preliminary location has been made.

An alternative approach is to calculate the M_E magnitude which requires integration of the whole seismogram and requires a bit more time. For neither Mw nor M_E automatic software is not available yet in the region, however ATWC has this software.

The tsunami warning method for Central America

After having reviewed the methods for tsunami warning in the world, it was concluded that the Mexican method (Shapiro et al., 1998) could fit better than any other in Central America. But because that system has not been implemented in Mexico (Pacheco, personal communication), it is not available for Central America yet. Then and due to slow communication between the networks of Central America, the tsunami warning system for Central America will start making location and determining magnitudes with the seismic network of the Red Sismologica Nacional de Costa Rica (RSN: ICE-UCR) and the broadband station located at the University of Costa Rica. A new data collection/processing system is set up independently of the current system to only handle stations in Costa Rica. Once the tsunami system declares an event based on Costa Rica stations, the normal CASC system will immediately be activated to collect additional information from fast connected stations only.

When the Mexican system is running in Mexico, the possibility to use it in Central America should be studied. In case of establishing the Mexican system in the region, the determination of the epicenter and the magnitude would be with several stations instead of one. This is possible and, in fact, guarantees the most reliable warning by reducing the residuals in the earthquake location (Pacheco, written communication). Also, the possibility to send all the waveforms to CASC via satellite should be analyzed.

Procedure to issue a warning for local tsunamis

The Central American Tsunami Warning Systems (CATWS) uses earthquake magnitude as the trigger for tsunami warning. The magnitude used for this purpose is M_w. All earthquakes with magnitude equal or larger than 7.0 and located near the MAT are considered as potential tsunamigenic events. When a large earthquake occurs in Central America, the Tsunami Warning System is activated and a warning, in case of tsunami, should be issued as soon as possible.

CASC makes a rapid location of the earthquake using the new collection/processing system and short-period stations and one broadband from Costa Rica. If the Central American network is working adequately at the moment of the earthquake, an improved location can be made with that network. The magnitude Mw will be determined automatically with seismograms recorded at the broadband station of Costa Rica. The waveforms are received in real-time from Costa Rica and the complete seismic analysis, that include determination of epicenter and magnitude, can be done. Once the earthquakes is located and the magnitude determined, CASC sends a bulletin containing seismic information to INETER first and to others seismic centers. INETER evaluates the seismic information and if the earthquake is a potential tsunamigenic one, sends a Tsunami

Warning to the National Emergency Office of the countries that are supposed to be affected. A tsunami watch is sent to those offices in the countries where the tsunami will not have extensive damage. The National Emergency Office actives the National Emergency Plan and sends the warning to the Local Emergency Offices at the coastal settlements. The Local Emergency Offices take actions to protect people from the tsunami.

The treatment of distant and regional tsunamis

Two regional tsunamis (one from Ecuador and another one from Chile) and one distant (from Alaska) tsunami have reached the Central American Coasts; the Alaskan Tsunami caused important damage and loss of lives at the Pacific Coast of El Salvador. Considering that, it is expected that future regional and distant tsunamis will hit these coasts again and therefore, coastal residents along them should also be protected from these types of tsunamis. To do this CATWS must be linked to the Pacific Tsunami Warning System throughout the Pacific Tsunami Warning Center (PTWC) or the Alaska Tsunami Warning Center (ATWC). In the event of a regional or distant tsunami the procedure will be the following:

1-PTWC or ATWC sends a tsunami warning to INETER indicating arrival time and height of the tsunami.

2-INETER has to evaluate the tsunami warning and if the height of the arrival tsunami is larger than 1 m, a tsunami warning for Central America should be issued.

3-The tsunami warning will be sent to all the National Emergency Offices of the region.

4-The National Emergency Office will send the warning to the coastal settlements and to broadcasting and TV stations.

5- A tsunami All Clear Bulletin by local authorities when the tsunami threat is over or if no damaging waves has materialized two hours after the estimated time of arrival.

6- A Tsunami Cancellation Bulletin is issued to cancel all previous bulletins and when it is determined that the tsunami threat is over or a wave poses no threat.

Tsunami Response/Education

All tsunami warning system requires an educated response to truly mitigate the effects of the phenomena. This response must be based on the knowledge of the hazard assessment and the warning systems. People and local authorities should know the areas that could be flooded in case of tsunami and the safety areas for the residents to stay. Knowledge of the warning is required to know when to evacuate and when it is safe to return. Without a good response even the fastest warning system could fail when a tsunami threatens the coast. Because the tsunami warning system of Central America is just starting, there is a lot of work regarding tsunami response/education. The first task will be to distribute posters including essential safety rules behavior and Booklets describing the tsunami warning system and what the public can do in time of tsunami warning. Also fully documented information on the past tsunami disasters will be distributed to authorities of coastal settlements of Central America.

Conclusions

There are reports of 9 destructive tsunamis along the coasts of Central America, 2 from the Caribbean and 7 from the Pacific. These have destroyed villages and killed 455 people. The most dangerous tsunamigenic zones are Honduras Gulf and Panama Coast in the Caribbean and the Guatemala-Nicaragua coastal segment in the Pacific. Destructive tsunamis are related to seismic activity in the Polochic-Motagua Fault System, the North Panama Deformed Belt and the Middle American Trench.

The scientific groups of Central America have started mitigating the effect of tsunamis in the region. A Tsunami Warning System has been designed. At the moment, there are difficulties for the system to operate efficiently but it is expected to solve the communication problems in the next years and have a good tsunami warning system in this tsunamigenic zone.

Acknowledgments

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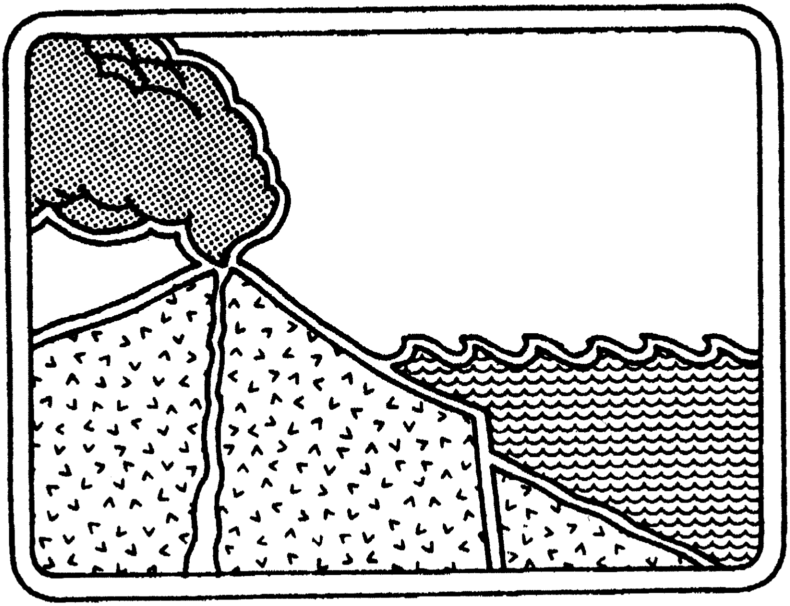

EVALUATION OF TSUNAMI RISK FOR MITIGATION AND WARNING

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ABSTRACT

A hazard is a potentially perilous event, such as a tsunami, while risk is the probability that the hazard will occur repeatedly and affect a specified population. Risk includes the frequency of occurrence, exposure, and magnitude. The International Decade for Disaster Reduction has focussed attention on assessing and mitigating the risk of tsunamis. Statistical and scenario methods of determining risk for rare and more common events are discussed. The problems of warning are emphasized. Examples of evaluation of relative risk are provided.

INTRODUCTION

The problem of estimates of the tsunami risk is very complex and should include human, economic, ecological, and social as well as technical factors. This problem is considered in the literature primarily from the viewpoint of runup characteristics; we will discuss the other factors also.

A hazard is a potentially perilous event, such as a tsunami. Risk is the probability that the hazard will occur repeatedly and affect a specified population. The components of risk are the probable frequency of occurrence (as a function of magnitude of danger) and the number of people (or facilities) exposed. Risk thus deals with the cumulative impacts in an area.

STATISTICAL APPROACH

The mathematical concepts of probability are applicable to the occurrence of natural hazards such as tsunamis. As for any rare event we may apply the methods of extreme statistics. Although the actual frequency distribution of tsunamis is not known, it appears to follow a Poisson distribution. The main characteristic of this distribution is an exceedance (cumulative) frequency of events; from the mathematical theory of extreme statistics (Gumbel, 1958), it is known that the cumulative frequency should be an exponential or power function of the tsunami runup height. When there are sufficient data of historical tsunamis, a statistical approach can be used, and a regression analysis determines the cumulative frequency as a function of tsunami runup height. A well-known example of the applicability of this approach was given by Wigen (1981) for Tofino (Canada), where 31 events occurred during 1906-1976 and by Cox (1964) for Hilo involving 28 events from 1832 to 1964. But for most areas of the world there are relatively small samples of numerical tsunami data, and such a stochastic approach will have a large statistical error. Several examples of the calculation of the cumulative frequency based on a small collection of historical tsunamis have been considered, in particular, for the East Coast of Australia and Sulawesi Island in Indonesia (Pelinovsky, 1996; Pelinovsky et al, 1996).

If the number of historical tsunamis is small in each locality, but enough for a geographic region, a combination of statistical and deterministic approaches may be used. For example, only 20 tsunamis are known for period 1737-1976 for such a large region as Kamchatka (Russia), and few visual observations are recorded. Considering, however, that the tsunami height is largely controlled by the coastal topography and the tsunami behavior in the open ocean is more uniform, it can be assumed that the cumulative frequency of tsunami wave height in the coastal ocean is the same for the whole Kamchatka region. The relationship between the tsunami wave height in the open ocean and the runup height may be estimated from numerical simulation of the deterministic tsunami wave propagation. This approach was used by Go, et al (1988) for estimates of the tsunami risk for the Pacific Coast of Russia.

SCENARIO APPROACH

If there is no valid information about historical tsunamis, only very rough estimates of tsunami risk can be made. For example, there is only one tsunami event in the Caspian Sea for a period of more than 200 years, while on the Mediterranean Coast of Israel for all history, there is only one description which includes a tsunami height (2 -2.5 m), in 1759. Rough estimates of the tsunami risk can be obtained from (i) an analysis of seismicity and extrapolation of the cumulative frequency for earthquakes, using empirical relations between the earthquake magnitude and tsunami wave height; this was used by Pelinovsky (1993) to estimate the tsunami risk in the Caspian Sea; or ii) from the deterministic analysis of possible scenarios of tsunami wave generation, as was used by Miloh and Striem (1978) to estimate the tsunami risk for the Israel Coast.

While calculations with such minimal data can only be crude estimates, they help set priorities for mitigation efforts among various hazards.

ESTIMATION PROCEDURE

The actual hazard may be discussed as the combination of event probability with the other factors which result in an estimation of risk of an event in a specific location, and the possibility of effective mitigation. Table I forms a basis for such analyses.

The matrix may be utilized as follows: available records of reasonable validity are compiled and must be sorted by source distance. The probability of occurrence of an event from each of the three general distance zones may then be estimated. Generally, if there are little or no data there is negligible risk and the analysis need proceed no further, although the study should be complete enough to ease public perception of the hazard. The exception would be a newly settled region but the exposure could be estimated from that of areas of similar exposure (see above). It is important to separate the probability estimates for various sources (distances) because the probability of an effective warning and of specific, feasible mitigation measures varies greatly with this factor.

The risk to a specific person or a structure obviously is limited to and depends on proximity to the shoreline. It is reasonable and fairly simple to consider the populace and facilities within 15 meters elevation above sea level as possibly being at risk, for a preliminary estimate. Considering the probability of a significant risk from all the sources previously evaluated, the human hazard/risk can be developed with respect to feasible mitigation measures. As noted in the table, in a few areas of the Pacific, inundation limits have been estimated by formal means; the use of these greatly reduces the apparent risk by reducing the exposed population. (Curtis, 1990). If there is a risk from distant (tele) tsunamis, ample notice will be available from the Tsunami Warning Centers and if some zonation is in effect the exposed population can be evacuated thus reducing their risk to zero. For closer events, a rapid response regional warning system using only fast seismic data may help reduce the risk if coupled with an immediate evacuation system and an educated public (Cox, 1964). Such warning systems are found in Japan and Alaska.

In the "non-warnable" areas, considered within 20 minutes in the table, the question of warning and evacuation is almost moot; public education to flee coastal areas when the ground shakes in the most useful tool. Of course, with respect to coastal facilities, the warning time is not a significant factor (although some shutdown and boat removal may be possible) and simple zonation may be used to indicate areas in which structures not required to be near the shore (hospitals, schools, theaters, power plants, etc.) should not be built (Morgan, 1982). In a few areas, Flood Insurance Rate Maps (FIRM) or similar maps indicate such zones for tsunamis in addition to stream flooding. Such analyses have been done for Hawaii and American Samoa under a U.S. government flood insurance program, and partially done for areas of Northern California, Oregon, and Japan.

Thus, it is apparent that there is an underlying (or fixed) risk in a coastal area whose probability can be roughly estimated, and a risk to the people in that area. This depends significantly on distance to the source(s) and the presence of an effective warning and evacuation system, as well as education of the public and the officials.

Some additional examples of risk evaluation are illustrative; it is emphasized that these are based on data the authors had on hand and are not intended to represent a full range of probabilities. A location with good historical and numerical records is Hilo, Hawaii. A map showing the actual maximum inundation, block-by-block for four events from 1946 to 1960 is available; thus estimating probable inundation from similar future events requires only minor extrapolation from the envelope of these limits. In addition, a probability plot of all events since 1832 was constructed by Cox, (1964). Although the actual source of some of these heights is unknown, it enables a reasonable estimate of the probability of tsunamis of a general magnitude. A plot of wave heights from the only local tsunami in the last 100 years was also shown, which indicated a low probability of occurrence, and with only modest waves in Hilo coupled, however with inadequate time for an effective warning nearer the geologically-expected source areas. By using all these data together, the probability of significant tsunamis for this specific location can be estimated.

An example of another category is the Oregon-California coast of the U.S. Here the two sources to be considered are Alaska-Kamchatka and the Cascadia fault area. Some records are available for the 1946, '52, '57, and '64 tsunamis, with 1964 as the most significant, with good records for Crescent City California. For Cascadia there are geological indications (and a probable record) of a 300 year event probability; however the fault is too close to the locale for an effective warning. Thus, there is a small statistical risk from the offshore source, with structural/usage zonation as possible mitigation tool but a considerably higher risk of a warnable Alaska event. Inundation and/or wave height analysis (by model) has been done for Humboldt Bay, Crescent City, and the Oregon Coast for a Cascadia event only. The risk from an Alaska-Kamchatka source remains relatively high for some locales in this region. History and some modeling indicates an extremely variable probability of damaging inundation on this coast and risk reduction would require careful evaluation for the inhabited sections along this coast.

FINAL CONSIDERATIONS

1. The social and economic factors of tsunami risk should be involved in any analysis in addition to the physical and statistical considerations discussed above.

2. Available data and analyses should be used to make a basic but quantitative assessment of tsunami risk for areas of the Pacific, and such assessment used to prioritize locations of higher risk for more intensive study. We believe this is presently feasible.

3. Development of mitigation measures should proceed in those high risk areas, but with due consideration of economic and social factors. Risk from other natural hazards must also be considered in a realistic analysis of risk and mitigation.

4. Risk probability statistics should be presented to officials and the public only with caution, and in terms they understand, and they must accept that are only estimates. One statement that is always true and may be most useful is: the longer since the last one, the nearer the next one.

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TSUNAMI RISK ASSESSMENT

FACTOR		COMMENTS
EVENT PROBABILITY		
GEOLOGIC INFO HISTORICAL RECORDED DATA	BY SOURCE	CRUDE PROBABILITY STATISTICS ARE DEVELOPED FROM THESE DATA
EFFECTIVE WARNING PROBABILITY		
LOCAL - <0.4 HR	-----	NONE - EDUCATION FOR OWN ACTION
REGIONAL - 0.4><2 HR	-----	MAYBE - QUICK RESPONSE SYSTEM; EDUCATION;SIMPLE ZONES
DISTANT - > 2 HR	-----	GOOD - PTWC; ZONES; EVACUATION SYSTEM; EDUICATION
LOCATION RISK		
COAST - UNKNOWN	-----	MOST AREAS
< 15 METERS RE MSL	-----	EASILY DETERMINED
IN KNOWN INUNDATION ZONE	-----	HAWAII, SOME JAPAN, OREGON IN PROGRESS; ALL MARINE FACILITIES

ALL THESE FACTORS MUST BE CONSIDERED TO EVALUATE THE SPECIFIC RISKS IN AN AREA AND DETERMINE WHAT ACTION, IF ANY, MAY BE WARRANTED

Table I

ANALYSIS OF MECHANISM OF TSUNAMI GENERATION IN LITUYA BAY

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ABSTRACT

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, were generated by a combination of disturbances triggered by a large, 8.3 magnitude earthquake along the Fairweather fault. Several mechanisms for the generation of the giant waves have been proposed, none of which can be conclusively supported by the data on hand. Generative causes include a combination of tectonic movements associated with the earthquake, movements of a tidal glacier front, a major subaerial rockfall in Gilbert Inlet, and the possible sudden drainage of a subglacial lake on the Lituya Glacier.

The following mechanism can account for the giant 1,720 foot wave runup at the head and the wave along the main body of Lituya Bay: The strong earthquake ground motions triggered a giant rockfall at the head of the bay. This rockfall acted as a monolith, and thus resembling an asteroid, 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. 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 water splashing action that reached the 1,720 foot elevation. The rockfall impact in combination with the net vertical crustal 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.

INTRODUCTION

The Lituya Bay Earthquake of July 9, 1958

On July 9, 1958, a large earthquake caused by tectonic movements along the Fairweather Fault struck Southeastern Alaska. Its epicenter was at lat 58.6'N., long 137.1`W., at a point near the Fairweather Range about 7.5 miles (12 km) east of the surface trace of the Fairweather fault and 13 miles (20.8 km) southeast of the head of Lituya Bay (Fig.1). The earthquake had a magnitude of 7.9, on the Richter Scale, although some sources have reported it to be as much as 8.3. (Brazee & Cloud, 1960).

This was the strongest earthquake in the region since the September 4, 1899, 8.2 magnitude, Cape Yakataga earthquake. The shock was felt at all cities in southeastern Alaska over an area of 400,000 square miles, and as far south as Seattle in the state of Washington, and as far eastward as Whitchorse, Y.T., Canada.

Ground displacements of 3.5 feet (1.05 m) upward and 21 feet (6.3 m) in the horizontal plane were measured on surface breaks along the Fairweather fault 6 to 10 miles southeast of Lituya Bay's Crillon Inlet (Tocher and Miller, 1959). It is presumed that similar displacements occurred along the Crillon and Gilbert inlets at the head of Lituya Bay.

The Giant Waves

Almost immediately, the earthquake of July 9, 1958, was followed by a massive wave that splashed to a maximum height of 1,720 feet on the southeast spur of Gilbert Inlet at the headland of Lituya Bay, then by a wave that wiped everything in its path over an area of about 4 square miles (10.4 sq. kms) on either side of the Bay.(Fig. 2)

There were three fishing boats anchored near the entrance of Lituya Bay on the day the giant waves occurred. One boat was sunk and the two people on board lost their lives. The other two boats were able to ride the waves. Among the survivors were William A. Swanson, and Howard G. Ulrich, who provided accounts of what they observed. Miller (1960) documented in great detail all accounts, measurements, and observations related to the giant waves in Lituya Bay. Waves of cataclysmic proportions have repeatedly occurred in Lituya Bay in the past (Miller, 1954). Because of the unique geologic and tectonic conditions of Lituya Bay, giant waves will undoubtedly occur again in the future.

Tectonic Setting

The Pacific and the North American tectonic plates move in complex, irregular patterns resulting in earthquakes with faulting that differs along their boundaries. The Fairweather fault in Southeastern Alaska marks one of these boundaries. To the south, in the vicinity of California, the boundary is marked primarily by a large transform fault system which is the San Andreas and the numerous secondary faults. The San Andreas fault is also the boundary between the Mendocino fault separating the Gorda and Pacific plates.

Immediately north of this area is the Cascadia subduction zone which marks the boundary between the Gorda and Juan de Fuca plates offshore and the North American plate. The Gorda plate is the block being subducted beneath the North American plate. However, a thrust fault of this type slopes gently relative to the earth's surface. Earthquakes along such a thrust fault push the rock above the ramp up and over the rock beneath it. In very active subduction zones, the boundary between the plates resembles a giant thrust fault, which usually extends for hundreds of miles in length. The locked part of the subduction interface is known as the megathrust. All of the worlds greatest earthquakes (with moment magnitude of 8.5 and larger) which have produced Pacific-wide tsunamis, are associated with ruptures of megathrusts along steeper angles.

The Fairweather fault in the vicinity of Lituya Bay, differs. It is not acting as a thrust fault but as a transform fault, but with substantial vertical movement of the oceanic crustal block upward. The great 1899 earthquake on the Fairweather, caused some dramatic vertical changes. Both the Crillon and Gilbert inlets at the head of Lituya Bay, and their extensions covered by glaciers on either side for a total distance of 12 miles, have been formed by trenching action along the Fairweather fault. The inlets themselves and the entire Bay are part of the oceanic plate, which actually rose by about 3.5 feet in this particular area, as a result of the July 9, 1958, earthquake. The fault line traverses the entire head of the Bay on the northeastern side of the inlets.

Geologic Setting

The entire Lituya Bay represents a valley carved by glaciers which begun retreating when the Wisconsin interglacial period begun, nearly ten thousand years ago. The U-shaped floor at the head of the Bay is underlain by recent terminal moraine deposits as well as from deposits of previous glaciation during the Tertiary period. The entrance to the bay is marked by a long spit, La Chaussee Spit, which is the remnant of an arcuate terminal moraine from the last period of glaciation (Fig.1).

Bathymetry

Bathymetric surveys made in 1926 and 1940 (U.S. Coast and Geodetic Survey, 1942), show the head of Lituya Bay to be a pronounced U-shaped trench with steep walls and a broad, flat floor sloping gently downward from the head of the bay to a maximum depth of 720 feet just south of Cenotaph Island. From there, the slope rises toward the outer part of the Bay. At the entrance to the Bay, the minimum depth is only 33 feet at mean lower low water. The outer portion of Lituya Bay is enclosed by La Chaussee Spit, with only a very narrow entrance of about 700-800 feet kept open by tidal currents. The tide in the bay is diurnal, with a mean range of 7 feet and a maximum range of about 15 feet (U.S. Coast and Geodetic Survey, 1957). The U-shape of the bay and the flatness of its floor indicate that extensive sedimentation has taken place, but the thickness of the sedimentary layers is not known.

ANALYSIS OF SOURCE MECHANISMS

It has been well documented in the scientific literature that waves with large energy content are generated impulsively by different mechanisms related to large earthquakes in regions of subduction, to volcanic and nuclear explosions, to landslides, and to large masses of water added suddenly to a body of water. To these we must also add the impulsive impacts from large rockfalls or from asteroids and comets falling on a body of water on earth. The characteristics of waves generated by such impulsive mechanisms will depend upon the disturbing force and the rate at which the force is applied. Resulting water waves may be oscillatory in character, nearly solitary in form, a complex non-linear wave existing entirely above the initial undisturbed water surface, or a bore (Prins, 1958a, 1958b).

The giant 1958 wave that rose to a maximum of 1,720 feet at the head of of Lituya Bay. and the subsequent huge wave along the main body the Bay, were caused by an impulsive event with a very large energy content. The mechanism that generated the giant wave runup of 1,720 feet above sea level has been a mystery that has baffled scientists. That such a giant wave is possible has been extensively doubted on theoretical grounds. Several mechanisms have been proposed, none of which can be conclusively supported by the data.

The giant wave must have been generated by a combination of disturbances triggered by the large earthquake. Factors that contributed were the result of cumulative effects rather than those from a single source. Generative causes included a combination of tectonic movements associated with the earthquake, movements of a tidal glacier front, the possible sudden drainage of a subglacial lake on the Lituya Glacier, but primarily as this study proposes, a major subaerial rockfall into Gilbert Inlet. In this paper we shall review and comment on all such impulsive mechanisms.

Landslide Mechanism

Landslides are not very effective mechanisms for tsunami generation. The energy imparted to the water body is about 4% of the total energy. No known landslide ever produced a wave that would approach the magnitude of the Lituya Bay event. The runup of 1,720 feet is more than 8 times the maximum height reached by the largest of the slide-generated waves in Norway. Simple displacement of water by material of an ordinary landslide cannot account for the 1720 foot runup observed on the other side of Gilbert inlet. Dr. Mader's modeling studies confirm that such high runup from such mechanism was not possible.

Tectonic Mechanism

Similarly, fault displacement could not have been an important contributing mechanism to the generation of the giant wave that reached the 1,720 ft. elevation at the spur of Gilbert Bay. As indicated previously, the Fairweather fault line in the vicinity of Lituya Bay, lies near the northeast side of Gilbert and Crillon Inlets. The earthquake resulted in tectonic displacements which were primarily in the horizontal plane. There was an upward movement of 3.5 feet and a horizontal movement of 21 feet.

Even if we assume that nearly the entire area under water at the head of Lituya bay moved relatively northwestward and up by 3.5 feet, such tectonic movement could not have displaced enough water to generate the extreme runup or the wave observed subsequently in the Bay. The wave motion resulting from such tectonic displacement should have been directed toward the northwest and southeast side of the bay and (or) toward the head of the bay. Vertical displacement of the bottom of the bay along the Fairweather fault would have generated waves as a line source across the head of the bay. However, according to eyewitnesses reports, this was not the case as there was a lapse ranging from 1 to 2.5 minutes between the onset of the earthquake and the first sighting of the wave at the head of the bay. Also, the eyewitness accounts and the subsequent observations indicated a wave source mechanism that resulted in a radial pattern of propagation from a point source in Gilbert Inlet. In conclusion, a tectonic mechanism alone could not displace sufficient volume of water to account for either the extreme runup at the head or the subsequent wave inundation in Lituya Bay. Also, Dr. Mader's modeling studies confirm it.

Sudden Glacial Lake Drainage Mechanism

A partly subglacial lake exists just northwest of the sharp bend in the Lituya Glacier at the head of Lituya Bay . Following the earthquake of July 9, 1958, an observation was made that the level of the lake had dropped by about 100 feet. Therefore a mechanism of sudden drainage of a large volume of water from this glacial lake has been s considered as the cause of the giant 1958 wave. However, such mechanism would also be unlikely for the following reasons. To hypothesize the great 1720 ft. runup from such mechanism, not only a great volume of water would need to be ponded in a chamber at an elevation high enough to produce the necessary hydraulic head, but a strong triggering mechanism would be needed to cause its sudden drainage into Gilbert Inlet.

Certainly the earthquake displacements and ground motions were sufficient to perhaps trigger such an event. Therefore, the remaining questions are: a) was there enough water drained to cause the 1720 ft. wave? b) was the hydraulic head high enough and the rate of drainage sudden and fast enough to account for the large runup? c) did the water roll down the face of the glacier or was it suddenly released beneath the glacier or through an ice tunnel below sea level in the front of Gilbert inlet?, and d) did subsequent wave inundation of the coast line in Gilbert and Crillon inlets as well as in the Lituya Bay validate such mechanism?

In answer to these questions the following can be said. The hydraulic head was high enough. However, there was no physical evidence that sudden drainage of the lake on the surface of Lituya glacier itself occurred. Since the water level was 100 feet lower following the earthquake, it is quite possible that a fairly large volume of water drained from the glacial lake through some glacial tunnel and resulted in some sudden up welling immediately in front of the glacier. It is believed that neither the volume of water nor the rate of drainage would have been sufficiently high to account for the 1720 ft. wave or to justify the subsequent wave observed in the Bay. Finally, given that such drainage would have occurred in front of Lituya Glacier, maximum runup would have been expected on the opposite side in Crillon inlet, rather than at the spur on the southwestern corner of Gilbert inlet. In view of these considerations, it can be concluded that sudden glacial drainage was not the mechanism that produced the extreme giant wave in Lituya Bay. There was not sufficient volume of water and the drainage was not sufficiently impulsive. Dr. Mader's modeling studies confirm also that this could not have been the mechanism.

Impulsive Rockfall Impact Mechanism

The giant wave runup of 1720 feet at the head of the Bay and the subsequent huge wave along the main body of Lituya Bay were caused primarily by the enormous subaerial rockfall into Gilbert Inlet (Fig. 3). The triggering mechanism of this rockfall and the effects that it produced were significantly different from those of subaerial or submarine landslides. This was not a gradual process as with a landslide, but a very sudden event. The giant rockfall was triggered impulsively. Thus, the term rockfall rather than rockslide or landslide, is used to distinguish this particular type of phenomenon and to explain the subsequent effects of its impulsive impact. In some respects, corrected for scale factors of mass, terminal velocity and angle of entry, the impact of this rockfall into Gilbert Inlet could be considered analogous to that of an asteroid falling on earth. To explain the impulsive mechanism of wave generation from such impact we must first examine the time history of events immediately following the onset of the earthquake and the intense ground motions and accelerations that triggered the rockfall.

Strong Ground Motions

Little is known about the ground motions in the immediate area at the head of the Bay. There were no strong motion recordings of this event. However, because of the proximity of the upper Lituya Bay to the epicenter and because of the geometric orientation with the Fairweather fault, the surface waves and the strong ground motions begun almost immediately after the onset of the earthquake. For an earthquake of this magnitude, it would be expected that the strong ground motions lasted anywhere from 40-60 seconds or even 90 seconds, perhaps with some interruption, but probably peaking at about 20-25 seconds after the beginning of the quake.

Intensities and Accelerations

The ground motions associated with the earthquake were of very high intensities. Eyewitness accounts confirm it. Survivor Swanson situated on a boat anchored near La Chaussee Spit close to the bay entrance, reported seeing the whole Lituya Glacier moving up and down. This may have been an optical illusion as the Lituya Glacier was out of his line of sight. However what he probably observed could have been happening on the other side of Gilbert inlet where a giant rockfall was triggered, or could have been ice going over the spur on the southwest wall of the inlet when the 1720 foot splash occurred.

An isosmeismal map of the U.S. Geological Survey indicates a distribution of high earthquake intensities from which we can infer very strong ground motions during the earthquake (Fig. 4). Maximum intensity of XI was reported in the main part of the Bay, although closer to the fault, at the head of the Bay, an intensity of XII is very possible. Earthquake ground motions of such high intensity (XI, XII on the Modified Mercalli scale) could have resulted in vertical accelerations of up to 0.75g and horizontal accelerations of as much as 2.0g. Such ground accelerations would have caused the movement of ice observed by Swanson.

In the absence of adequate data for the Lituya Bay event to support these assumptions, analogies can be drawn from recorded recent large earthquakes elsewhere. For example, such high horizontal and vertical accelerations were associated with the 17 January 1994, Northridge earthquake in California. This earthquake, although of moderate 6.7 magnitude, produced vertical accelerations of as much as .75 g, horizontal accelerations of 2.0 g. and caused extreme and unexpected damage in San Fernando Valley (Fig. 5). The Northridge earthquake occurred along the White Wolf fault in the Transverse Ranges north of Los Angeles which, in contrast to other segments of the San Andreas fault system, is characterized primarily by transform faulting, similar to what occurs along the Fairweather fault.

Scenario and Time History of Events

The 8.3 magnitude earthquake of July 9, 1958 in Lituya Bay was associated with ground motions of high intensity which, as with the Northridge earthquake, could have resulted in very high ground accelerations near the head of the Bay. Such strong motions and accelerations must have been present to trigger the extreme events which subsequently occurred, almost immediately following the earthquake. Eyewitness accounts and subsequent measurements support the following scenario of events and impulsive rockfall impact mechanism.

Beginning at about 10:16 p.m. on July 9, 1958, within 15-20 seconds following the onset of the earthquake, the southwest side and probably most of the bottom of Gilbert and Crillon Inlets begun to move northwestward and up relative to the northeast shore at the head of Lituya Bay, on the opposite side of the Fairweather fault. Because of the proximity to the epicenter and to the fault, strong ground motions peaked within 25-30 seconds. Within 50 to 60 seconds, net tectonic displacements had pushed the entire inlet and its extensions along the Crillon and Lituya Glaciers by 3.5 feet upward and 21 feet in the horizontal plane, tilting the entire Bay in a seaward direction. These tectonic displacements are supported by observations of the surface breakage along the Fairweather fault 6 to 10 miles southeast of Crillon Inlet (Tocher and Miller, 1959).

Intense shaking in Lituya Bay continued for at least 1 minute according to the account of Swanson, and possibly as much as 4 minutes according to Ulrich. However, it is doubtful that the earthquake shaking could have lasted as long as 4 minutes as Ulrich reported.

During the first 50-60 seconds, the tectonic displacements, in combination with the stronger ground motions and high vertical and horizontal accelerations of surface seismic waves, weakened a large slab of rock on the precipitous northeast shore at the head of Lituya Bay. Both Ulrich's and Swanson's accounts, indicate almost certainly that the rockfall was triggered by the earthquake. According to eyewitness Ulrich, a deafening crash, resembling an explosion, was heard at the head of the bay approximately 2.5 minutes after the earthquake was first felt. He also reported that the wave definitely started in Gilbert Inlet, just before the end of the quake. According to him the water did not go up to the 1,720 foot elevation, but splashed to that elevation. However, the timing of the explosion sound and the appearance of the wave are somewhat inconsistent in his account. As it was indicated above, for an earthquake of that size, the ground motions would not have lasted more than 60-90 seconds. A wave would not have appeared before the explosion sound. The other eyewitness, Bill Swanson, reported seeing the glacier riding high into sight from behind the western mountain, followed by a great wave of water washing over its steep face.

In spite of some uncertainty in the chronology of events, the accounts support the following conclusions: No less than 50-60 seconds and no more than 150 seconds after the earthquake begun, a large mass of rock material along the very steep mountain side on the northeast side of Gilbert Inlet at the head of Lituya Bay, on the other side of the Fairweather fault, cleaved and ruptured. The giant rock mass had more than 40 million cubic yards of material and extended as high as 3,000 feet, with a center of gravity at about 2,000 feet above sea level. Driven by gravity force of almost 1g, this rock mass plunged practically as a monolithic unit into Gilbert Inlet at a very steep angle of perhaps as much as 75-80 degrees, as the sides of the Bay were truly precipitous. The rockfall left a giant scar on the mountain. The impact of the large rockfall on the surface of the water was the explosion-like sound heard by Ulrich. The impact of this mass of rock, not only displaced with great force the water but struck the bottom of Gilbert inlet and created a large radial crater, displacing and folding an equivalent volume of recent glacial sediments and deeper semi consolidated Tertiary layers, to an arcual distance estimated to be least 800 feet out from the front of the precipitous shore.

The sudden rockfall impact, the displaced water, and the folding of the bottom sediments, in combination with the dynamic ground motions, sheared 1300 feet of ice from the entire Lituya Glacier front, leaving a vertical wall of ice almost normal to the trend of Gilbert inlet. Also, the rockfall impact generated a non-linear wave existing entirely above the initial undisturbed water surface, which splashed as a sheet of water to the 1720 foot elevation on the other side of Gilbert inlet, three times the water depth.

The rockfall impact, with some contribution from the net vertical crustal uplift of about 3.5 feet, and from the overall tilting seaward of the entire crustal block on which Lituya Bay was situated, generated a solitary gravity wave. This huge wave originated in Gilbert inlet and propagated outward the head of the Bay where its height was estimated at 100 feet or even much greater by Ulrich. Because of its point origin and initial orientation the wave moved in a southerly direction striking first against the steep cliffs on the south side of the main bay in the vicinity of Mudslide Creek where maximum runup occurred. Then the wave reflected and refracted toward the north shore into the main portion of Lituya Bay, and again back to the south shore near the vicinity of Coal Creek. Time estimates by eyewitnesses Ulrich and Swanson of the time elapsed from the first sighting of the wave at the head of the bay until it reached their boats, indicate that the wave must have been traveling at an average speed ranging between 97 and 130 miles per hour, at least in the deeper portion of the bay south of Cenotaph Island.

Navier-Stokes Verification of the Lituya Bay Impulsive Rockfall Source Mechanism - Asteroid Model Validation

An analytical solution of this impulsive rockfall mechanism can further support the 1720-foot runup at the spur of Gilbert inlet and the giant wave in Lituya Bay. Preliminary modeling by Dr. Charles Mader shows that there is a sufficient volume and an adequately deep layer of water to account for the giant wave runup and the subsequent inundation. Dr. Mader suggested full Navier-Stokes modeling, as with asteroid generated tsunami waves.

Because of the similarity of wave generation to that of asteroid impact, full Navier-Stokes modeling of this impulsive rockfall mechanism may be useful also in the validation of the asteroid model. With proper scale corrections, analogies can be drawn between the impulsive impact of the Lituya Bay rockfall to asteroid impact on ocean floor sediments and on wave generation. Although, the trajectory angle, terminal velocity and total mass and density of material of an asteroid would be significantly different, these can be scaled and adjusted for the purpose of validating the model. For example, an asteroid would be expected to approach the earth at a much lower angle of perhaps only 15 degrees from horizontal and may impact the ocean with a terminal speed which may be 20 km/second or more. Because of differences in mass, trajectory angle, and speed at impact, the effects on the ocean floor will be markedly different, but these too could be scaled.

For example, even a small asteroid of perhaps the same dimensions and mass would be expected to disturb the ocean sediments to a far greater extent than the gravity driven rockfall of Lituya Bay. A small asteroid of only 1/3 mile in diameter falling in the ocean at 20 km /second at a low angle of entry, would be expected to carve a path of at least twelve miles on the ocean floor and to create a much larger cavity which would be cylindrical rather than radial. Horizontal and vertical accelerations of seismic waves from asteroid impact may be much greater. However, because of the lower trajectory angle of entry, wave generation and splashing action to a nearby shoreline will not be as great as that caused by the Lituya Bay rockfall. Also, a hard basalt ocean bottom with a thin layer of sediment may not cause the same effect as the Lituya rockfall on softer sediment layers. Yet, in spite of differences, analogies could be drawn. Known input and wave runup output parameters of the rockfall can be used, first to calibrate the Lituya Bay model, then to validate the asteroid model.

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, can 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.

Additionally, since the incompressible Navier-Stokes equations are used to describe tsunami propagation in deep water following the impact of an asteroid on the ocean, and since these equations have limited direct application in shallow water and no application at all when turbulent, chaotic processes are encountered, the Lituya Bay rockfall and its subsequent wave generation can be used to further refine, calibrate and validate a model where turbulent flow and friction are significant factors in determining the extent of inundation. For example, based on the measured parameters of inundation, speed, and water particle velocities of the giant 1958 Lituya Bay waves, coefficients of friction can be derived empirically. These coefficients can be used to estimate more realistically wave attenuation over a land mass, of an asteroid-generated tsunami as it travels chaotically past the sea-land boundary.

SUMMARY AND CONCLUSIONS

The giant wave runup of 1720 feet at the head of the Bay and the subsequent huge wave along the main body of Lituya Bay which occurred on July 9, 1958, were caused primarily by an enormous subaerial rockfall into Gilbert Inlet at the head of Lituya Bay, triggered by dynamic earthquake ground motions. The large mass of rock, acting as a monolith and thus resembling an asteroid, impacted with great force the bottom of the inlet. The impact created a crater which displaced and folded recent and Tertiary deposits and sedimentary layers. The displaced water and the folding of sediments broke and uplifted 1300 feet of ice along the entire front of the Lituya Glacier. Also, the impact resulted in water splashing action that reached the 1720 foot elevation on the other side of the inlet. The same rockfall impact, in combination with strong ground movements, the net vertical crustal uplift of about 3.5 feet, and an overall tilting seaward of the entire crustal block on which Lituya Bay was situated, generated the giant solitary gravity wave which swept the main body of the bay.

Mathematical modeling studies conducted by Dr. Charles Mader, support this mechanism as there is a sufficient volume and an adequately deep layer of water in the Lituya Bay inlet to account for the giant wave runup and subsequent inundation. Because of the similarity to asteroid generated tsunami waves, full Navier-Stokes modeling, as suggested by Dr. Mader, could further verify this impulsive rockfall mechanism. Measurable output parameters derived from mathematical modeling and analysis of the Lituya Bay event, adjusted for scale, can be applied to the calibration, verification and validation of asteroid models of tsunami generation. Based on measured parameters of inundation, speed, and water particle velocities of the giant 1958 Lituya Bay waves, coefficients of friction can be derived empirically which may be used to estimate more realistically attenuation over a land mass, of an asteroid-generated tsunami as it travels chaotically past the sea-land boundary.

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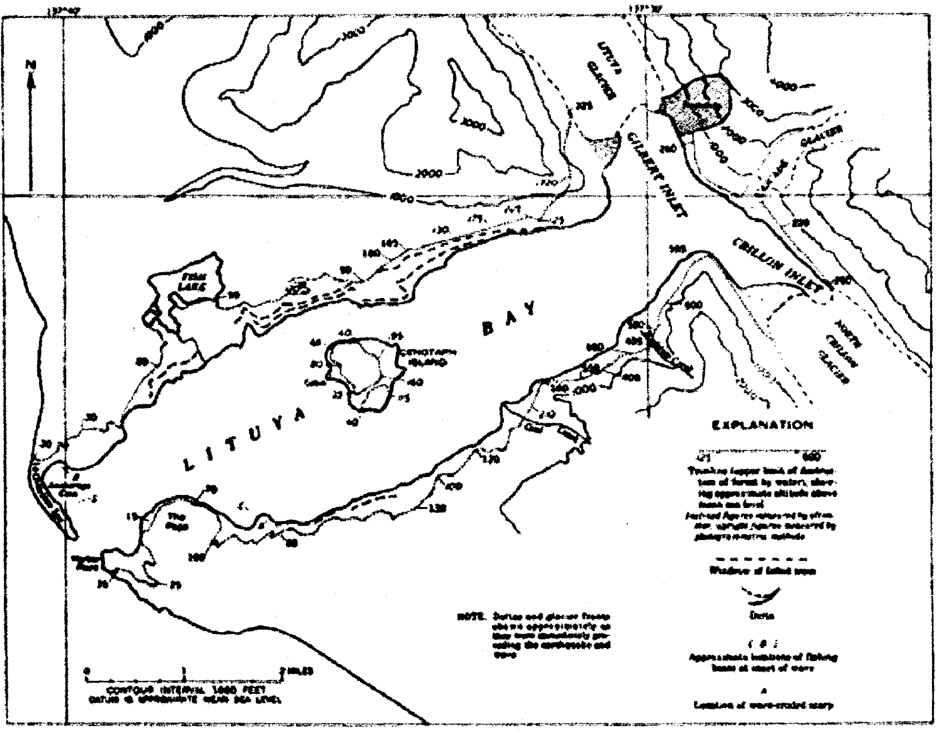

Figure 1. Map of Lituya Bay showing setting and effects of 1958 giant wave. (After Miller, 1960)

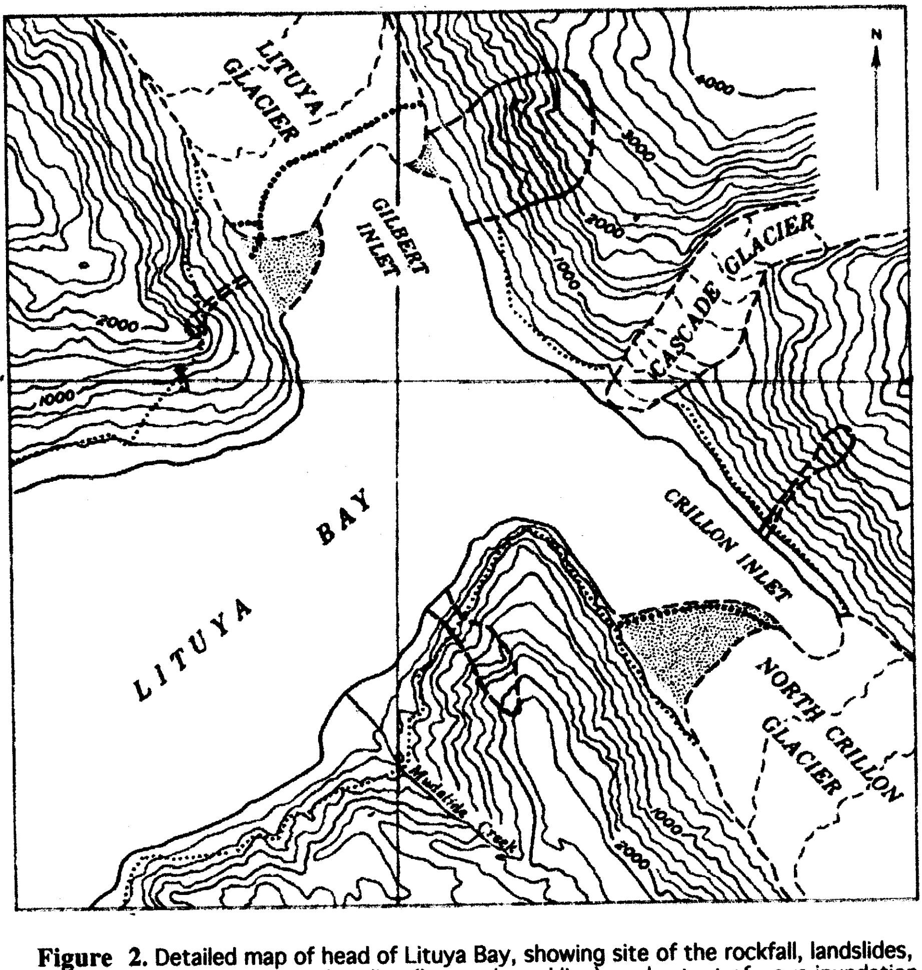

Figure 2. Detailed map of head of Lituya Bay, showing site of the rockfall, landslides, Changes in the shoreline (heavy dotted line), and extent of wave inundation (light dotted line) from the 1958 earthquake and the giant wave it triggered. Lighter barred line depicts shoreline just prior to the earthquake and wave. (Modified after Miller, 1960)

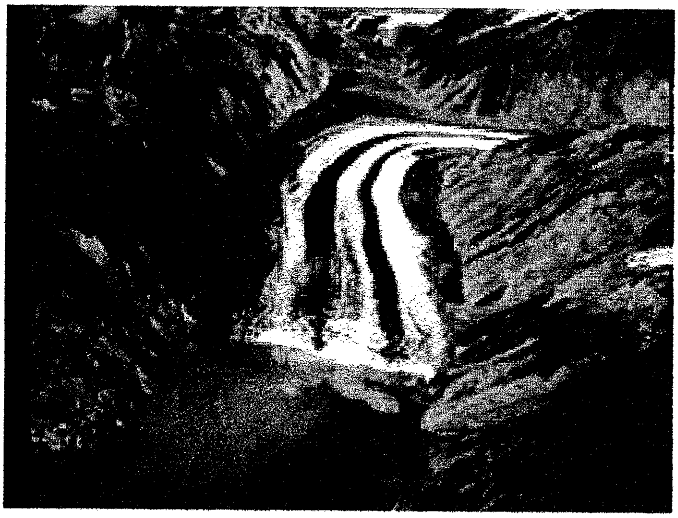

Figure 3. U.S.G.S. photograph showing an aerial view of Gilbert Inlet taken after the earthquake of July 9, 1958, showing the Lituya Glacier, the scar left by the enormous subaerial rockfall (right side of the photo), and the effect of the giant wave runup of 1720 feet at the southeastern spur (left side of the photo) in clearing all trees and vegetation.

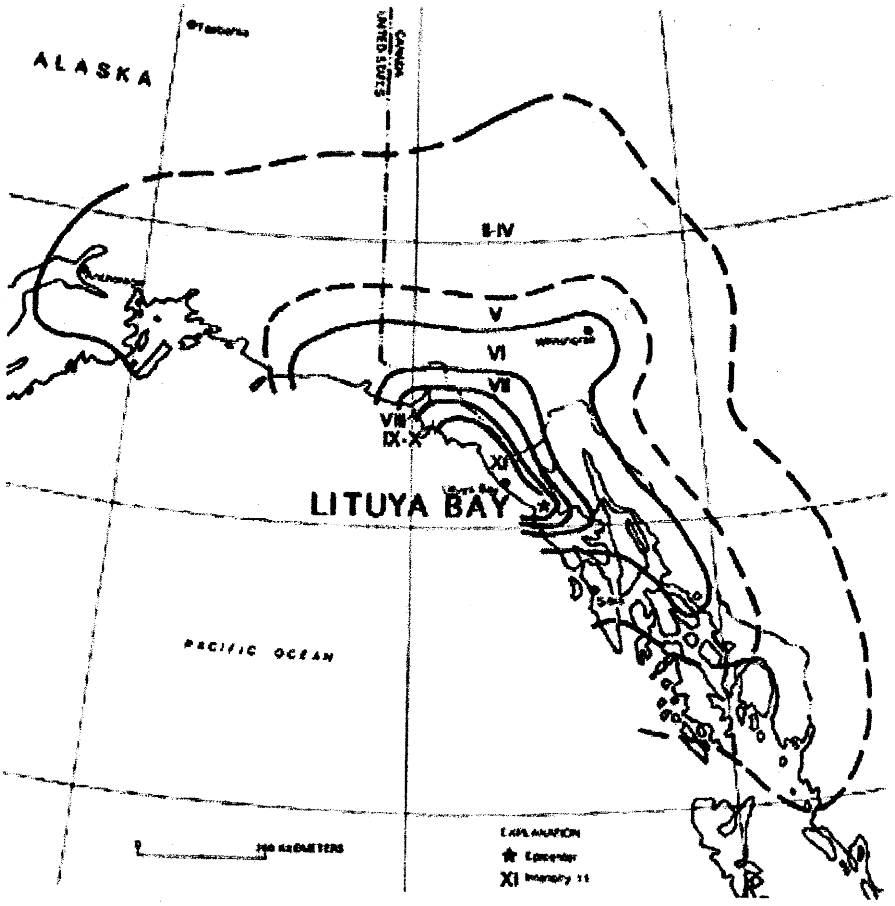

Figure 4. Isosmeismal map of the earthquake of July 9, 1958 showing distribution of intensities from which very strong ground motions can be inferred for Lituya Bay. (Modified after a U.S. Geological Survey map).

BOOK REVIEW

Tsunami!
Second Edition

by Walter Dudley and Min Lee

University of Hawaii Press, Honolulu, 1998

Ten years after publication of their unique paperback *Tsunami!*, Dudley and Lee have produced a new edition that is more than twice as long, fully updated, and far more comprehensive. Although the table of contents is largely the same, the emphasis has moved away from Hilo – the focal point for U.S. tsunamis – to a deeper, and wider treatment of the subject. The edition retains a mix of personalized information, scientific data, and history told in a style that satisisfies both technical and lay readers.

Actually, publication of the original version produced many more contacts, stories, and photos that the authors have built on to enable major additions and improvements, resulting in far more than a "second edition". For example, a new first-person account of the 1975 local tsunami in Hawaii brings the tragedy out in more detail. Observation of tsunami waves offshore visually and by radar will be new to many researchers. Portions dealing with the warning systems and research to improve them are current and comprehensive. Historic Japanese tsunami examples are included.

New chapters deal with very recent tsunamis in several Pacific locations, which show the scope of the threat; however these lack the depth of the other sections and seem more "newsy". Readers will, however, find them factual and concise accounts of events they may recall from media reports. These stories do emphasize the need to prepare for tsunamis in places such as Hawaii, where we have not experienced a Pacific-wide damaging tsunami since 1964.

Progress in such preparations on the U.S. West Coast is reported, as the need there was formally recognized, and Federal funds became available. Such sections and the problems in obtaining such support and funds, will benefit politicians and those who have to deal with them in matters of public safety. Although the book mentions that the tsunami inundation project underway on the West coast will continue to Hawaii in 1999, the evacuation and zoning program was accomplished in Hawaii in 1991 with funds milked out the the Hawaii legislature; and the methodology was later used for two regions of California by University of Hawaii researchers. There are other minor ways the book could benefit from more review, but it will undoubtably become a reliable guide for the public and researchers, just as the original edition has. In fact, the only real problem with the publication is the cover; it suffers from the current fad of a type of stock that is enameled on one side and so curls up in a humid coastal climate – where it is published. Let us hope the UH Press corrects that in the next printing!

Reviewed by George D. Curtis, University of Hawaii-Hilo and
Joint Institute for Marine and Atmospheric Research

THE TSUNAMI SOCIETY AWARD

In Recognition of Outstanding and Original Contributions to the Science of Tsunami Hazards

May 26, 1999 - The First Tsunami Symposium

Dr. Doak C. Cox

Dr. Cox created Hawaii's first tsunami evacuation map and dedicated himself to collecting historical data on the effects of Hawaii tsunamis. His work provides the data base for evaluating tsunami hazards and testing tsunami models.

Mr. George D. Curtis

Mr. Curtis is the Tsunami Advisor to Island of Hawaii Civil Defense Agency and spent a decade developing the present Hawaii tsunami evacuation maps.

Dr. Augustine Furumoto

Dr. Furumoto is the Hawaii State Tsunami Advisor. He developed a method for evaluating the tsunami risk to Hawaii based on an earthquake's source.

Dr. Daniel A. Walker

Dr. Walker is the Oahu Civil Defense Tsunami Advisor. He has used his own money to develop tsunami hazard literature and has taught thousands of children how to save their lives in the event of a tsunami. He also developed and placed tsunami inundation measurement devices across the state at his own expense.

Mr. James F. Lander

Mr. Lander is retired from the National Oceanic and Atmospheric Administration where he continues to collect and publish tsunami data and to alert areas of the world, such as the Caribbean, to the tsunami hazards they face.

The Honolulu Star Bulletin headlined an article describing the Tsunami Society Awards as "THE FABULOUS FIVE" and stated "five retired scientists - four from Hawaii and one from Colorado - have been recognized by the Tsunami Society for their outstanding and original contributions to the science of tsunami hazards."

The awards were presented at the First Tsunami Symposium Banquet. An engraved plaque was presented by Awards Chairman Dr. T. Murty to each of the fabulous five. They also received the high Hawaiian honor of a Maile lei.

FIRST TSUNAMI SYMPOSIUM

Front Row, Left to Right

1. Dale Domeney-Howes, 2. Daniel Walker, 3. Tom Sokolowski, 4. Jonathan Nott, 5. Glenn Shepherd, 6. xxxxxxxxxx, 7. Gerald Fryer, 8. Corrine Lander, 9. Mario Ferandez, 10. Jackie Miller, 11. Barbara Keating, 12. Allan Morton, 13. Edward Myers

Second Row, Left to Right

14. Charles Mader, 15. Emma Jean Mader, 16. Tad Murty, 17. Gus Furumoto, 18. Jack Hills, 19. Patrick Goda, 20. Jim Lyons, 21. James Lander, 22. Charles McCreery, 23, Karen O'Loughlin, 24. Richard Hagermeyer, 25. xxxxxxxxxx, 26. George Curtis, 27. Jack Rynn, 28. Ian Hutchinson, 29. Johndale Solem, 30. S. I. Iwasaki, 31. Michell Teng

Others Attending Symposium

Erik Asphaug, Michael Blackford, Doak Cox, Jocelyn Davies, E. A. Felton, Dennis Nottingham, Tom Schroeder, Coastas Synolakis, Stuart Weinstein, Brian Yanagi.

Be in the next Tsunami Symposium Group Photograph at the UH East-West Center, Honolulu, Hawaii

SECOND TSUNAMI SYMPOSIUM - May 28-30, 2002

Application for Membership

THE TSUNAMI SOCIETY
P. O. Box 25218
Honolulu, Hawaii 96825, USA

I desire admission into the Tsunami Society.

NAME ______________________________

ADDRESS ______________________________

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Telephone/FAX ______________________________

E-MAIL ADDRESS ______________________________

Mail Registration to The Tsunami Society, P. O. Box 25218, Honolulu, Hawaii, 96825, USA. The Membership Fee is $30.00 for individual Members and $100.00 for Institutions. Please make check to"The Tsunami Society".

Send dues for one year with application. Membership shall date from January 1 of the year in which the applicant joins. Membership of an applicant applying on or after October 1 will begin with January 1 or the following calendar year and his first dues payment will be applied to that year.

Membership includes a subscription to the society journal *Science of Tsunami Hazards*