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## Proposed Tsunami Warning System

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# Abstract

A striking correlation between the occurrence of a short period earthquake phase ("T" phase) travelling through the ocean with the speed of sound in sea water and the occurrence of Tsunamis has been observed. The characteristics of the T phase are described and the data upon which the correlation is based are presented. Although further study is needed, the evidence at hand warrants the inclusion of instruments suitable for recording the T phase in Tsunami warning systems. It is quite possible that SOFAR listening stations would be valuable adjuncts in the detection of Tsunami producing earthquakes since they offer the best means of recording the "T" phase.

## Introduction

The T phase was first identified as a compressional wave propagated through the ocean by Tolstoy, Ewing, and Press[1] in 1948. It had previously been observed by Linehan[2] in the Weston records of earthquakes in the West Indian region. Linehan stated that it probably was a new phase, but he did not undertake to determine the path or mechanism of propagation involved. In the recent work the "T" phase was observed on the Benioff short period instruments at Weston, Fordham, and Ottawa, and on the Wood Anderson seismographs at Seven Falls and Shawingan Falls for a series of major and minor Dominican Republic shocks. In addition the "T" phase was observed on the Benioff short period seismograms of the Pasadena network of stations, Mt. Hamilton and mineral stations, and on the Neumann-Labarre at Honolulu for a series of major Japanese and Aleutian shocks.

## Description of the "T" Phase

For a complete description of the "T" phase, the reader is referred to the report of Tolstoy, Ewing, and Press[3]. Only a brief summary is given here.

The "T" phase is characterized by periods of 0.5 sec. or less, a velocity identical with that of sound in water for the part of its path crossing deep water and by speeds from 12000 to 18000 ft/sec (3.7 to 5.5 km/sec) across shallow water or land.

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[1] Ivan Tolstoy, Maurice Ewing, and Frank Press, The "T" Phase of Shallow Focus Submarine Earthquakes, Tech. Rep. No. 1, under Contract W-28-099 ac-396 between Columbia University and Geophysical Research Directorate of the Cambridge Field Station, AMC, U.S. Air Force, Jan., 1948.

[2] Daniel Linehan, Earthquakes in the West Indian Region, Trans. Amer. Geoph. Union, Pt. 2, p. 229-232, 1940.

[3] Tolstoy, Ewing, and Press, loc. cit.

The amplitude of the "T" phase decays much more rapidly over land than other phases. For small amplitudes due either to weak shocks or propagation over land, the duration of the "T" phase decreases and the apparent travel time increases, until for very small amplitudes only a very small and short signal is visible. The ground motion of the "T" phase is complex. At Weston it appears as a series of successive P and SV-SH arrivals, the transverse components being particularly large.

The conditions of propagation are more favorable for propagation of the "T" phase from epicenters off the Dominican Republic to stations on the east coast, T having been observed with large amplitude for a large number of major and minor shocks originating in that area. Conditions are less favorable for Pacific coast stations, since only shocks of magnitude 7 or over produce small amplitude "T" phases.

## Method of Propagation of "T" Phase

Press and Ewing[4] have treated the propagation of sound in a liquid layer overlying an infinite solid, generalizing the work of Pekeris[5] in which the underlying medium is a liquid. These calculations provide the theory for sound propagation in an ocean with either a solid or a liquid bottom. In both cases it is shown that short period oscillations, travelling with the speed of sound in the upper layer, can be transmitted over great distances.

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[4] Frank Press and Maurice Ewing, A Theory of Microseisms with Geological Applications, Trans. Amer. Geoph. Union, Vol. 29, No. 2, pp. 163-174, 1948.

[5] C. L. Pekeris, Theory of Propagation of Explosive Sounds in Shallow Water in Propagation of Sound in the Ocean, Mem. No. 27, Geol. Soc. Amer., 1948.

This theoretical result explained the observations of Worzel and Ewing[6], who found high frequency waves propagated at the speed of sound in water from explosions in shallow water. The shallow water experiments may be considered as scale models for the study of propagation across deep water, leading one to expect a corresponding phase for earthquake waves travelling oceanic paths. This type of propagation will be referred to as normal mode propagation.

In the work just described, the velocity of sound was taken to be independent of depth in the water. Actually, in the deep ocean the velocity of sound has a minimum value at 400 to 700 fathoms, and the work of Ewing and Worzel[7] on the SOFAR sound channel has shown that sounds originating from a small bomb near the depth of minimum sound velocity will travel across the ocean with very little attenuation. In the SOFAR experiments, the wavelengths used were all so short that propagation could be represented by rays refracted back and forth across the sound channel. This type of propagation will be referred to as sound channel propagation.

Knowledge of the frequency spectrum of the "T" phase is scanty due to instrumental limitations, but the available data give a predominant period somewhat less than 0.5 sec, which falls

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[6] J. L. Worzel and Maurice Ewing, Explosive Sounds in Shallow Water, in Propagation of Sound in the Ocean, Mem. No. 27, Geol. Soc. Amer., 1948.

[7] Maurice Ewing and J. L. Worzel, Long Range Sound Transmission, in Propagation of Sound in the Ocean, Mem. No. 27, Geol. Soc. Amer., 1948.

in the region where transition from sound channel to normal mode transmission takes place. It is probable that with suitable instruments both types of transmission can be detected.

### Correlation between "T" Phase and Tsunamis

A remarkable correlation has been found between the occurrence of the "T" phase and the occurrence of Tsunamis[8]. The following list of Pacific Ocean Tsunamis is taken from the list of of Heck[9]. It includes all entries in his list later than 1932 except 6 tsunamis from earthquakes which would not be expected to produce "T" phases at the California stations due to intervening land.

Table 1. Pacific Tsunamis 1933-1948

| | |
|---|---|
| 1933 Mar 2. | Japan, Sanriku coast, Ryori Bay. Waves 96 feet high at head of funnel-shaped bay; Sasu, 45 feet; and elsewhere in proportion. Horizontal movement of induced current said to have been strong enough to stop progress of 12-knot boat. |
| 1938 Nov 10. | Violent seaquake off Alaskan Peninsula sent tidal waves across Pacific. Epicenter 55.5° N, 157.3° W. |
| 1944 Dec 7. | Violent seaquake off Japan. Seawave recorded in California. |
| 1946 Apr 1. | Hawaiian Islands and elsewhere. Epicenter in Aleutian trench, 53.5° N, 163° W. Greatest casualties at Hilo, where 20-foot wave struck. One hundred seventy-three killed, damage estimated at $10,000,000. Waves reported from west coast of North and South America and many islands in Pacific. Five lost at Scotch Cap light station, Unimak Island, Alaska. |
| 1946 Dec 21. | Japan. Fifteen hundred killed on Shikoku Island. Two thousand houses destroyed. Epicenter 33.3° N, 134° E. |

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[8] Tolstoy, Ewing, and Press, loc. cit.

[9] N. H. Heck, List of Seismic Sea Waves, Bull. Seis. Soc. Amer., Vol. 37, No. 4, pp. 269-286, 1947.

Of the tsunamis listed in Table 1, all except 1946 April 1 produced "T" phases. Furthermore, except for the earthquake of 1948 May 14, which produced no tsunami, no other "T" phases were produced. Hence during this period there were 5 Pacific tsunamis, of which 4 were accompanied by "T" phases, and 5 "T" phases, of which 4 were accompanied by tsunamis. Further study might reveal the reason for these discrepancies.

In the Atlantic Ocean, in the period 1939 to 1948, only West Indian shocks produced "T" phases recorded at Weston, Fordham, and Ottawa. The only other shocks which need be considered are those of magnitude 7 or greater on the Mid-Atlantic Ridge. Two were completely blocked by the Mid-Atlantic Ridge, and one was partially blocked. It is unfortunate that there is not cleancut evidence of whether the Mid-Atlantic shocks can produce "T" phases. During this interval 20 shocks produced "T" phases. Of these, 4 had magnitudes greater than 7. All of these were located just north of the Dominican Republic. The 16 shocks of magnitude less than 7 are of no importance for correlation with tsunamis, being mainly small after shocks. They have been studied in the effort to understand the great strength of T in comparison with P in this area, which is accounted for by the shorter distance, the more favorable angle of incidence upon the coastline, and possibly on other factors. Conversely, the conditions in this part of the Atlantic Ocean minimize the effects of tsunamis upon coast lines. It has often been stated that this occurs primarily through the shielding effect of the broad continental shelves and the blocking action of the Mid-Atlantic Ridge, but the fact that Bermuda has never experienced a destructive tsunami may be interpreted to mean less efficient generation of the gravity wave than for the Pacific shocks.

Of the 4 Dominican Republic shocks of magnitude 7 or greater, namely August 4, August 8, August 21, and October 1, 1946, that of August 4 (magnitude 8) produced a destructive tsunami in the vicinity of the epicenter and was well recorded on the tide gauge at St. Georges, Bermuda. The August 8 (magnitude 7.6) shock produced a questionable record on the tide gauge at St. Georges. The August 21 (magnitude 7.0) and October 4 (magnitude 7) did not produce definite evidence of tsunami on any tide gauge in the Atlantic so far as can be determined. Apparently there is good correlation between "T" phases and tsunamis in the Atlantic, but the ratio between the two is much different from that in the Pacific. It would be necessary, but probably simple, to make allowance for this factor in operating a warning system.

## Generation of the "T" Phase

If the focus is beneath the horizontal floor of the ocean, energy can enter the ocean for normal mode propagation only by diffraction of cylindrical or spherical waves. This can occur to an appreciable extent only if the focus is at or within approximately a wavelength of the ocean bottom. The theory of the effect has been worked out and will appear in a later report. The results are analagous to those of Lamb[10], on the influence of depth of focus on the production of Rayleigh Waves, or even more to those of Sezawa[11] on Love Waves. When the ocean floor is

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[10] Horace Lamb, On the Propagation of Tremors over the Surface of an Elastic Solid, Phil. Trans. Roy. Soc. Lon., Ser. A, Vol. 203, pp. 1-42, 1904.

[11] Katsutada Sezawa, Love Waves Generated from a Source of a Certain Depth, Bull. Earth Res. Inst., Tokyo, Vol. 13, pt. 1, pp. 1-17, 1935.

horizontal, it is even more difficult to introduce energy into the sound channel unless the sound is above the bottom.

For epicenters over a slope such as the continental shelf, energy from the shock can be available for either sound channel or normal mode propagation, the availability of the energy being greater for shocks whose foci are very near the ocean floor. But even when the foci are considerably deeper, much more energy is available than for the horizontal bottom, the inclination of the slope facilitating entrance of energy into the ocean in a manner analagous to the prism of the Lummer-Gehrke plate in optics.

## Relevant Facts and Previous Theories on Tsunamis

Tsunamis are gravity waves of period 15 to 30 minutes, which are propagated with a velocity of approximately $\sqrt{gh}$. The wave train consists of several oscillatory waves. Tsunamis are generated by shallow focus earthquakes, under or near the sea, particularly at steeply dipping coasts. The circum-Pacific earthquake belt is the principal source of destructive tsunamis.

The principal theories for generation of these large gravity waves have been submarine volcanic eruptions, submarine slumping by earthquakes either under the ocean or near to it, or submarine faulting, particularly that involving vertical displacements.

## Proposed Warning System

The strong correlation between the occurrence of the "T" phase and destructive Tsunamis warrants the inclusion of instruments suitable for recording T in stations of an earthquake warning system. The "T" phase observed in California are probably too small for practical use. It is believed that SOFAR listening stations would receive far better signals. The relative merits of short period seismographs on land and of hydrophones in the sound channel can be determined by an experimental station having both types of equipment.

Although many points deserve further study, the available knowledge and experience indicates that the utilization of the "T" phase in Tsunami warning systems and the possible installation of hydrophones in the sound channel to augment the present installations is justified.

## Some Points which Deserve Further Study

The relative importance of normal mode and sound channel propagation should be determined. The spectrum of the received signal should be explored. The effect of prolongation of a signal by propagation across land should be determined. The relation between frequency of sound in the water to that received at an inland station should be determined. The feasibility of accurate location of submarine epicenters through use of SOFAR triangulation should be tested.

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