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Title SOURCE AND CHARACTERISTICS OF THE TSUNAMI OBSERVED ALONG THE COAST OF THE PACIFIC NORTHWEST ON MARCH 28, 1964

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The physical linkage between oceanic earthquakes and most tsunamis is generally accepted. The commonly offered method of generation of a tsunami calls for displacement of submarine blocks of the earth's crust. But, the mechanism of communication of seismic energy to the water by the impulsive movements of the sea floor is still not wholly understood. As a result, the actual nature of the tsunami waves that will develop in a given instance cannot as yet be reliably predicted.

The observed and recorded information concerning the Prince William Sound earthquake of March 28, 1964 and its associated tsunami provides significant material for the study of a tsunami's mode of generation and transformation. The earthquake and its aftershocks were located in a region where the gross geological setting of the epicentral area is well known. The arrival of the

waves at various locations is described by eyewitness accounts and tide gage records.

The predominant distribution of the aftershocks along the continental slope adjoining the Aleutian Trench, and the vertical dislocation of land masses bordering the Gulf of Alaska, suggest that the tsunami was produced by uplift and subsidence of submarine crustal blocks. Based upon assumed dislocation shapes, calculations indicate that the initial tsunami energy was approximately 1.5×10^{22} ergs.

Enroute from its origin to the coast of the Pacific Northwest, the tsunami evidently folllowed a pathy typical of a shallow water wave. The degree and type of transformation of the waves, as they entered an estuary, was principally a consequence of the underwater and coastal features peculiar to that sea-inlet.

SOURCE AND CHARACTERISTICS OF THE TSUNAMI OBSERVED ALONG THE COAST OF THE PACIFIC NORTHWEST ON MARCH 28, 1964

by

CLIFFORD EUGENE SCHATZ

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SOURCE AND CHARACTERISTICS OF THE TSUNAMI OBSERVED ALONG THE COAST OF THE PACIFIC NORTHWEST ON MARCH 28, 1964

INTRODUCTION

The story of gigantic ocean swells, arriving silently and unannounced, rolling over beaches and engulfing small islands, leaving devastation and ruin in their wake, has been told and recorded for centuries. These abnormal waves originally called tidal waves but now more frequently termed tsunamis have been correlated with distant earthquakes. The nature of their generation has, however, remained shrouded in mystery. Scientists still are not absolutely certain what really does happen when the ground trembles violently in an earthquake. The Algonquian Indians used to say the Great Tortoise who supported the world was shifting his weight. Aristotle had an equally mistaken notion: He thought earthquakes were caused by powerful subterranean winds (9, p. 140). Recent theoretical considerations of tsunami generation have included block type (molar) dislocations of the sea-bed, both uplift and down-drop; submarine landslides; special resonance effects related to the deep ocean trenches; atmospheric pulsation through direct air-water coupling; and long seismic waves.

The Prince William Sound Earthquake of March 28, 1964, with its accompanying tsunami, may well provide essential facts which will clarify the generation mechanism of tsunamis. This earthquake was one of the largest ever to occur in the United States. Furthermore, its epicenter was located in an area where the seismic history is well known (12, p. 1343-1370; 17, p. 2). The high quality World-Wide Standard Seismograph System, now almost completely installed and in operation, has provided scientists with more observations on this earthquake than on any other earthquake ever recorded (17, p. 1). The estimated extent of seafloor motion based on adjacent land uplift or down-drop, the location and number of aftershocks, and the type of wave action observed and recorded may permit a realistic determination regarding the tsunami generation area and mechanism.

Of equal importance is the behavior of the tsunamis after generation. We still know little about transformations of the waves due to topographic irregularities; such as, bottom slope and curvature, which influence directly the refraction, reflection, scattering and dissipation of the waves. The marigrams from tidal stations along our coasts, coupled with observations by personnel witnessing the arrival of this tsunami, may permit some evaluation of the transition that takes place from source to destination.

RECENT TSUNAMIS TOUCHING THE SHORES OF THE PACIFIC NORTHWEST

Certain populated coasts, notably those of Chile, Peru, Japan and Hawaii, have been swept again and again by great waves of tsunamis surging as high as 60 feet above normal sea level. A comprehensive list of the known major tsunamis that have occurred since the time of 479 B. C. has been compiled by Heck (3, p. 269-286). For the 50 years from 1897 to 1946, Heck's listing gives an incidence of about four major tsunamis every three years (20, p. 43). Since 1946 there have been five notable tsunamis arriving on the shores of the Pacific Northwest alone. This rate is approximately consistent with the above.

The following table lists some statistics on the magnitude of the shock and on the damage sustained in the areas given due to the resultant tsunamis (8, p. 21-37; 16, p. 1). For all but the last tsunami the figures indicating loss of life and property damage are for Hawaii. The figures for the 1964 tsunami are estimates of losses in Alaska due to the combined effect of earthquake and tsunami.

Table 1. Major tsunamis 1946-1964.

Date	Earthquake Epicenter	Magnitude (Richter Scale)	Lives Lost	Damage
April 1, 1946	Aleutian Is.	$7\frac{1}{4}$	173	$ 25,000,000
Nov. 4, 1952	Kamchatka	$8\frac{1}{2}$	0	800,000
Mar. 9, 1957	Aleutian Is.	$8\frac{1}{2}$	0	3,000,000
May 22, 1960	Chilean Coast	$8\frac{1}{2}$	61	23,550,000
Mar. 28, 1964	Prince William Sound	$8\frac{1}{2}$	116	311,000,000

In Table 2 a comparison is made of the amplitudes of the greatest waves recorded for each of the tsunamis listed in Table 1. The data indicated for the tsunami accompanying the Prince William Sound Earthquake are from preliminary estimates (16, p. 2; 17, p. 48). The 1964 value for Crescent City is based upon extrapolation of the initial signature received prior to the flooding of tide gage during the onslaught of the tsunami. The values are given in feet.

Table 2. Maximum recorded rise or fall of water level.

Station	1946	1952	1957	1960	1964
Sitka	2.6	1.5	2.6	3.0	14.6
Neah Bay	1.2	1.5	1.0	2.4	4.6
Crescent City	5.9	6.8	4.3	10.9	14.5

It is well known that proximity to the source area of a tsunami is not necessarily a criterion as to the height of the wave that may occur. For example, after the 1960 Chilean tsunami the maximum rise of water level was 10.9 feet at Crescent City and 5.5 feet at Honolulu. The respective great circle distance to these stations is 5,529 and 5,923 nautical miles. But, the maximum change was as much as 12.9 feet along the coast of Japan over 9,100 nautical miles from the origin (16, p. 21-27).

In an ocean basin of variable depth the wave fronts propagate according to Fermat0s principle (principle of least time or shortest path) and the rays are not precisely great circle routes. Nevertheless, the great circle approximation has been used extensively, and in fact computed and observed travel times have generally been in accord within a few percent (4, p. 659). The most important effect of nonuniformity in depth occurs near the shoreline where the wave height amplifies tremendously. In this way a small amplitude, long period wave is converted into a highly destructive phenomenon.

The fact that tsunamis at least approximately follow great circle paths has probably been a life and property saving factor to the U.S. Pacific Coast. A review of a great circle chart of the North Pacific Ocean (U.S. Naval Oceanographic Office Chart 5300) simultaneously with a chart that gives some indication of the bottom topography of the Pacific Ocean (Bathymetric Chart of the North

Pacific Ocean, U. S. Naval Oceanographic Office Chart 5486) will show that the great circle paths to our coast line of tsunamis generated in or near Japan and the Aleutian Islands lead the disturbances through shallow depths where they rapidly dissipate.

CHARACTERISTICS OF THE TSUNAMI OF MARCH 28, 1964

The tsunami arrived along the coast of the Pacific Northwest during the night of March 27 and the early morning hours of March 28, Pacific Standard Time. Evidence of the tsunami's passing and its rise above normal water level is shown in Figures 1 through 4.

Speed of the Waves

The speed of a tsunami is very approximately equal to the square root of the product of depth of water and acceleration due to gravity, $c = (gh)^{\frac{1}{2}}$. If nautical units of measurement are used, this equation reduces to $c = 8.23\,(h \text{ fathoms})^{\frac{1}{2}}$ = speed in knots. This relation is illustrated in Table 3.

Table 3. Wave speed for various depths.

Depth (fathoms)	Speed (knots)	Depth (fathoms)	Speed (knots)
100	82	2000	368
500	184	2500	412
1000	260	3000	451

Wave speed will vary during the travel period due to the irregular depth. Since the tsunami travel time is the only factor determined with fair accuracy, the computed speed is the average for the entire distance from the generation area to the observing station.

Figure 1. Ona State Park, Waldport, Oregon, March 28, 1964

Figure 2. Pier in Waldport Bay, Oregon, March 28, 1964

Figure 3. Tillamook Bay, Oregon, March 28, 1964

Figure 4. Beach near Coos Bay, Oregon, March 28, 1964

Based on the arrival times of the tsunami and the great circle distances from the earthquake epicenter in Prince William Sound, the average speed to stations along the Pacific Northwest coast is presented in Table 4.

Table 4. Computed tsunami speed.

Station	Distance (nautical miles)	Travel time (minutes)	Speed (knots)
Sitka	465	92	303
Neah Bay	1092	222	295
Astoria	1214	260	280
Newport	1288	249	310
Crescent City	1433	248	348

Wave Period

The wave period for a tsunami is difficult to measure accurately on a marigram due to the inherent damping features of a tide gage plus the indeterminate reactions and resonance caused by locally reflected waves (2, p. 87). The most accurate method of measuring the period on a marigram is to read the half-period of the first wave. This method of determining the period of earth seismic waves is in general use by seismologists. Table 5 provides periods taken from marigrams of March 28 for the indicated stations.

Table 5. Wave period of the tsunami.

Station	Half-period (minutes)	Period (minutes)
Sitka	41	82
Neah Bay	27	54
Astoria	20	40
Crescent City	24	48

In studying the marigram from the Sitka station, Figure 5, one can infer that the long period at this station was due to local resonance. It has been confirmed by personal communication that the tide gage is in fact located well inside Sitka Sound. There was, of course, resonance effects on the marigrams of the other stations. However, in the opinion of the author, these effects were not as evident during the initial half-periods.

There was no tide gage installed in Yaquina Bay on the date of this tsunami; however, reliable Coast Guard personnel reported a half-period of 25 minutes which is in good agreement with the other three stations in Table 5 (11, p. 231-232). Combining this information with the periods for Neah Bay, Astoria and Crescent City we find an average period of 48 minutes.

Wave Length

The wave length for the tsunami can be computed using the

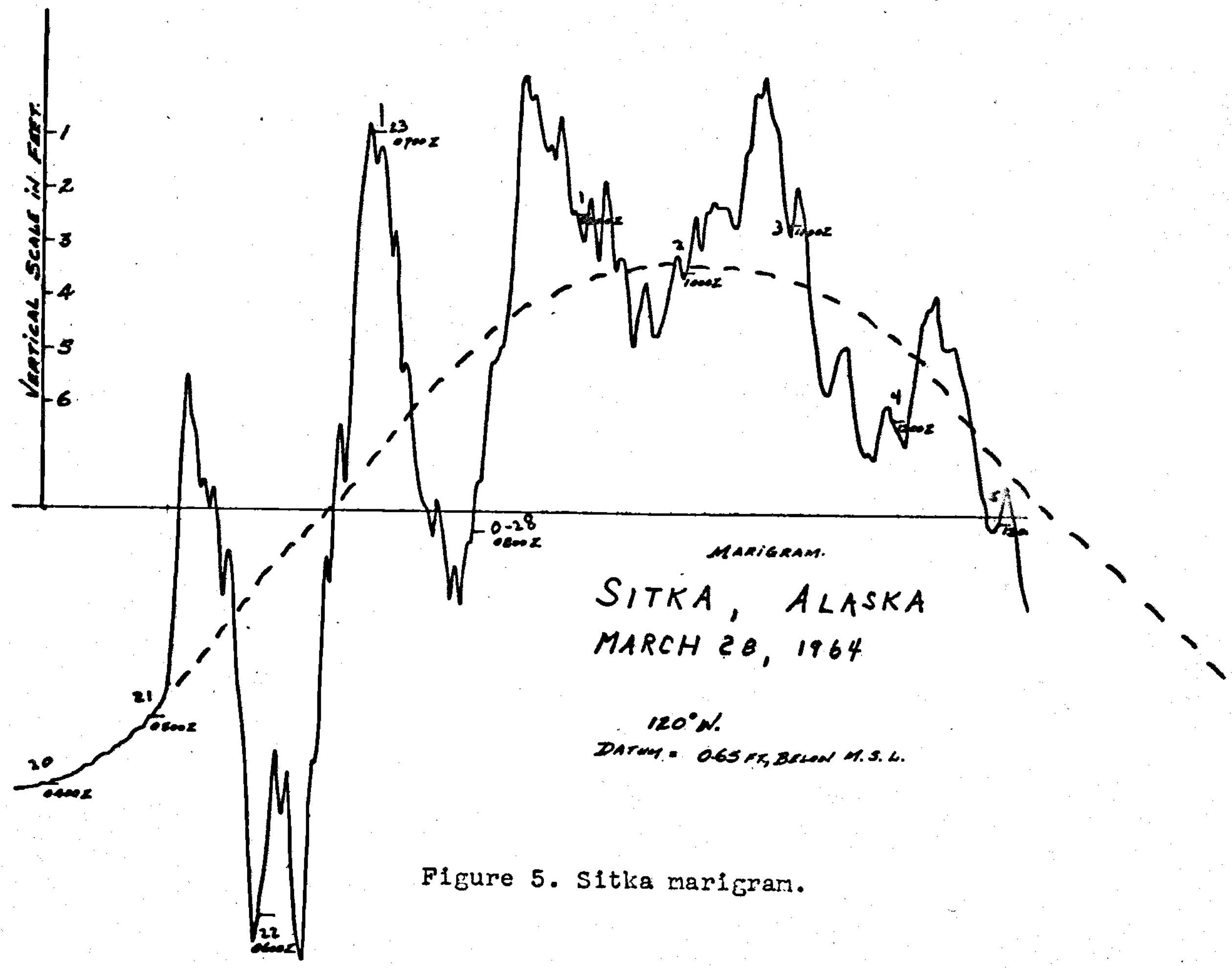


Figure 5. Sitka marigram.

average period and the average speeds based on the distances to the epicenter and the arrival times. However, it seems more realistic to note that the average depth for the greater part of the travel distance to the above stations was about 2000 fathoms (U.S. Coast and Geodetic Survey Chart 9000). A shallow water wave moving in this depth of water will have a speed of 368 knots (Table 3). The period of 48 minutes and this speed yields a wave length of 294 nautical miles. It is problematical as to whether this is representative of the wave length in the open sea.

Wave Path

The path of the initial wave front terminated in part on the shores of the Pacific Northwest. The point of origin of the tsunami, however, is not as readily defined. The author hypothesizes that the tsunami was generated on the continental slope bordering the Aleutian Trench as it extends into the Gulf of Alaska. This hypothesis is based principally on evidence that the aftershocks predominantly occurred in the Cretaceous substructure on the continental slope and that land movements reported were of uplift and subsidence, respectively, in the Prince William Sound vicinity and Kodiak Island (17, p. 23).

A wave front coincident with the Aleutian Trench is shown in Figure 6. Successive wave fronts were constructed, according to

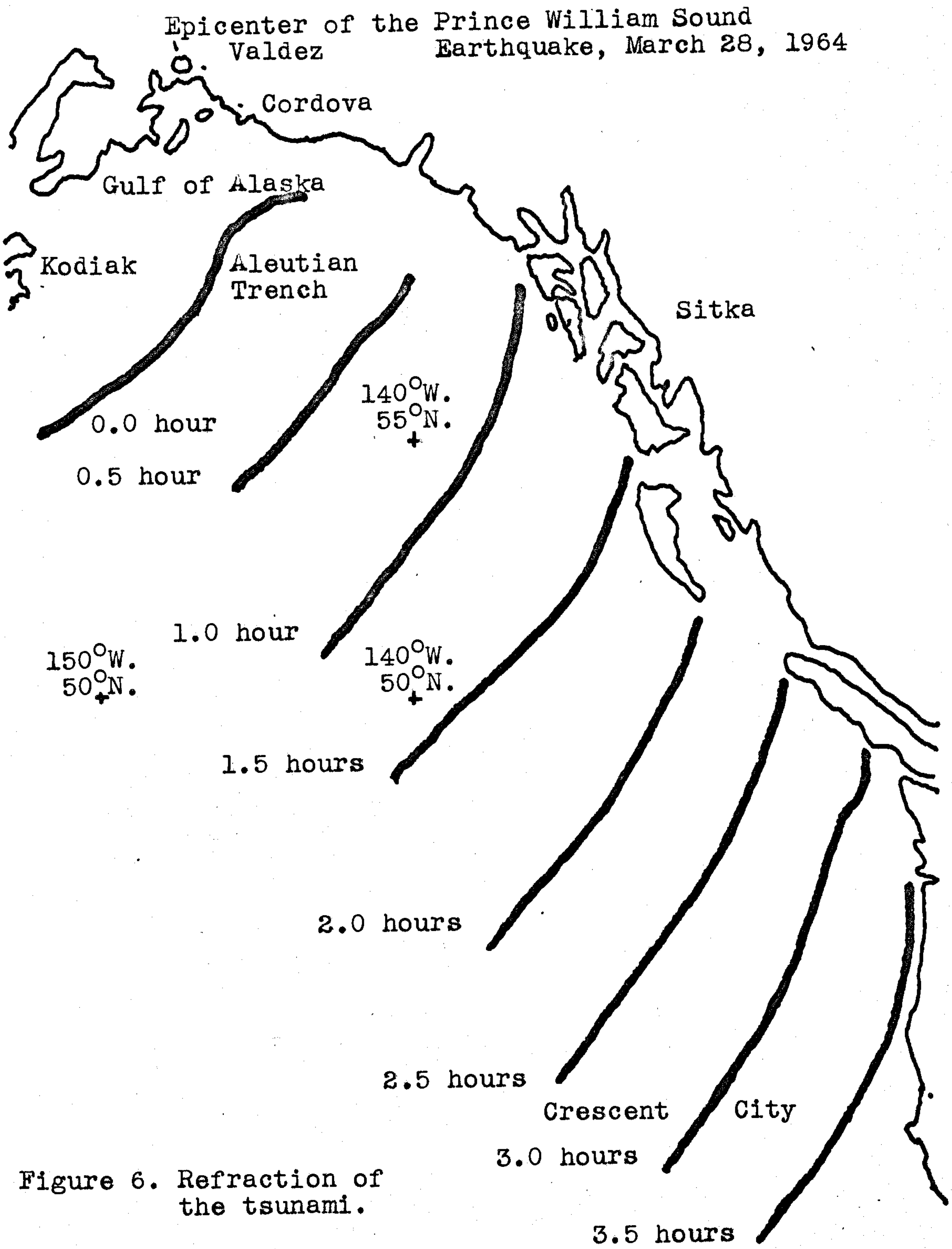


Figure 6. Refraction of the tsunami.

Huygen's method for refraction, at ten minute intervals until the fronts intersected the coast of the Pacific Northwest between Sitka and Crescent City. This method of refraction relates the wave speed and the angle between the wave crest and bottom contour at any two depths. It makes use of Snell's Law and is valid for any bottom contour configuration (10, p. 856-866).

The combined graphical numerical construction of the wave refraction diagram was based on the assumptions that (1) the velocity of the wave crest depends only upon the average still water depth under the crest at each point; (2) the elements of the wave crest advance in a direction perpendicular to the crest line; (3) the waves are long crested; and, (4) the bottom features with dimensions small compared with the wave length do not influence the motion of the wave to any appreciable extent.

The actual graphical work was accomplished using overlays on United States Coast and Geodetic Survey Chart Number 9000. Figure 6 is a sketch of the main features of the original construction. Final numerical calculations of wave front arrival times were based upon depths determined from various small scale charts for the particular coastal stations. Table 6 shows the travel times measured in comparison with travel times computed using the time of the earthquake and the recorded tsunami arrival times at the indicated stations.

Table 6. Travel time comparisons between graphical and computed times.

Station	Travel Time Graphical	Travel Time Computed	Difference Minutes	Difference Percent
Sitka	90	92	-2	2
Neah Bay	223	222	+1	~1
Astoria	260	254	+6	2
Newport	250	249	+1	~1
Crescent City	254	248	+6	2

The differences shown in Table 6 are all very small, two percent or less. They are obviously not significant. In consideration of the inherent inaccuracies involved in the graphical numerical refraction method used, the lag of each tide gage, the probable errors in certain charted depths, and the expected small variations from the basic assumptions; differences in travel time of ten minutes or more would not have been surprising nor would they have invalidated the hypothesis that the tsunami originated in the vicinity specified. The small differences also do not prove that the origin hypothesized is the only one possible. They are only indicative that (1) the origin is approximately correct, (2) the tsunami behaved like a theoretical shallow water wave and/or (3) the refraction was not significant in lengthening the path.

Wave Heights

The wave height of a tsunami in deep water is very small. During the catastrophic Hawaiian tsunami of April 1, 1946, the master of a ship lying offshore near Hilo reported feeling no unusual waves pass his ship, although he could see the great waves breaking on the shore (18, p. 63). The nearest thing to a measurement in the open ocean of the tsunami of March 28, was made with the specially designed long period Van Dorn wave recorder on Wake Island. The increase in sea level was less than half a foot (19).

The negligible deep water wave heights of a tsunami is at considerable variance with the heights recorded by tide gages and water level recorders near coasts and bays. The tsunami waves as they propagate over the discontinuity of the continental shelf are subject to the scattering and modifying effect of the bottom topography and coastline. The elevation reached by the waves at a particular point depends upon the local offshore characteristics of the waves, diffraction, the slope and configuration of the shore, and resonance.

The wave heights recorded at Sitka, Neah Bay and Crescent City for this tsunami are given in Table 2. The maximum wave heights reached at Oregon coastal communities were measured from available visual evidence. Measurements were made by survey teams from Oregon State University's Oceanography Department consisting of faculty and student members (Appendix I). In Figure 7, Robert K. Lane of Oregon State University points to the highest level reached by the tsunami at Paradise Cove while E. Iseri, a local resident, indicates the normal high tide mark. The maximum heights measured along the Oregon coast are shown in Figure 8 (11, p. 232).

Figure 7. Paradise Cove, Nehalem River, Oregon.

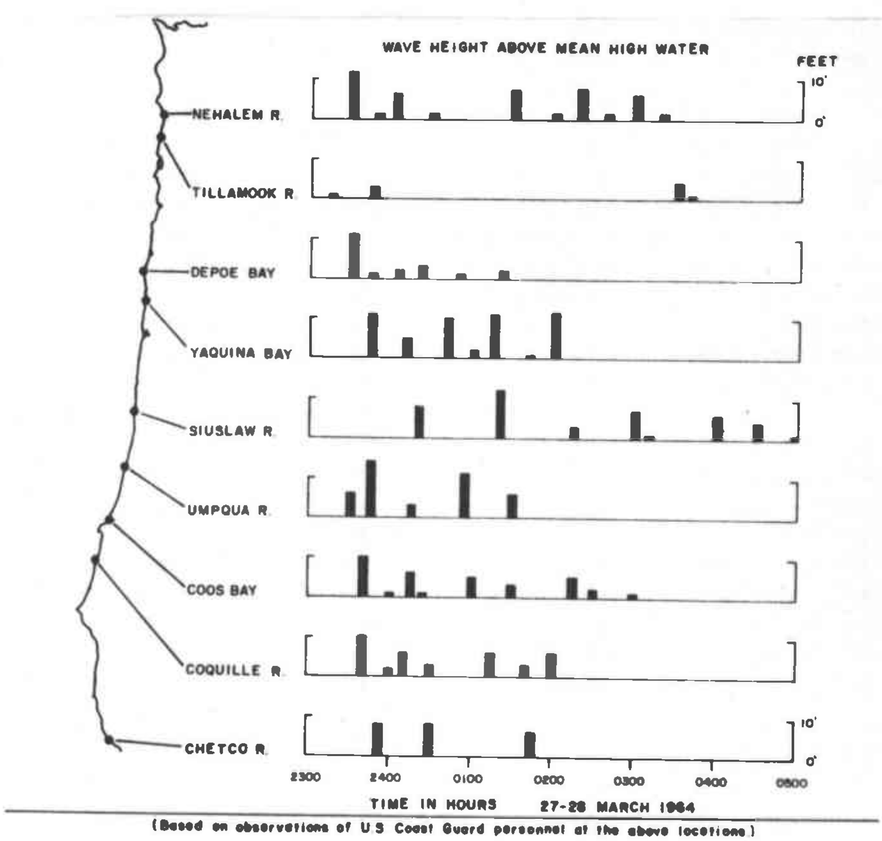


Figure 8. Wave height above mean high water.

CHARACTERISTICS AND SOURCE MECHANISMS OF TSUNAMIS

Following the devastating tsunami of April 1, 1946, a Seismic Sea Warning System was set up by the U. S. Coast and Geodetic Survey (15, p. 9-10). This organization provides for seismological observatories for detecting and reporting earthquakes in the Pacific area, tide stations located throughout the Pacific for detecting and reporting the resulting seismic sea waves, a central station in Honolulu for receiving and evaluating the reports, and rapid communication service to alert military and civil authorities. These warnings have undoubtedly prevented great loss of life and property. The basic difficulty is that it has not been possible from the seismic record of an earthquake to determine whether or not a tsunami has been generated. Two earthquakes which are seismically indistinguishable with regard to location and energy can generate tsunamis whose amplitudes differ by an order of magnitude (4, p. 661).

For evidence that a tsunami has been generated recourse has to be made to the inspection of tide records near the epicenter. A further difficulty is that the marigrams of different tsunamis at any one station look somewhat alike, whereas the marigrams of one tsunami at different stations has few reproducible characteristics. The conclusion must be that the tide gage records are principally influenced by the bottom topography and the filtering action of the hydrographic features in the vicinity of the station, and by the inherent peculiarities of the individual instruments (14, p. 19).

General features of tsunamis are fairly well known. Present knowledge of tsunamis is primarily wanting in three respects; first as regards the generation mechanism, second as regards the types of waves generated and the transformations they are subject to up to the point of their striking a coastline (20, p. S-1) and third as regards to some degree of correlation that can be demonstrated between the characteristics of earthquakes and of tsunamis that might permit the prediction of the occurrence of the latter.

The generation mechanism most favored as of September 1961 at the Tsunami Meetings Associated with the Tenth Pacific Science Congress in Honolulu is that of tectonic displacement of the sea floor (1, p. 1). The nature of the displacements generating the tsunami is however still open to conjecture.

Based upon considerable statistics tsunamis evidently accompany only those earthquakes whose epicenters are at fairly shallow depths (less than 200 kilometers) beneath the level of the ocean floor or close to shore (6, p. 167-173). Some tsunamis are, however, distinctly generated by landslides and by submarine volcanic explosions. Although the latter was once thought to be the most frequent cause, current analysis indicates otherwise (1, p. 2). Model studies have shown that both submarine fault movements and submarine land slides can cause waves with the characteristics of tsunamis (13, p. 235-248).

Seismic statistics have also been accumulated that show the epicenters of some tsunami-generating earthquakes were concentrated on continental slopes, between adjacent troughs and the shore line (7, p. 38-39).

TSUNAMI GENERATION AND ENERGY

Tsunamis of seismic origin appear to be caused by faulting and/or landslides of the ocean floor during earthquakes. The velocity of a fault displacement resulting from an earthquake is extremely great (it can exceed the speed of propagation of sound in water) and the amplitudes may reach a few dozens of meters; consequently, faults can lead to an almost instantaneous change in the local ocean volume. These disturbances, on reaching the surface of the water, could cause the very long surface waves that are referred to as tsunamis (7, p. 38).

Earthquakes accompanied by tsunamis are always followed by many aftershocks (5, p. 7-18). There appears to be a definite relationship between the earthquakes' potential energy and the energy released in generating a tsunami. This relationship is perhaps between the volume of aftershock region and the earthquake magnitude. In general it has been noted, as expected, that the greater the magnitude of an earthquake, the greater the magnitude of any accompanying tsunami; and, also the greater the magnitude of an earthquake, the larger the area of aftershock activity (5, p. 13-15). Tsunamis are therefore considered to arise in the epicentral area of an earthquake resulting from a crustal deformation of the sea bottom, such as rising, sinking, or faulting; and the area of tsunami origin may be approximately estimated by the aftershock area, which can be fixed by seismic observation.

In an analysis on the spectra and the mechanism of generation of tsunamis, Takahasi of Tokyo University's Earthquake Research Institute, has determined that the magnitude of an earthquake has a linear relationship with the logarithm of the energy of the earthquake, and that this energy is proportional to the aftershock area of the earthquake and to the square of the dislocation area of the accompanying tsunami (14, p. 24-25). By experimental studies as well as theoretical, Takahasi further concludes that the wave length of a tsunami is about twice the diameter of the dislocation area. The locations of 677 aftershocks of the Prince William Sound Earthquake are shown in Figure 9. These were reported by the United States Coast and Geodetic Survey on Preliminary Determination of Epicenter Cards 28-64 through 39-64. From this figure it can be estimated that the average width of the dislocation area is about 138 nautical miles. (A northwest-southeast axis was used for this estimate.) Twice this width or 276 nautical miles compares favorably with the 294 nautical mile wave length computed as a function of period and depth.

It has also been generally found that tsunamis accompany only those earthquakes whose epicenters are at shallow depths (less than 200 kilometers) beneath the ocean floor or adjacent shore (6, p. 167).

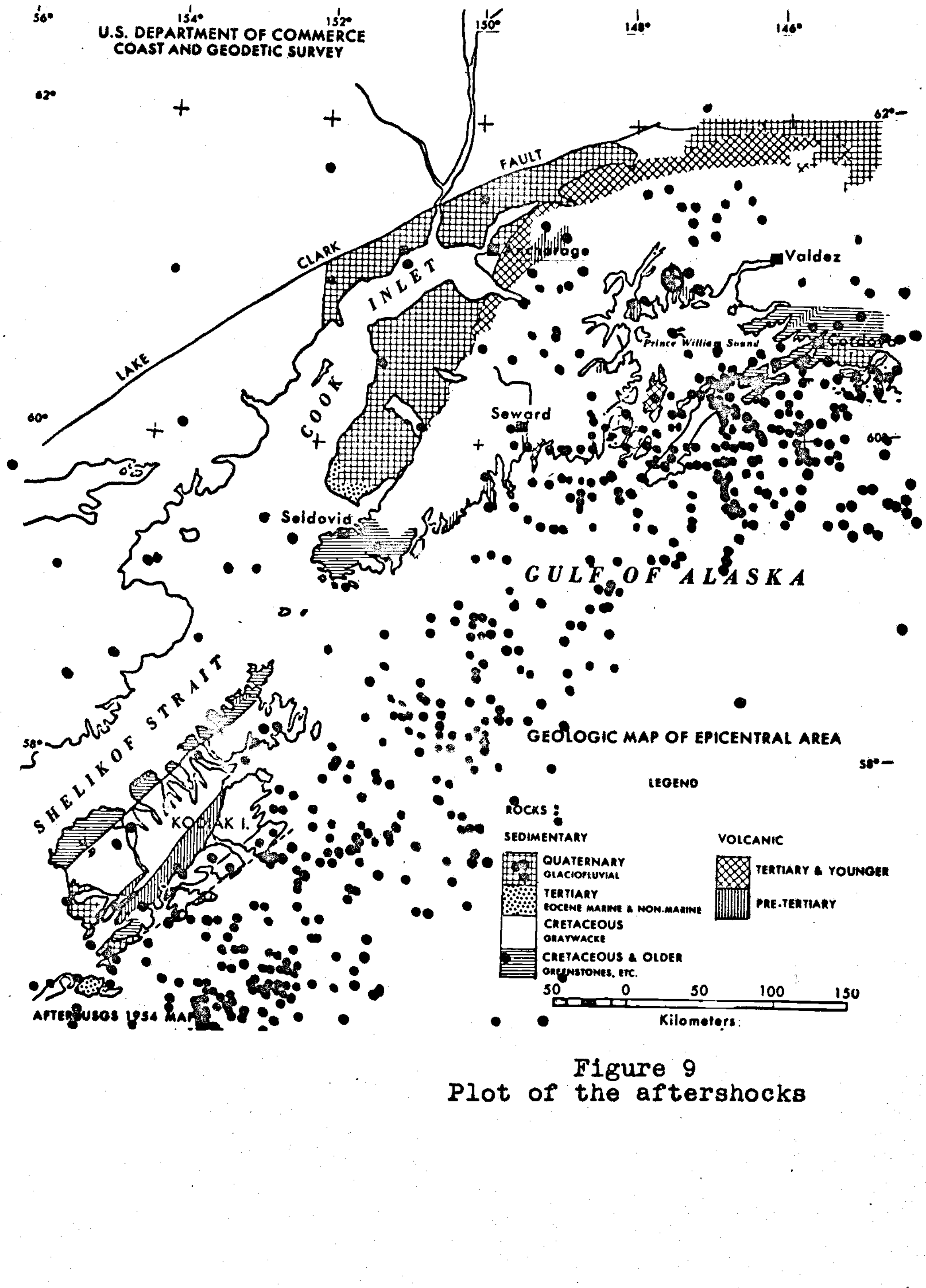


Figure 9
Plot of the aftershocks

Thus, tsunami magnitudes apparently depend on several factors: magnitude of the earthquake, focal depth and area of crustal deformation.

The tsunami energy is derived from the energy transferred from the sea floor to the water. Assuming the sudden vertical displacement of a dislocated area A of the ocean floor, the work done on the water by the sea floor dislocation due to the earthquake is approximately expressed as

$$E_1 = \rho g \int_o^b bh\, dA$$

where b is the vertical displacement of the small area element dA in the dislocated zone, h is the water depth at this position, ρ is the density of sea water and g is the acceleration due to gravity. This is simply the work to lift b feet a column of water h feet tall with a surface area of dA.

The above work should be consumed in increasing the potential energy of the sea water and in the energy transformed into the tsunami waves. The former portion of the work can be arrived at by considering the hydrodynamics involved, then

$$E_2 = \int_{V_1}^{V_2} P dV$$ where dV is the incremental volume

$$= \int_o^b \rho g(h-b)\left(\int dA\right) db$$

$$= \rho g \int (bh - \frac{b^2}{2}) dA \text{ or}$$

$$= \rho g \int b(h - \frac{b}{2}) dA.$$

The energy transformed into the tsunami waves must therefore be equal to

$$E = E_1 - E_2 = \frac{1}{2} \rho g \int b^2 dA.$$

By letting the average vertical displacement be b_m and the area of tsunami origin be A' at the dislocation area dA, the above equation reduces approximately to

$$E = \frac{1}{2} \rho g \, b_m^2 A' \text{ (10, p. 167-169).}$$

This gives us a very useful equation for estimating the tsunami energy when the approximate area of dislocation and the vertical displacement of the seafloor is known.

For example, in the case of the subject tsunami, let us take the crustal deformed area of the sea bottom to be the zone of aftershocks located between land areas and the Aleutian Trench as indicated in Figure 9. And, since it was reported that the northeastern portion of this area was one of uplift and that the portion near Kodiak was one of subsidence (17, p. 23); one could assume two shapes as producers of volume displacement. Possible shapes are sketched in Figure 10 with estimated dimensions as shown. Figure 10 can be used as an overlay on Figure 9. Based on preliminary reports it is estimated that the entire eastern shape was uplifted seven feet and the western shape subsided five feet (17, p. 23). The area of the shapes can be computed from the dimensions shown and these values with the above are inserted in the above equation to give:

$$E\ (\text{Eastern}) = \frac{1}{2}\ (64.5\ \text{lbs/ft}^3)(7\ \text{ft})^2(8,100\ \text{nautical miles}^2)$$

$$= 4.7\text{x}10^{14}\ \text{ft-lbs.}$$

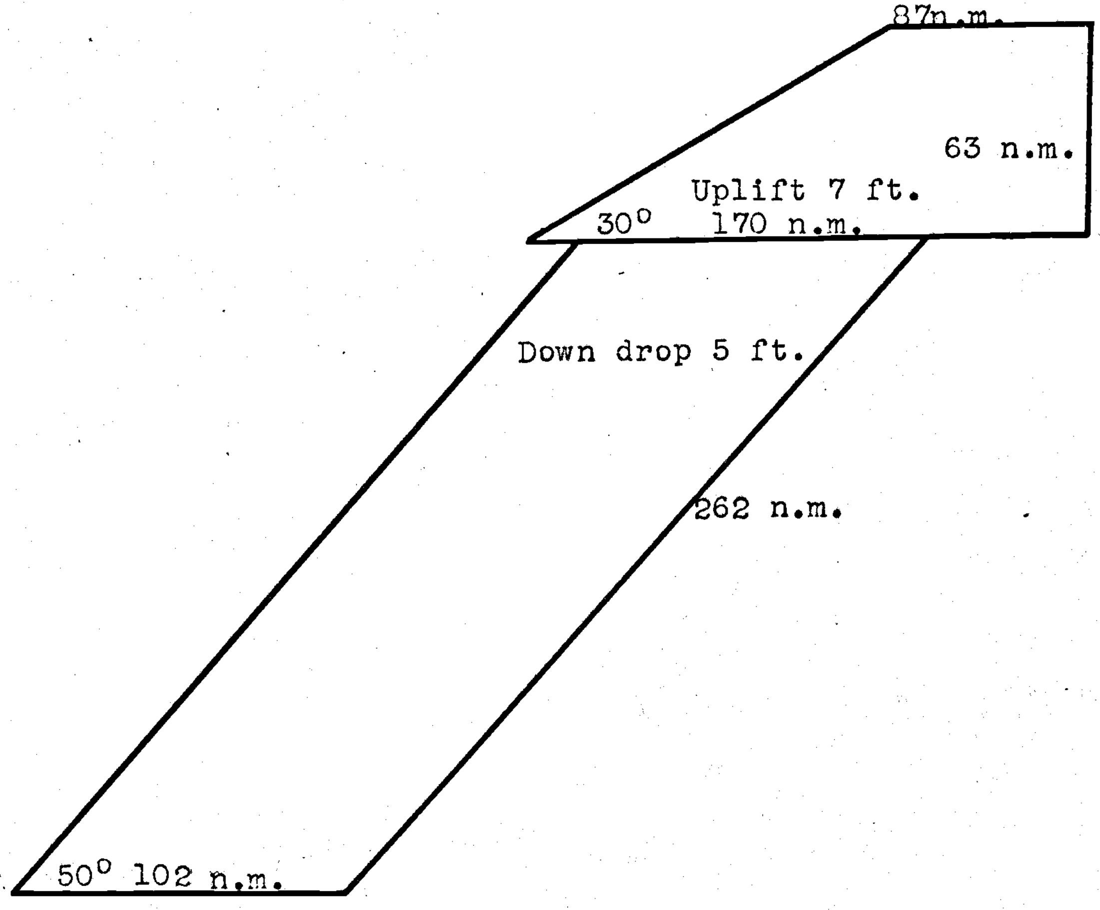
$$E\ (\text{Western}) = \frac{1}{2}\ (64.5\ \text{lbs/ft}^3)(5\ \text{ft})^2(20,450\ \text{nautical miles}^2)$$

$$= 6.1\text{x}10^{14}\ \text{ft-lbs.}$$

$$E\ (\text{Total}) = 10.8\text{x}10^{14}\ \text{ft-lbs} = 1.5\text{x}10^{22}\ \text{ergs.}$$

The total energy is comparable to the $2.3\text{x}10^{21}$ ergs and the $2.7\text{x}10^{22}$ ergs computed by Van Dorn for this tsunami and the March 9, 1957 tsunami, respectively (19).

Figure 10. Molar dislocation shapes.



SUMMARY AND CONCLUSIONS

The characteristics of the tsunami observed along the coast of the Pacific Northwest on March 28, 1964, very closely approximated the theoretical characteristics predicted for tsunamis by recent investigators. The speed of propagation was in close agreement with that provided for by the Laplacian equation, $C = (gh)^{\frac{1}{2}}$. The wave period can really only be estimated since seismic waves are influenced to a considerable degree by the local bathymetry. The wave length must be only an estimation also, if it is computed as a function of the period. If further statistics verify Takahasi's conclusion that the wave length is a function of the dislocation area diameter, then perhaps a more accurate estimate can be made. For this tsunami, a fairly favorable correlation was found by first computing the wave length as a function of the period; and then separately, by computing the wave length as a function of the diameter.

The travel times determined by the refraction method used, verified that the wave was refracted throughout its length of travel. This appraisal corroborates the wave theories of investigators that the tsunami should be treated as a "shallow water" wave.

The number of after shocks and their location strongly indicates that this tsunami was caused by a molar dislocation, either an uplift or depression, or a combination of this type of sea floor movement.

Since Alaska is located in an earthquake zone there is a good possibility that in the future tsunamis will be generated of such magnitude that they will endanger the coast of the Pacific Northwest. However, it is probable that those tsunamis generated in the Aleutian Islands and near Japan will continue to offer comparatively little danger to our coast due to their dissipation in the relatively shallow waters along their great circle routes.

Clearly, a practical method for rapidly predicting what any given earthquake in an oceanic basin will do to seaboard communities on its boundaries is still needed. This entails knowing when earthquakes will happen and if tsunamis will occur, how the waves will propagate and focus their energy, and what the consequences will be at particular locations as a consequence of the submarine topography.

The conclusions concerning the tsunami observed along the coast of the Pacific Northwest on March 28, 1964, are as follows:

(1) The origin was on the continental slope bordering the Aleutian Trench along a perimeter nearly bounded by Longitudes 143^{o} West and 153^{o} West.

(2) The generation mechanism was the sea-bed movement in the form of an uplift and a depression.

(3) The initial energy at its source was approximately 1.5×10^{22} ergs.

(4) The propagation through deep water was characteristic of a

"shallow water" wave.

(5) The transformation and height enhancement of the waves entering estuaries was primarily determined by the existing marine environment.

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APPENDIX

APPENDIX I

TSUNAMIS ON THE OREGON COAST

By Clifford E. Schatz, Herbert Curl, Jr., and Wayne V. Burt
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During the early hours of the morning of March 28, 1964 a tsunami struck the Oregon coast. This phenomenon, commonly called a "tidal wave," was generated by the earthquake that had shaken Alaska the evening before. The seismic waves forming the tsunami originated in the vicinity of the earthquake's epicenter and traveled in all directions to ocean shorelines where they were eventually dissipated; in some areas there was substantial loss of life and property.

Residents along the Oregon coast can be thankful that this tsunami caused relatively little loss along our shores. A tsunami of comparable magnitude struck the Hawaiian Islands in 1946 resulting in the loss of 159 lives and a $25 million property damage. Hawaii was 2, 300 miles away from the epicenter in the Aleutians of that devastating earthquake, whereas our coast is only about 1, 500 miles from Alaska. Oregon was fortunate this time for several reasons: the initial direction of impetus imparted to the seismic waves was away from our coast; the intervening continental shelf topography aided in refracting and dissipating the waves; and, finally, the generally high and rugged coast line of Oregon resulted in ultimate dissipation of the waves on unpopulated shorelines.

The Department of Oceanography, Oregon State University, in keeping with the national goal of oceanography to further man's knowledge of the oceans for the public's interest and welfare, dispatched survey teams up and down the Oregon coast to study the effects of this tsunami. A preliminary study of the data collected by these teams very pointedly emphasizes the perhaps obvious fact that major waves will be rapidly dissipated on our rugged open coast, but that our estuaries are especially vulnerable. Since the areas surrounding the latter are generally densely populated and will become more so within the next few years, it is apparent that a study should be conducted to determine to what extent a larger tsunami may affect the estuaries and the action which can be taken to reduce loss of life and property.

Each estuary has its own peculiarities. The location of jetties and sea walls, the existence of tidal flats and sloughs, the shape and length of the channel and the depth and width of the basin enter into the effects abnormal waves can produce. For example, referring to the accompanying chart: (1) At Coos Bay, the initial wave of about 10 feet above mean high water was dissipated in its travel up the channel by the wide tidal flats and was of negligible height by the time it reached Pony Point about 7 miles up the channel. (2) At Florence, on the Siuslaw River, the initial wave was about 8 feet above mean high water at the Coast Guard Station near the entrance, but due to a fairly narrow channel the wave was apparently only slightly dissipated by the time it reached Florence in the South Slough and surrounding tidal flats. (3) At Reedsport, about 10 miles up the Umpqua River only negligible indications existed of the 14-foot wave that was measured at the entrance. The meandering river with its wide tidal flats quickly dissipated in the wave's energy. (4) In Yaquina Bay, four large waves of almost equal height were observed; whereas, in the other estuaries the subsequent waves generally decreased in magnitude following the second wave. This effect at Yaquina Bay could possibly be attributed to a seiche characteristic which is similar to the rocking motion of water from side to side in an open basin.

Since the Oregon coast is faced across the Pacific Ocean by many areas of strong earthquake activity, it is highly probable that many tsunamis have struck, and will continue to strike, our coast. It is possible that the next tsunami may be of considerably greater magnitude than this most recent one, which could increase the loss of life and property logarithmically. The Department of Oceanography at Oregon State University, therefore, proposes to initiate further studies of the major estuaries as personnel and funds permit to determine probable effects of direct seismic waves, tidal bores, and seiches of more powerful tsunamis. In line with this, survey teams made up of graduate students and staff members will be organized and briefed at the beginning of each term, and will be sent to the coast whenever reliable information predicts the approach of a tsunami. It is hoped that the results of these studies, along with those of other agencies, will prove rewarding and timely.