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BIOPHYSICAL MARKERS FOR DELINEATION OF INUNDATION LIMITS OF TSUNAMIS AND STORM SURGES

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ABSTRACT

The Storm Surge and Tsunami inundation limits help in understanding of tidal waves thus created. Various Biophysical parameters(such as electrical conductivity, ionic concentrations, leaf and vegetation reflectance, leaf injury symptoms, salinity sensitive plant species, etc.) are suggested as indicators either individualy or in various combinations. These biophysical signatures left by the waves may be traceable, even after the wave inundation events, to delineate the inundation limits. The information so gathered would be helpful in protection and mitigatation efforts to safeguard from such natural disasters.

1. INTRODUCTION:

The significance of accurate information about exact limits of inundation by Tsunamis and Storm Surges has been emphasized (Loomis, 1978., Wigen and Ward, 1981. Murty, 1989). Among other things, information about the limits of the inundation would be of great value in understanding the phenominon, designing important structures and establishing evacuation zones (Curtis, 1982). Curtis further emphasized this need in saying that,

"It is vital that the effects of a Tsunami disaster be properly surveyed and investigated as it is only through such studies that we can learn something concrete and measureable about such infrequent events for future benefits"

Apparent signs of inundation by the Tsunamis and Storm Surges may disappear or become vague soon after the events(Murty,1989). However biophysical signatures left in soils and vegetation can give indication of the exact limits of inundation.

2. PARAMETERS:

Among the biophysical parameters that can be used for studying effects of environmental stresses, the following may be selected for indication of the inundation limits of the sea water.

a) ELECTRICAL CONDUCTIVITY:

The highly elevated electrical conductivity of the upper horizons of soil would be a good indication of inundation. The soils inundated with sea water will have considerably high electrical conductivity as compared to uninundated soils due to high total salt content of sea water. A portable conductivity meter can be used for field observations. A standard method of conductivity measurement should be used. The conductivity so observed would be proportional to the total salinity of the soils.

b) IONIC CONCENTRATIONS:

Levels of Cl^-, Mg^{++} and Na^+ ions in the soils can indicate the presence or absence of inundation as there are wide differences in the soils that have been subjected to saline sea waters as compared to the soils that have been exposed to rain or irrigation water. Table 1 shows the typical comparison of sea water and fresh water content of these ions. Ion specific electrodes can be used to check the levels in the field. Cl^- is considered as a good tracer as it is not adsorbed by soil and is not altered by plants and other organisms (Sawyer and McCarty, 1978).

TABLE I. Comparison of selected sea water and fresh water contents (from Riley and Chester, 1971.)

ION	SEA WATER (ug/l)	FRESH WATER (ug/l
Na^+	11.05×10^6	9,000
Mg^{++}	1.326×10^6	4,100
Cl^-	1.987×10^7	8,000

c) LEAF AND VEGETATION REFLECTANCE:

The foliar reflectance has been used to express chlorophyll level in both individual leaf and the general vegetation. After the inundation of the sensitive low plants the lower level of chlorophyll would be expressed as eteolation which can be detected by using a hand held reflectance meter. Similarly a stand of low vegetation would show changes in reflectance which in correlation with ground observations can be used to show the inundation limits on color photographs.

d) LEAF INJURY SYMPTOMS:

Sodium chloride (a major component of sea water chemistry) can cause severe damage to vegetation (Mulhotra and Blaul, 1980). The leaf injury symptoms, primarily caused by chloride accumulation in leaf tissue, can be utilized in demarcation of the inundated area. The local sensitive species may show characteristic symptoms and color changes of the leaf tissue. Various groups of plants (including crustaceous lichens, and bryophytes of the area) can be used as indicators. It is important that the observer should be able to distinguish the salt injury from injury by other causes. A correlation of injury with Cl^- content of the foliar tissue would be required. Foliar tissue are such effective accumulators of chloride that the chloride concentration in the leaves may be several times higher than that of the surrounding soil (Mulhotra and Blaul, 1980).

e) SALINITY SENSITIVE PLANT SPECIES:

Absence of the salinity sensitive plant species, from their typical ecosystems in which they are normaly found, can be another indication of the area's inundation. However care must be taken to assess their salinity tolerence limits and their phytosociological association with specific habitats should be known.

f) SALINITY SENSITIVE SOIL MICROBIOTA:

Drastic changes in the soil salinity would be expressed in the changes of the sensitive microbes (such as soil fungi) in the upper horizons of soil. Plating of the soil from various sites using suitable growth media would indicate the salinity affected soils even after some time from the occurence of the Tsunamis and Storm Surges.

g) STEREOSCOPY OF THE INUNDATED AREA PHOTOGRAPHS:

Correlation of the above mentioned parameters with the small scale photographs taken after the inundation can be a useful tool to map the inundated area by remote sensing and would be useful for future observations.

3. DISCUSSION:

The parameters described above may be used in various combinations to indicate the inundation limits. The converging evidence so developed can be used to indicate precise limits of inundation. The biophysical signature left on the inundated landscape could be established for future reference.

The evidence of limits of inundation so emerged should be dependable. However a multidiscipilinary approach would require a multidiscipilinary background and training of personnel performing the survey. A pre-inundation biophysical survey of the high risk areas would be greatly helpful for later studies as a baseline information. The parameters suggested should be further subjected to experimentation to assess the local limitations.

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ON SOURCES OF ERROR IN CALCULATION OF TSUNAMI TRAVEL TIMES

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ABSTRACT

Sources of error in calculating tsunami travel times are examined. Factors contributing to overestimation include using a constant map scale factor in areas where the actual map factor is larger, neglect of influences of the earth's rotation, and neglect of resonance with an undulating sea bottom. Factors contributing to underestimation are sub–grid scale fluctuations in bottom topography and use of the long wave formula for large depths and/or short wavelengths. Recommendations are made for improving computation of tsunami travel times.

1. INTRODUCTION

The tsunami travel time is the time elapsed between the creation of a tsunami and its arrival at a given point. The travel time is often overestimated when calculated by conventional techniques (Murty *et al.*, 1987). That is, the actual tsunami arrives sooner than predicted. This can have potentially disastrous effects if the premature arrival of the tsunami catches people unprepared. A late arrival of the tsunami can also have serious consequences if people assume the warning was a false alarm and resume their normal activities. Finding the causes of the errors in computed tsunami travel times and designing improved methods are important problems.

The time required for a tsunami to travel from its point of origin A to another point B is (Braddock *et al.* (1981, Eq. (2))

$$\tau = \min \int_A^B \frac{ds}{c} \tag{1}$$

where c is the speed of the wave and ds is a horizontal line segment on the earth's surface. The integral is minimized with respect to all possible paths between points A and B.

Usually one sets

$$c = c_0 \tag{2}$$

where

$$c_0 = (gh)^{\frac{1}{2}} \tag{3}$$

is the speed of a long gravity wave on a non–rotating earth and h is the water depth.

Sources of error in employing (1)–(3) are discussed in Section 2. Recommendations for improved methods are presented in Section 3.

2. SOURCES OF ERROR IN CALCULATION OF TSUNAMI TRAVEL TIMES

2.1 Improper Use of Map Projections with a Variable Map Scale Factor

The map scale factor is defined as

$$m = \frac{dS}{ds} \tag{4}$$

where dS is the length of a horizontal line segment on the projection.

As an example, consider a case in which c is constant and point B lies directly north of A. Then

$$ds = a\, d\varphi \tag{5}$$

where a is the earth's radius and φ is latitude. Substituting (5) in (1) yields

$$\tau = \frac{a(\varphi - \varphi_0)}{c} \tag{6}$$

where φ and φ_0 are the latitudes of the final point and source, respectively.

Now

$$c = \frac{\dot{Y}}{m} \tag{7}$$

where Y is the northward distance on the projection and the dot denotes the substantial derivative. Substituting (7) in (1) gives

$$\tau = \int_{\varphi_0}^{\varphi} \frac{m\ a d\varphi}{\dot{Y}} . \tag{8}$$

Assume a Mercator projection is used for which

$$m = \frac{\cos\ \varphi_s}{\cos\ \varphi} \tag{9}$$

where φ_s is the standard latitude (latitude at which $m = 1$). Suppose one makes the approximation that variations of m in (7) may be ignored and that $m = 1$. Then

$$\dot{Y} = c . \tag{10}$$

Substituting (9) and (10) in (8) yields the calculated travel time

$$\tau' = \frac{a\ \cos\ \varphi_s}{c}\ \ell n \left[\frac{(1\ +\ \sin\ \varphi)\cos\ \varphi_0}{(1\ +\ \sin\ \varphi_0)\cos\ \varphi} \right] \tag{11}$$

which differs from the correct travel time (6).

Define the relative error

$$\epsilon = \frac{\tau' - \tau}{\tau} . \tag{12}$$

Substituting (6) and (11) in (12) gives

$$\epsilon = \frac{\cos\ \varphi_s\ \ell n \left[\frac{(1\ +\ \sin\ \varphi)\cos\ \varphi_0}{(1\ +\ \sin\ \varphi_0)\cos\ \varphi} \right]}{(\varphi - \varphi_0)} - 1 . \tag{13}$$

Note that ϵ is independent of c. To obtain numerical values, let $\varphi_s = \varphi_0 = 0$ and $\varphi = \pi/3$ (60° N). Then (12) gives

$$\epsilon = 0.26 .$$

Note that $\epsilon > 0$, the computed time is too large, and the tsunami arrives sooner than expected. This is because $m \geq 1$ from (9). Setting $m = 1$ in (7) understimates $\dot{Y}$ (the speed on the projection) and overestimates the travel time. To alleviate this error one should use the local value of m when computing $\dot{Y}$ from (7).

2.2 Neglect of Rotational Effects

The speed of free surface waves is increased by rotational effects, particularly for long wavelengths and shallow depths (Haltiner and Williams (1980, p. 42)). Eq. (2) should be replaced by

$$c = c_r \tag{14}$$

where

$$c_r = c_0\left[1 + \frac{(fL/2\pi)^2}{gh}\right] \tag{15}$$

f is the Coriolis parameter and L is the wavelength. For $f = 10^{-4}s^{-1}$, $L = 1000$ km and $h = 100$ m, (15) gives

$$\frac{c_r}{c_0} = 1.12 \, .$$

For $h = 1000$ m,

$$\frac{c_r}{c_0} = 1.01 \, .$$

Since (2) underestimates the speed, its use will overestimate the travel time and the tsunami will arrive sooner than expected.

2.3 Sub-Grid Scale Fluctuations in Bottom Topography

Holloway *et al.* (1986) showed that the effect of unresolved depth variations (what they termed "roughness") resulted in Eq. (3) overestimating c_0 when the smoothed depth is used in place of the actual depth. Hence the travel time is underestimated and the tsunami arrives later than expected.

One way to explain this effect (not give by Holloway *et al.*) is to define

$$\hat{c}_0 = (g\bar{h})^{\frac{1}{2}} \tag{16}$$

and

$$\bar{c}_0 = \overline{(gh)^{\frac{1}{2}}} \tag{17}$$

where the bar denotes a space average between two points. Computing the travel time from (17) is more accurate than using (16). We will show that $\hat{c}_0 > \bar{c}_0$. That is, neglecting the variations in h leads to an overestimate in the wave speed.

Let

$$\eta = h^{\frac{1}{2}} \, . \tag{18}$$

Now

$$\overline{\eta^2} = \bar{\eta}^2 + \overline{\eta'^2} \tag{19}$$

where $\eta' = \eta - \bar{\eta}$ and $\overline{\eta'} = 0$. Eq. (19) holds for any variable, not just (18). From (19),

$$\overline{\eta^2} > \bar{\eta}^2 \, .$$

Therefore

$$\overline{\eta^2}^{\frac{1}{2}} > \overline{\eta} \, . \tag{20}$$

Substitute (18) in (20):

$$\overline{h}^{\frac{1}{2}} > \overline{h^{\frac{1}{2}}} \, . \tag{21}$$

From (16) and (17), (21) implies that

$$\hat{c}_0 > \overline{c}_0 \, . \tag{22}$$

That is, ignoring fluctuations in h and using (16) instead of the more accurate (17) results in an overestimate in the wave speed.

2.4 Other Influences

From the results in Section 2.3, one would expect non–uniform water depths to cause a reduction in the phase speed of long gravity waves. However McGoldrick (1968) (summarized by Murty *et al.* (1987)) reported that for a range of wavelengths of the bottom profile close to the wavelength of the surface wave, the wave is not retarded but instead travels faster than the speed based on the average depth given by (16). This is due to a type of resonance in which (2) is no longer strictly valid.

Eq. (2) is the upper limit to the phase speed for large L/h. The more general expression is

$$c = c_0 \left[\frac{1}{\mu} \tanh \mu\right]^{\frac{1}{2}} \tag{23}$$

where $\mu = 2\pi h/L$. For $L/h = 10$, $c/c_0 = 0.942$. For $L/h = 20$, $c/c_0 = 0.984$. Thus for large depths and/or short wavelengths, (2) overestimates the phase speed.

2.5 Summary of Factors Affecting Tsunami Travel Times

The following factors can result in an underestimate of the wave speed and an overestimate of the tsunami travel time (tsunami arrives sooner than expected):

- use of a constant map scale factor (ratio of distance on the projection to the actual distance on the earth's surface) in areas where the correct map factor is greater than the constant value used (Section 2.1).
- neglect of effects of the earth's rotation (Section 2.2).
- neglect of resonance with an undulating sea bottom (Section 2.4).

The following influences can lead to an overestimate in wave speed and an underestimate in tsunami travel time (tsunami arrives later than predicted):

- sub–grid scale variations in bottom topography (Section 2.3).
- use of Eq. (2) for short wavelengths and/or large depths for which (2) overestimates the wave speed (Section 2.4).

3. IMPROVING THE ACCURACY OF CALCULATED TSUNAMI TRAVEL TIMES

The source of error noted in Section 2.1, assuming the map factor is constant whereas it actually varies, is easily avoided. Solve (4) for $ds = dS/m$ and substitute in (1) to give

$$\tau = \int \frac{dS}{mc} . \tag{24}$$

In (24) mc is the wave speed on the projection. In evaluating (24), simply use the local value of m instead of a constant value. In the example discussed in Section 2.1, $m \geq 1$ and setting $m = 1$ in (24) underestimates the wave speed on the projection and overestimates the travel time. Another way to avoid the problem is to use spherical coordinates.

Incorporating rotational effects by using (14) and (15) is straightforward if L is known. This may be determined by applying spectral analysis to water levels to find the period T of the component whose amplitude is largest. Then L is evaluated from

$$L = cT \tag{25}$$

which may be approximated by

$$L = c_0 T \tag{26}$$

since c is not yet known.

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CONTRIBUTION FOR THE STUDY OF TECTONIC ACTIVITY OF THE MEDITERRANEAN SEA FROM VOLCANIC ACTIVITY AT SEA AND NEW ISLANDS EMERGED IN HISTORIC TIME

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ABSTRACT

A new list of submarine volcanic eruptions occurred since the year 186 B.C. in the Central and Eastern Mediterranean is presented. The list may be added to the Smithsonian Catalogue of Volcanoes and Volcanic Eruptions of the World. A list of new islands emerged in historic time in the Central and Eastern Mediterranean and Azores Islands is included. The analysis of the data presented confirms the stability of volcanic activity at sea in the Lipari Islands (South Tyrrhenian) and in Santorini (Aegean Sea). The analysis of the data confirms also the hazard caused by volcanic activity under the sea.

The first scientific work of volcanology comes from Bernhardt VAREN (1622-1650), latinized in Varenius, that with his "*Geographia generalis in qua affectiones generales telluris explicantur*" (1650) treating of volcanoes and of the dates of the relative eruptions.

The most recent and complete list of volcanoes and relative eruptions is that of SIMKIN *et al.* (1981) with 5564 dated events.

The present note, concerns almost only the Central and Eastern Mediterranean regions and contains a list of submarine volcanic eruptions, where some of them generated new islands.

The birth of new islands, although some of them lived only for a short time, and the submarine eruptions are geographically and geologically very important for assessing tsunamis and seismic risk and also for the studies of the tectonics of the region: herein we limit the present note to a list of emerged islands in historic time as well as to the volcanic eruptions not included in the catalogue of SIMKIN *et al.* (1981), probably for the lack of knowledge of the works of CAPOCCI (1861a; 1861b; 1863).

The historiographic research mainly follows the galileian experimental principles that gave a remarkable contribution to the study and, sometimes, to the solution of many important problems, such as the determination of the variation of the ancient level of the Thyrrenian Sea which was made through the survey of swimming pools, fishing ponds and harbor's piers of Greek and Roman times (CAPUTO and PIERI, 1976), the formulation of catalogues of earthquakes (*e.g.* CAPUTO and POSTPISCHL, 1975; CAPUTO, 1979a) and of tsunamis (CAPUTO and FAITA, 1984; BEDOSTI and CAPUTO, 1986) with the aim to establish the seismic and tsunami hazards of the Italian coasts and also the study of the bradyseism of the Phlegrean Fields (*e.g.* CAPUTO, 1979b).

The seismic hazard is well known from a long time, while the tsunami hazard was almost completely neglected untill the above mentioned Authors payed attention, for the italian coasts, on these phenomena and to the problem of the damage prevention and of the human safeguard.

The historic documents consulted for the above mentioned research revealed an inexaustible source of information of great scientific interest and, in particular, geographical, geological and sociological and are usefull to estimate the possibility to prevent and protect ourselves from the natural disasters.

In particular our attention was attracted to the volcanic eruptions on the sea floor and by the formation of new islands occurred in historic time.

In general these phenomena did not cause great damage or casualties and therefore did not receive much attention in the chronicles of their time; while those on land often caused damages although the most striking natural phenomenon, which happened in historic time, is the eruption of the Krakatoa (August 27th, 1883), with rumblings heard 5000 km far, with ash ejected as high as 80 km and that caused a tsunami almost all over the world with waves taller than 30 metres.

The chroniclers and the historians did not pay much attention to the phenomena occurred on the bottom of the sea. Nevertheless, patient researches and an increasing care may improve our knowledge on the frequence and the assessment of the entity of these phenomena.

A usefull example of the importance of the expanding of the historic research in improving the quality of the catalogues of natural phenomena of the past is the succession of the italian catalogues of earthquakes: that of CAPUTO and POSTPISCHL (1975), prepared in 1969, with about 5000 events, was followed by CARROZZO *et al.* (1973) with about 10000 events; then, has been published the catalogue of ENEL (1979) with more than 20000 events and finally that of CNR (1985) with more than 41000 events and the notice that is necessary a complete revision of the catalogue itself.

Analogously for the catalogues of tsunamis a first study (CAPUTO and FAITA, 1982) of the informations collected seemed to allow to establish, to some approximation, the intensity of many events, about the hundred of the one hundred forty events on which some information was available, and to doubt the nature of the others.

But the same authors, after a more accurate study of the information (CAPUTO and FAITA, 1984), decided that is not reliable to consider the most catastrophic chronicles of an event as those referring tha maximum damage.

Sometimes those chronicles are due to the most emotional and imaginative reporter.

A good example of these exagerations is the chronicle of the "exceptional" facts of the year 890 when many disastrous earthquakes occurred. In order to accentuate the exceptionality of the events occurred in that year a reporter (BONITO, 1698) narrates of a wolf entering the city of Arezzo and killing more than hundred persons and that no weapon could injure it.

If the presentation of the fact occurred in that city is to be taken as figurative, then we may ask ourselves which is the real fact occurred in the city and, more important, in how many other circumstances the real facts have been exagerated.

These considerations are to be applied also to the catalogues of earthquakes and tsunamis; and the intensity of an earthquake or of a tsunami should be accepted only when the reporter has a reputation of professionality and objectivity beyond any doubt or when there are at least two sources which report the same fact and the sources are really independent.

The cases in which the sources could seem independent, but in practice are not independent, are too frequent and extreme caution should be used in assigning the intensity.

The caution used in the first catalogues of tsunamis (CAPUTO and FAITA, 1984) and its first updating (BEDOSTI and CAPUTO, 1986) where only the information gathered was quoted without sorting any measure of the event should be used also for this list of new islands and submarine volcanic eruptions. As for the catalogues of earthquakes and those of tsunamis, also for the list of new islands, generally of volcanic origin, and submarine volcanic eruptions, the completeness will be reached in successive steps as we noted already.

Here we will limit ourselves to report the information by means of a direct quotation from the original chronicle in the original language of the text.

We will treat the submarine eruptions as important as the new islands because both are indicative of an intense tectonic activity.

Often it is difficult to estimate the amount of material erupted because of the difficulty in establishing the location where the phenomenon occurred and therefore the depth of the water.

Two main features of the tectonic activity are the volcanic and the seismic activity. It is important to stress the differences and the similarities between the two phenomena for a better understanding of the data recorded in historic times; expecially the differences, because of the different approach which follows for the study of tectonics.

First of all, while the seismicity is usually widespread over an area, the volcanic activity is concentrated in few and limited zones (excluding mid-oceanic rifts not existing in the Mediterranean). An example is the Aegean region where is noted that seismicity covers almost all the area while volcanism is concentrated in few points. This difference is shown in figure 1 where are reported the epicentres of the shallow earthquakes of the period 1901-1985 (COMNINAKIS and PAPAZACHOS, 1986) and the volcanoes active in historic time (375 B.C.-1987).

The volcanism is always a superficial feature of deep magmatism directly related to the upper mantle or to magmatic chambers in the middle-lower crust.

Moreover, the seismicity is strictly related to the stress field which could be of any type (compressional, shear, extensional); the volcanism, considered as an appendix of the deep magmatism, is possible only in an extensional regime (see back-arc areas, mid-oceanic rifts, grabens, etc.). In figure 1 is also possible to see that all the volcanoes active in historic time are enclosed in an area undergoing to a tensional regime.

In a more global view, an important feature of the seismicity is the direct and tight relation with the tectonics of the plates. While volcanism presents diverse kinds of relationships: this is very close along the mid-oceanic rifts;

is secondary in the back-arc systems and finally there is no relationship in the hot-spot centres.

After these considerations is easy to understand why the volcanic eruptions, due to their concentration in few locations mostly at sea, have so scarce historic record, and consequently the analysis of the evolution of the phenomena concerning them is more difficult.

The importance of the record in historic time of the volcanic phenomenon, follows also from the actualism theory, so important for the development of the Earth Sciences. In such a way studying the evolution and the cyclicity of the volcanoes, in historic time, we could explain phenomena occurred during older volcanic acitivity.

Fortunately the Mediterranean region is the most provided of ancient records. At this regard is interesting the analysis made by SIMKIN *et al.* (1981) of the relation between the historic record and the growth of the population in the world; they denote an exponential increase of the number of known volcanoes almost parallel to the exponential increase of the world population. Striking is the difference between the world trend and the Mediterranean one. Nearly 2,000 years ago, while in the world were known only few percent of the actually known volcanoes, in the Mediterranean region, the almost totality was already known and their activity recorded.

In this list of submarine events are also few which occurred near the Azores, therefore very far from the Mediterranean; we have listed them because the information may be useful for other researches of this type.

From what we said follows that the discovery of three historic documents of the same author (CAPOCCI, 1861a; 1861b; 1863) brought to the knowledge of 10 and 4 volcanic eruptions in the Central-Eastern Mediterranean and in the Azores Islands, respectively, which were not reported in the catalogue of SIMKIN *et al.* (1981) that consider the regional file and the chronology of the volcanism of the last 10,000 years. Furthermore, this catalogue contains the italian one of IMBO (1965) where are reported detailed descriptions of the volcanoes and of the eruptions.

Nevertheless, the addition of ten eruptions to the catalogue of SIMKIN *et al.* (1981) represents a small percentage of the whole number of known events in the Mediterranean region and it confirms the validity of the catalogue of the Mediterranean region with respect to the world's one.

The benefit of a historic research of the emerged islands has been stressed in a previous work (BEDOSTI and CAPUTO, 1986) and, in this note, we considered also the submarine eruptions that did not generate new islands because it is not possible to distinguish the geographic interest from the geological one, neither the social interest from the geographic and geological ones.

For the navigation, it is all the same if a submarine eruption built a lava reef few metres below the sea level or above it and subsequently eroded by the waves or a more permanent island: all of them are extremely dangerous. Geologically they are equally important volcanic phenomena and eventually they prove the tectonic activity.

Note for the catalogue

The date corresponds to the day, month and year of the eruption or it indicates the period of almost continuous eruptions. Sometimes was possible only to indicate the year of the event.

The dates with an asterisk refer to the events not included in the catalogue of SIMKIN *et al.* (1981).

Locality is referred to the main volcanic region of the Mediterranean and the Azores Islands.

Reference codes are listed below; the number(s) after the code, in the catalogue, indicate(s) the page(s) of the original paper.

BA = BARATTA, 1901
BU = BULLARD, 1962
C1 = CAPOCCI, 1861a
C2 = CAPOCCI, 1861b
C3 = CAPOCCI, 1863
MA = MALLET, 1852-1854
ME = MERCALLI, 1907
MR = MALARODA and RAIMONDI, 1957

Date 186 B.C.* and 19 A.D.*.

Locality: Aegean.

Reference: **ME, 259**: "Negli anni 186 av Cr. e 19 d. Cr. si formarono due isolotti, che, fusi insieme, costituirono la Paleokameni, [...]".

[In the years 186 B.C. and 19 A.D. two islets were formed, merging together, they created the Paleakameni].

Date: 183 B.C.

Locality: Southern Tyrrhenian.

Reference: **ME, 261**: "Forse in modo simile ebbe origine Vulcanello (isole Eolie) nel 183 av. Cr., per una eruzione sottomarina descritta da Polibio; esso, infatti, è costituito essenzialmente come Giorgio I, cioè da un nucleo di lave andesitiche surmontate da un conetto di detriti con tre crateri".

[Perhaps, in a similar way Vulcanello (Eolie Islands) was generated in 183 B.C., because of a submarine eruption described by Polybius; it is mainly made, like Giorgio I, by a nucleus of andesitic lavas overflowed by a little detritic cone with three craters] (see refer. 4.2.1866).

BU, 182: "Pliny records that an island emerged from the sea among the Lipari Islands early in the second century B.C. and later Grosius give the date as 182 B.C. Apparently on the strength of these references and on the assumption that the island was Vulcanello, the British Admiralty Handbook gives the date for the birth of Vulcanello as about 183 B.C. Judd (1875), Di Fiore (1922), and others have accepted this date for the birth of Vulcanello. It is the one commonly found in the literature".

Date: 41 A.D.*.

Locality: Aegean.

Reference: **C2, 389**: "germoglio vulcanico, simile a quello dell'anno 41 descritto da Seneca".

[Volcanic sprout, similar to that of the 41 A.D. described by Seneca] (see refer. 726 A.D.).

Date: 31.12.46.

Locality: Aegean.

Reference: **C1, 337**: "31 dicembre di notte eruzione di una nuova isola nell'Egeo".

[31st of December, during the night, eruption of a new island in the Aegean].

C2, 380: "Quest'isola apparve tra le altre due Thera e Theramme, nel gruppo vulcanico ora detto dell'isola di Santorino. Dione pone il fenomeno nell'anno seguente; ma Bonito fa notare che, attesa la data dell'ultimo giorno dell'anno, ciò non si oppone a ciò che dice Seneca e tanti altri autori cioè l'anno 46".

[This island appeared between the other two, Thera and Theramme, in the volcanic group actually called of the Santorini Island. Dione places the phenomenon in the following year; but Bonito notes that, confirming the last day of the year, this does not contradict the assertion of Seneca and many other Authors, *i.e.* 46 A.D.].

Date: 726 A.D.

Locality: Aegean.

Reference: **C1, 338**: "Eruzione di una nuova isola nell'Egeo fra Thera e Therasia detta Jera".

[Eruption of a new island in the Aegean, in between Thera and Therasia Islands, called Jera].

C2, 389: "Hoc anno cum tamquam ex camino vapor ebulliret inter Theram et Thorasiam insulas, tandem concreti lapides, ut pumices erumperunt, qui Asiam, Lesbum, Abydum et maritima Macedonie fere obruerunt; tandem prope Insulam Sacram Insula erupit, cum ante nulla esset. Quest'isola fu detta Iera (Hiera, Sacra) e viene anche attestato da Teofane e da Niceforo. E' un altro germoglio vulcanico simile a quello dell'anno 41 descritto da Seneca".

[This year, between the islands of Santorini and Thorasia, the vapour began to rise, as from a chimney, untill stones like pumice were ejected drapping the Asia, Lesbo Island, Abydo and the Macedonian coast and then, near the Isola Sacra an island was born where nothing was before. This island was called Iera (Hiera, Sacer) and this is testified also by Teofane and Niceforo. This is another volcanic sprout similar to that of the year 41 described by Seneca].

Date: 4.2.1444.

Locality: Southern Tyrrhenian.

Reference: **BU, 183**: "The modern history of Vulcano begins with accounts by Frazello, a native of Sicily, who described the great eruption of February 4, 1444, which shook all the Sicily and was felt as far away as Naples. It is said that the sea "boiled" all around the island [of Vulcano] and that vast rocks were discharged into it. Submarine eruptions were indicated by reports that smoke was rising from the waves at a number of points. Following the eruption navigation around the island was totally changed because of the presence of many new rocks".

Date: 5 or 30.12.1456*.

Locality: Aegean.

Reference: **C3, 302**: "L'emersione della nuova isola nell'Arcipelago vien registrata da Bzovio, da Enea Silvio ecc. dicendo questo ne' Comentari delle cose memorabili <Tum quoque in Aegeo Pelago insula emersit, numquam ante visa, parva circuitu, verum alta super aquas 40 cubitis, arsitque diebus aliquot donec flammae defuit bitumen>".

[The rise of the new island in the Archipelago, has been recorded by Bzovio, Enea Silvius etc. saying this in the Comentari delle cose memorabili <Then, in the Aegean Sea too an island rose, never seen before above the sea level, small in diameter but 40 cubiti high (roughly 18 m) and burned for some days untill the bitumen finished>].

C1, 341: "Eruzione di una nuova isola nell'Egeo".

[Eruption of a new island in the Aegean].

Date: 1570-1573.

Locality: Aegean.

Reference: **ME, 259**: "[...] a nord-est della quale [Paleakameni] sorse negli anni 1570-1573 un'altra isola detta Mikrakameni".

[North-eastern of the Paleakameni an other island, called Mikrakameni, was born during the years 1570-1573].

Date: 3.2.1624*.

Locality: Azores Islands.

Reference: **C1, 345**: "Anche nelle Azzorre forte terremoto, durante l'eruzione di una nuova isola".

[In the Azores Islands too a strong earthquake happened during the eruption of a new island].

Date: 11.1624*.

Locality: Azores Islands.

Reference: **C1, 345**: "Novembre; eruzione di una nuova isola presso S[an] Michele nelle Azzorridi".

[November; eruption of a new island close to Saint Michel in the Azores Islands].

Date: 1631*.

Locality: Strait of Sicily.

Reference: **C1, 346**: "Eruzione di una nuova isola nel mar di Sicilia".

[Eruption of a new island in the Sea of Sicily].

Date: 2.1632.

Locality: Strait of Sicily.

Reference: **C1, 346**: "Ma a mezzo febbraio [...]. In questo torno dicesi si formasse una nuova isola nel mar di Sicilia".

[In the mid of February [...]. It is sayed that in this time a new island was formed in the Sea of Sicily].

Date: 1638.

Locality: Azores Islands.

Reference: **ME, 266**: "Nello stesso arcipelago della Azzorre, altre quattro volte, cioé nel 1638, nel 1720, nel 1757 e nel 1811, comparvero sopra le acque nuove isole di detriti vulcanici [...]. L'eruzione del 1638 avvenne presso S[an] Michele".

[In the Azores Archipelago, four more times, *i.e.* in 1638, 1720, 1757 and 1811, new islands of volcanic detritus appeared above the sea level [...]. The eruption of 1638 occurred close to Saint Michel] (see refer. *ad annos*).

BU, 311: "In 1638, and again in 1811, submarine eruptions near the eastern end of the group formed weak ash and cinder cones which were soon destroyed by wave erosion".

Date: 1650.

Locality: Aegean.

Reference: **ME, 259-260**: "Nel 1650 avvenne un'eruzione sottomarina fuori del recinto [di Santorino], a N.E., e costruì un isolotto che venne poi demolito dal mare, restando la Secca Culombo".

[In 1650, a submarine eruption occurred outside the crater of Santorini, northeast of it, and built an islet, which was later destroyed by the sea, creating the shallows Culombo].

Date: 1707.

Locality: Aegean.

Reference: **C1, 351**: "Apparizione di una nuova isola nell'Arcipelago presso Santorino".

[Apparition of a new island in the Archipelago close to Santorini].

Date: 1707-1709.

Locality: Aegean.

Reference: **ME, 260**: "Un'eruzione più forte ebbe luogo dal 1707 al 1709, e per essa si formò la Neakameni situata tra Micra e Paleokameni".

[A stronger eruption occurred from the 1707 to the 1709 and the Neakameni was formed between the Mikrakameni and the Paleokameni] (see refer. 1638).

Date: 1719-1720.

Locality: Azores Islands.

Reference: **ME, 266-267**: "[...] quella [eruzione] del 1719-20 [avvenne] presso Terceira (a 38° 29' lat. N. e 26° 43' W. di Gr.)".

[The eruption of 1719-20 occurred near Terceira at 38° 29' N, 26° 43' W].

Date: 10.1756*.

Locality: Southern Tyrrhenian.

Reference: **C1, 353**: "In Ottobre dicesi apparisse nell'Arcipelago una nuova isola".

[In October it is sayed that a new island appeared in the Archipelago].

Date: 1757*.

Locality: Azores Islands.

Reference: **ME, 267**: "[...] e quella [eruzione] del 1757 [avvenne] più vicino a S[an] Giorgio. Nel 1757 comparvero in mare 18 piccole isolette nuove (Von Hoff e Trans. Fil. di Londra, an. 1792)".

[The eruption of 1757 occurred closer to Saint George. In 1757 eighteen new small islets were born in the sea] (see refer. 1638).

Date: 1794*.

Locality: Asia Minor.

Reference: **C1, 356**: "Nuovo isolotto vulcanico sorto tra Tenedo e la spiaggia asiatica".

[New volcanic islet born between Tenedus and the asiatic beach].

Date: 13.6.1811.

Locality: Azores Islands.

Reference: **ME, 266-267**: "Nello stesso arcipelago delle Azzorre, altre quattro volte, cioé nel 1638, nel 1720, nel 1757 e nel 1811, comparvero sopra le acque nuove isole di detriti vulcanici, l'ultima delle quali, di 90 metri di altezza, venne chiamata isola Sabrina. Ma tutte scomparvero, come l'isola Giulia, distrutte rapidamente dal mare. La formazione dell'isola Sabrina è così descritta in un opuscolo del tempo (Tradition écrite dans l'opuscole de Jeronimo Emiliano d'Andrad. Copia m[ano]s[critta] nella biblioteca di A. Perrey, ora posseduta dalla Società nap[oletana] di Storia patria.). <Le 13 juin 1811, a 2 kilom[ètre] de la cote de l'ile S[ain]t Michel, en face la pointe de Ferraria, en mer, une éruption volcanique, qui causa dans l'ile de frequents et violents tremblements de terre, lança du sein des eaux et de la profondeur de 70 m. environ des turbillons de cendres, de feu, de fumée, et de blocs de pierres accompagnés d'une clarté tres vive et d'un bruit semblable a celui de l'artillerie, puis de la mosqueterie alternée. La mer fut couverte de poissons morts et de dejéctions volcanique> ... <Le 14 juillet l'éruption et les commotions avaient cessé. L'equipage d'un batiment anglais descendit sur l'ilot...> Il chiarore assai vivo attesta probabilmente la presenza di fiamme (come nel 1867 presso Terceira), e la piccola profondità di 70 m. spiega come tanto rapidamente il Vulcano sia divenuto subaereo".

[In the same Azores Archipelago, other four times, *i.e.* in 1638, 1720, 1757 and 1811, new islands of volcanic detritus appeared above the sea level, the last one of which 90 m high was called Sabrina. But all of them disappeared, like the Ferdinandea Island, suddenly destroyed by the sea. The formation of the Sabrina Island is described as follows in a booklet of that time (Tradition ecrite dans l'opuscole de Jeronimo Emiliano d'Andrad. Manuscript of the library of A. Perrey, and now of the Società napoletana di Storia patria.). <Le 13 juin 1811, a 2 kilomètre de la cote de l'ile St. Michel, en face la pointe de Ferraria, en mer, une éruption volcanique, qui causa dans l'ile de frequents et violents tremblements de terre, lança du sein des eaux et de la profondeur de 70 m environ des turbillons de cendres, de feu, de fume, et de blocs de pierres accompagnés d'un clarté tres vive et d'un bruit semblable a celui de l'artillerie, puis de la mosqueterie alternée. La mer fut couverte de poissons morts et de dejections volcanique> ... <Le 14 juillet l'éruption et les commotions avaient cessé. L'equipage d'un batiment anglais descendit sur l'ilot...>). The strong brightness probably witnesses the presence of flames (as in 1867 near Terceira) and the shallow depth (70 m) explains how quickly the volcano emerged] (see refer. 1638).

BU, 311: "in 1811, submarine eruptions near the eastern end of the group formed weak ash and cinder cones which were soon destroyed by wave erosion. The eruption of 1811 formed Sabrina Island, off the coast of Sao Miguel, in the eastern Azores. It consisted of loose cinders and atteined a height of three hundred feet above sea level with a circumference of about one mile. The eruption lasted eight days, but soon thereafter Sabrina was destroyed by wave erosion".

Date: 27.10.1811*.
Locality: Azores Islands.
Reference: **C1, 358:** "Apparizione di una nuova isola (Sabrina) nelle Azzorridi, indi distrutta dalle onde".

[Apparition of a new island (Sabrina) in the Azores Islands, then destroyed by the waves].

Date: 2.7.1831.
Locality: Strait of Sicily.
Reference: **C1, 362:** "Ai 28 giugno principia l'eruzione sottomarina, che formò la nuova isola temporanea di Sciacca".

[The 28th of June began the submarine eruption which generated the new temporary island of Sciacca].

BA, 365-366: "Al 28 giugno, a 21h 15m ital[iane] a Sciacca forte scossa ond[ulatoria] sentita anche nella costa vicina e nel mare fra questa e l'isola di Pantelleria, il 30 giugno, ad 11h 40m se ne ebbe una più forte delle precedenti che causò molto panico nella popolazione [...]. A 7h di mattina ed a

4h circa di sera del 1 luglio lievi tremori; a 7h del 2 scossa molto forte: a 16h della stessa giornata una alquanto intensa ed a 22h altra lieve. Queste scosse ed altre parecchie leggiere, avvertite da pochi, furono i prodromi dell'eruzione sottomarina: cessate le scosse, nel giorno 2 fu avvertito un insolito ribollimento del mare tra la Sicilia e l'Affrica a 30 miglia circa SW di Sciacca e precisamente a 37° 2' di lat. N e 30° 16' di long. E dall'isola di Ferro. Tale eruzione sottomarina diede luogo alla formazione dell'effimera isola Giulia o Ferdinandea, la cui massima estensione fu raggiunta circa il 25 agosto, dopo di cui l'azione erosiva delle onde ne iniziò la rapida demolizione".

[The 28th of June, at 9.15 p.m. italian time, strong earthquake at Sciacca felt also along the near coast and in the sea between this and Pantelleria; the 30th at 11.40 a.m., a stronger one caused panic in the people. ... At 7.00 a.m. and at 4.00 p.m. of the 1st of July, light quakes; at 7.00 a.m. of the 2nd, very strong earthquake: at 4.00 p.m. of the same day, one very strong and at 10.00 p.m. a light one. These earthquakes and many light others, felt by few, announced the submarine eruption: when the shakes had ceased, the 2nd of July was felt an unusual bubbleing of the sea between Sicily and Africa 30 miles southwest of Sciacca and exactly at 37° 2' N, 30° 16' E of the Ferro Island. This submarine eruption generated the shortlived Giulia or Ferdinandea Island, the maximum extension of which was reached the 25th of August, after that the erosion of the waves began its quick destruction].

MA, 225: "a. 1831, June 28. 5 p.m. In Sicily, expecially at Sciacca. Also felt at Palermo. Very severe shocks, followed by others, up to the 11th of July. Several shocks were felt this day on board the ship Britannia, Admiral Malcom, over the place where new island afterwards appeared. Followed, in July and at the beginning of August, by violent submarine eruption, and the upheaval of a new island between Sciacca and the island of Pantelleria".

MR, 321: "6-7-1831. Bonno Graam (Sciacca-Pantelleria) sottomarina eruzione".

[Submarine eruption at Bonno Graam (Sciacca-Pantelleria)].

Date: 16.2.1832*.

Locality: Strait of Sicily.

Reference: **C1, 362**: "Anche a Sciacca si risente, e vedesi del vapore sul luogo prima occupato dalla nuova isola distrutta".

[It is felt also at Sciacca, and vapor is seen in the location which was earlier occupied by the new island now destroyed].

Date: 18.6.1845*.

Locality: Central Mediterranean.

Reference: **C1, 366:** "Ai 18 giugno ancora il Vesuvio e nello stesso tempo eruzione sottomarina, poco lungi da Malta".

[The 18th of June again the Vesuvius meanwhile a submarine eruption occurred not far away Malta].

Date: 15.2.1866.

Locality: Aegean.

Reference: **ME, 261:** "Intanto verso il 15 febbraio, un secondo domo cominciò ad apparire in mare, pure a sud della Neakameni, ma un poco più ad ovest del primo [Giorgio I], e, superato il livello del mare, si squarciò pure, e diede esplosioni, che però cessarono dopo pochi mesi. Questo secondo domo venne chiamato Aphroessa".

[Nearly the 15th of February, a second dome began to appear at sea, south of the Neakameni Island, but west of the first one (George I) and, when it emerged above the sea level, it broke and gave rise to explosions which ceased in few months. This second dome was called Aphroessa].

Date: 10.3.1866.

Locality: Aegean.

Reference: **ME, 261:** "In modo simile, verso il 10 marzo, appena una diecina di metri a SW di Aphroessa, un terzo isolotto, detto Reka, più piccolo degli altri due [Giorgio I ed Aphroessa]. Dai fianchi squarciati di questi tre domi, sgorgava da molte parti la lava, che, solidificando prontamente, estendeva rapidamente la superficie dei tre isolotti. A poco a poco Aphroessa e Reka si riunirono con Giorgio I e questo colla Neakameni, la quale in tal modo venne più che triplicata di estensione".

[In a similar way, the 10th of March, just ten meters SW of Aphroessa, a third islet, called Reka and smaller of the other two (George I and Aphroessa) was born. From the broken sides of these three domes, lava overflowed and by solidifying it extended the surface of the three islets. Little by little Aphroessa and Reka merged with George I and this with the Neakameni Island which was extended three time in surface].

Date: 5.1866.

Locality: Aegean.

Reference: **ME, 261**: "Verso la fine di maggio (1866) tra Aphroessa e Paleakameni apparvero nuovi scogli (denominati isole di maggio), i quali, secondo Fouque, corrispondevano a nuovi punti d'efflusso sottomarino; invece, secondo Reiss e Stubel, sarebbero semplicemente porzioni affioranti sopra l'acqua di colate d'Aphroessa. A me pare più attendibile la supposizione di Fouque, perchè le isole di maggio erano perfettamente allineate con Giorgio I e Aphroessa".

[At the end of May 1866, between Aphroessa and Paleakameni, new reefs appeared (called the Islands of May) that, following Fouque, corresponded to new points of submarine overflow; on the contrary, following Reiss and Stubel, they should only be outcropping portions of the Aphroessa's lava flows. I think that the supposition of Fouque is more reliable because the Islands of May were perfectly alligned with George I and Aphroessa].

Date: 6.1867.

Locality: Azores Islands.

Reference: **ME, 266**: "Nel giugno 1867, presso Terceira (Isole Azzorre), dopo forti terremoti, si alzarono in mare alte ed impetuose colonne di acqua e di vapori da sei punti principali, disposti in direzione SW-NE, sopra uno spazio ellittico di 5 chilom[etri] di lunghezza per uno di larghezza. Col fumo venivano lanciati in aria getti di nere scorie e il mare appariva intensamente colorato da materia fangose fino alla distanza di 10 miglia. Dopo sette giorni, cessarono i fenomeni eruttivi, continuarono solo sbuffi di gaz infiammabili. Non si notò la formazione di nessun edificio vulcanico, precisamente come a Pantelleria".

[In June 1867, near Terceira (Azores Islands), after strong earthquakes, high and raging columns of water and vapour rose from the sea in six principal sites along a SW-NE direction, in an elliptical space five km long and one km large. With the smoke were ejected in the air black scoring and the sea was coloured by muddy stuff as far as ten miles. After seven days, the eruptions ceased and only snorts of inflammable gas continued. No volcanic cone was noted exactly like at Pantelleria] (see refer. 17.10.1891).

Date: 4.2.1866 - 10.1870.

Locality: Aegean.

Reference: **ME, 260-261**: "L'ultima eruzione cominciò il 4 febbraio 1866. In una baja a sud della Neakameni, dove l'acqua era poco profonda, si squarciò il fondo del mare, e cominciò a sgorgare la lava tranquillamente e silenziosamente. L'azione refrigerante dell'acqua sopra un magma acido, già per se stesso molto viscoso, lo fece accumulare rapidamente verso il punto efflusso, in forma di domo parzialmente solidificato alla superficie. In pochi giorni il domo si alzò, come una grande intumescenza spinta in alto dal nuovo magma, che continuava a sgorgare. Ma appena questa massa lavica, fluida nell'interno, ma esternamente ricoperta di blocchi sconnessi, superò il livello del mare, si squarciò verso la parte centrale e cominciarono le esplosioni, le quali continuarono poi per parecchi anni. Al nuovo isolotto venne imposto il nome di Giorgio I. Le esplosioni cominciarono il 12 febbraio, ma al 4 aprile il cratere era ancora molto piccolo, cioè una apertura di sette metri di diametro formata dall'incrocio di parecchie spaccature (Schmidt).[...] Verso la fine del 1869 Giorgio I era alto 123 m. sul l[ivello] d[el] m[are]. Le esplosioni intermittenti continuarono fino all'ottobre 1870".

[The last eruption began the 4th of February 1866. In a bay south of Neakameni, where the water was shallow, the bottom of the sea broke and lava flows began to overflow quietly and silently. The refreshing action of the water on an acid and very viscous magma acted to quickly generate a dome, near the point of efflux partly solidifyed at the surface. In few days the dome rose up like a big swell pushed up by the still overflowing magma. When the lava, fluid inside but externally covered by blocks, was above the sea level it broke in the central part and the explosions began and continued for many years. The new islet was called George I. The explosions began the 12th of February, but the 4th of April the crater still was very little, that is seven meters of diameter formed by the crossing of many fractures (Schmidt) ... At the end of 1869, George I was 123 m high. The intermittent explosions continued till October 1870].

Date: 19 & 22.11.1888, 30.3 & 11.9.1889, 14.12.1892.
Locality: Southern Tyrrhenian.
Reference: **BU, 185**: "A submarine cable connects Lipari with Milazzo in Sicily. This cable runs about three miles to the east of Vulcano, where the water is from seven hundred to thousand meters in depth. During the eruption the cable was broken five times. The first break occurred on November 22, 1888, and the last on December 14, 1892, nearly eighteen months after activity had ceased in the crater of Vulcano. At the point of the break, usually, a violent boiling of the sea occurred, and pumice or scoria appeared either on the bottom or floating near the location of the break. Without doubt the breaks marked points of eruption on the submerged flank of Vulcano".

Date: 17.10.1891.
Locality: Strait of Sicily.

Reference: **ME, 265-266**: "L'esistenza di un vulcano sottomarino si manifestò nel 1891, nello stesso mare di Sicilia vicino all'isola di Pantelleria. Durante il 1890, si notarono in quest'isola diversi fenomeni precursori, cioè: un sensibile incremento di attività delle fumarole, parecchie scosse di terremoto, e un sollevamento permanente della costa NE dell'isola del valore di circa un metro. Questo innalzamento ebbe due fasi: la prima seguì dopo un forte terremoto del 24-25 maggio 1890; la seconda, più rapida, nella notte 14-15 ottobre 1891 ossia due giorni prima dello scoppio dell'eruzione. Nella notte 16-17 ottobre scosse forti e sussultorie si sentirono in Pantelleria. Durante l'eruzione, le scosse diminuirono rapidamente d'intensità e poi cessarono. La mattina del 17 ottobre cominciarono i fenomeni eruttivi in mare; diverse colonne di vapore e di fumo, accompagnate da boati si alzarono sulle acque sopra una linea di circa 850-1000 m. di lunghezza, diretta NE-SW. Poi i fenomeni si concentrarono in due punti di questa linea vicini tra loro, e distanti 5 chilom[etri] circa dalla costa NW di Pantelleria. Venivano a galla migliaja di blocchi subsferici, aventi nell'interno una cavità più o meno grande ripiena di sostanze gassose. Erano formati da una roccia nerastra vetroso-scoriacea, di natura basaltica (pag. 245 analisi), e appena giunti alla superficie del mare, il maggiore numero scoppiavano lanciando i pezzi fino a 15-20 m. di altezza ed emettendo vapore misto ad anidride solforosa ed acido solfidrico. Le esplosioni si succedevano con rapidità tale che pareva di assistere ad un combattimento (Ricco). I blocchi erano caldi e qualcuno appariva incandescente nell'interno: essi galleggiavano per i gaz che tenevano inclusi; ma, appena scoppiati, i loro frammenti cadevano al fondo. I più grossi avevano una striscia allungata SW-NE come la colonna di vapore del giorno 17. L'eruzione cessò nel giorno 25 ottobre, e per essa non si formò nessun rilievo subacqueo. Infatti dopo l'eruzione, si trovò una profondità variante da 194 a 394 m.; mentre la profondità anteriore non è ben nota, ma non pare che fosse maggiore".

[The existence of a submarine volcano showed itself in 1891, in the same Sea of Sicily near Pantelleria Island. During the 1890, diverse precursors were noted in this island, that is: a notable increasing of the fumaroles activity, several earthquakes, and a permanent lifting, of nearly one metre, of the northeast coast of the island. This lifting was in two phases: the first one followed the strong earthquake of the 24th-25th of May 1890; the second one was quicker and during the night of the 14th-15th of October 1891 that is two days before of the explosion of the eruption. In the night of the 16th-17th of October, strong and vertical quakes were felt in Pantelleria. During the eruption, the quakes quickly reduced in intensity and then ceased. The morning of the 17th of October the eruptive phenomena began at sea; several columns of vapour and smoke, together with rumbles rose over the waters along a NE-SW line 850-1000 m long. Then the phenomena gathered in two points along this line, and nearly 5 km NW from the coast of Pantelleria. Thousands of subspherical blocks emerged, with a more or less big cavity inside and containing gasseous substances. They were formed of a blackish vitreous-scoriaceous rock, basaltic (analysis at page 245), and when they met the surface of the sea most of them bursted throwing pieces 15-20 m high and emitting vapour mixed with sulphurous anhydrite and sulphydric acid. The explosions were so frequent that it seemed to wittness a battle (Ricco). The blocks were hot and someone appeared incandescent inside: they float because of the gases close inside; but, just bursted, them fragments fell to the sea-bottom. The bigger ones had a lengthened NE-SW strip like the vapour column of the 17th. The eruption ceases the 25th of October, and no submarine relief was formed because of it. In fact, after the eruption the depth was between 194 and 394 m; while the previous depth is not well known, but it does not seem it was deeper].

Date: 9.1957-1958.
Locality: Azores Islands.
Reference: **BU, 312**: "From September 16 to 27 earthquakes were felt with increasing frequency near the rocks of Capelinhos, off the western end of Fayal, but they were not of great violence. On September 27 at about 8:00am the first signs of the eruption were observed at the surface of the sea. The water was boiling at the site; intermittent vapor clouds were observed near the surface of the sea; and the water was discolored or muddy for a half mile or more surrounding the area. On September 29, about 2:00am, explosions began. Cinders were thrown 300 feet or more above the sea, and an eruption cloud rose to more than a mile, but the fall of the cinders was not remarkable. During the next few days activity increased, and on October 1 cinders were thrown to 2,000 feet. On the following day the eruption was particularly violent, and cinder fell over a radius of a few miles out to sea. A islet now began to form around the crater. After October 3 the explosions continued to be violent but were less frequent. On October 7 the cone-shaped island was reported to be 200 feet high and 700 yards in diameter, but already it exposed side, to the northwest, was beginning to be destroyed by waves. On October 11 the island was 330 feet high and 800 yards in diameter. It was a horseshoe-shaped cone with the opening to the southwest. The sea flooded the crater through this opening so that the actual vent of the volcano was under water, and for this reason the explosions were extremely violent and the new lava was disrupted into ash and cinders. Explosions continued through October 15, but at the same time the size of the island was being reduced by wave erosion. In the following week the island was cut into two parts, and on the morning of October 30 no portion of either part

was visible above the level of the sea. It appeared that the waves won in the struggle.

However, in early November explosive eruptions were renewed and a second cone was constructed. By mid-November this cone was tied to Fayal Island by a narrow bar of black ash. Explosive eruption continued throughout the winter of 1957-1958, and by the end of March, 1958, the volcano had built a broad peninsula at the western end of Fayal Island, adding more than a square mile of land area to the island. This Strombolian-type eruptions continued intermittently through the summer of 1958".

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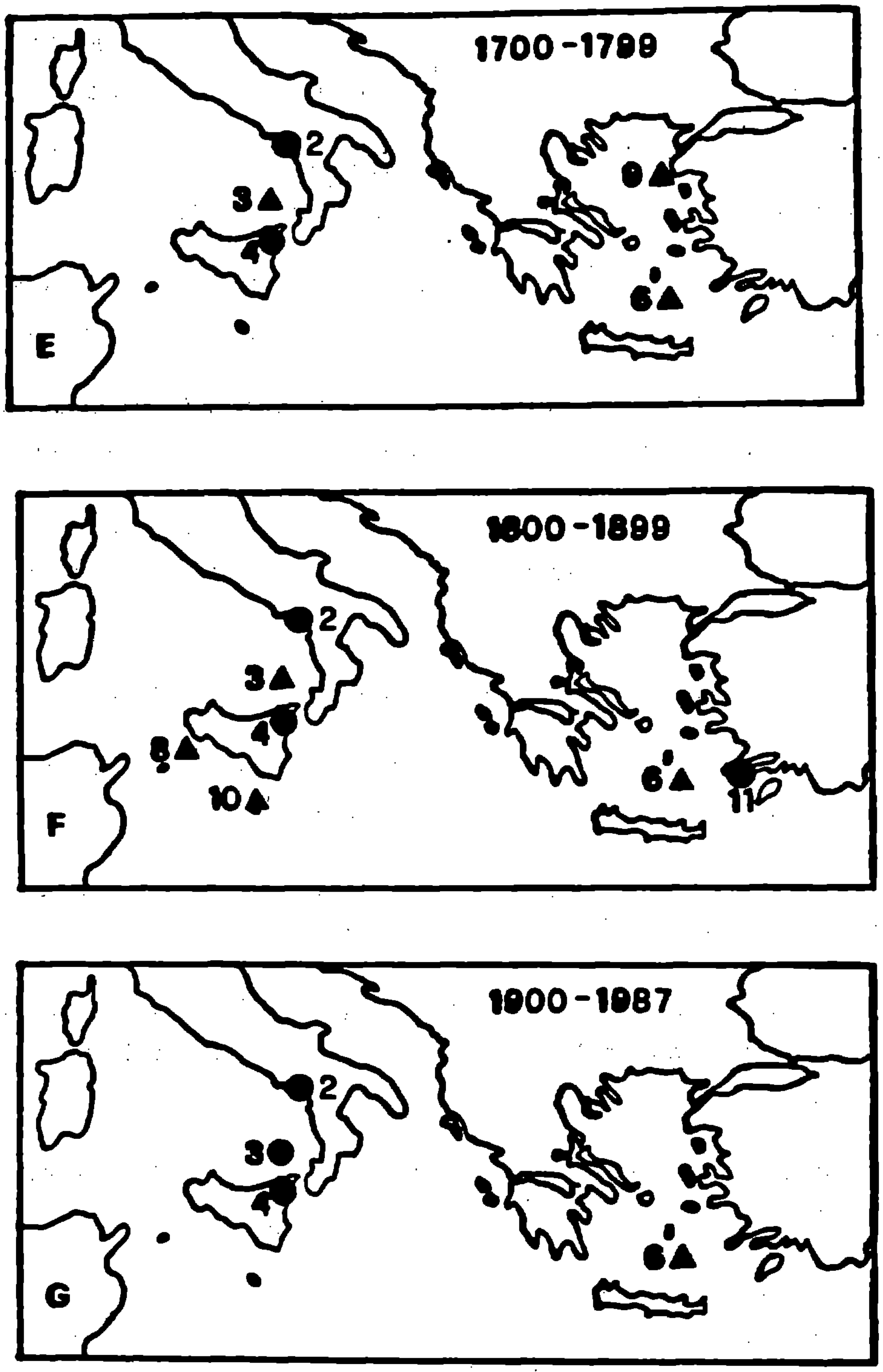
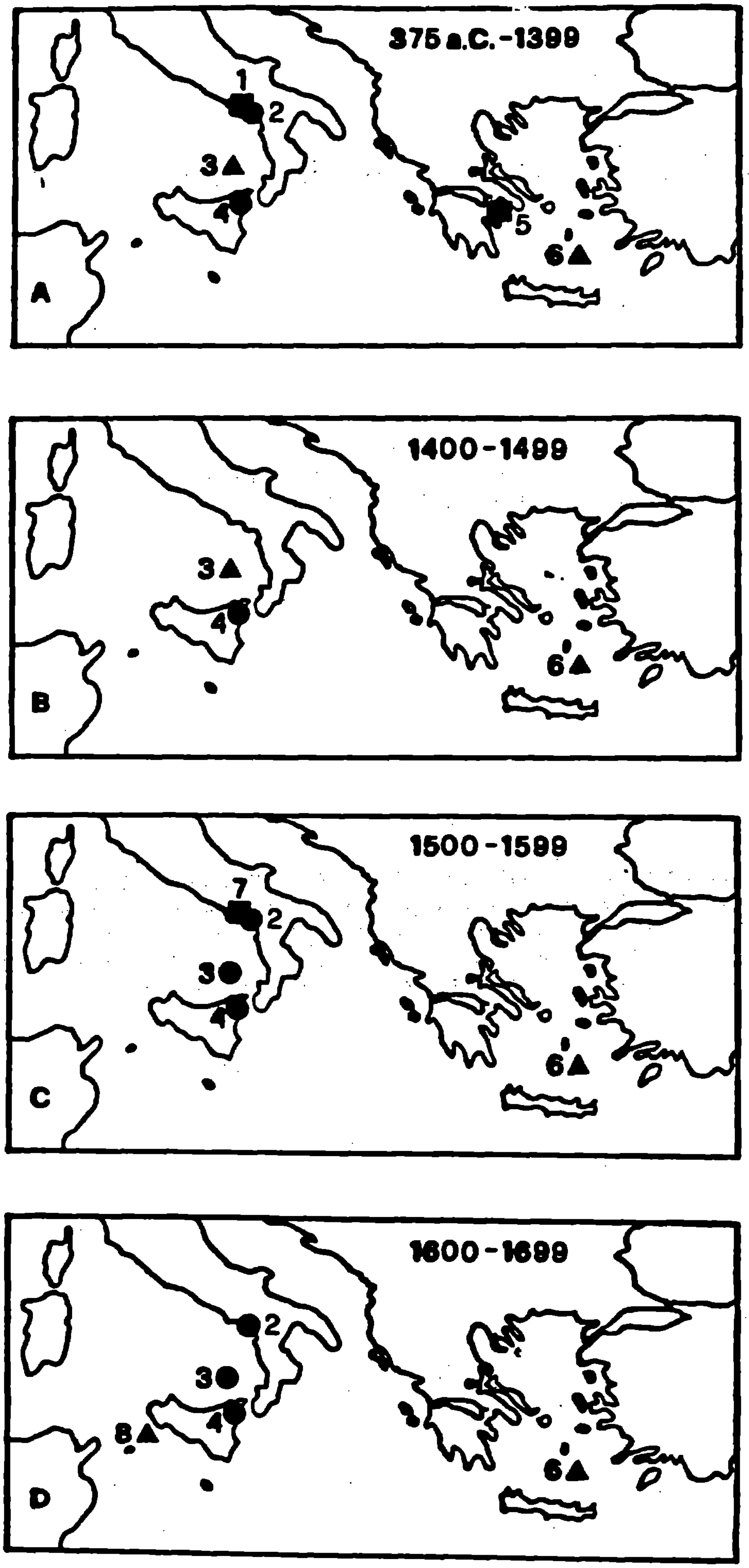


Figure 1 - Volcanic activity of the Central and Eastern Mediterranean in historic time (375 B.C. - 1987) divided into seven periods: a) 375 B.C.-1399; b) 1400-1499; c) 1500-1599; d) 1600-1699; e) 1700-1799; f) 1800-1899; g) 1900-1987. The data are from the catalogue of Simkin et al. (1981) and from the present paper. The circles represent the pre-existing volcanoes with recorded activity during the shown period; the squares represent the formation of new volcanoes on land; the triangles represent the new marine volcanoes (formation of new islands and submarine eruptions). 1: Mt. Arso (Italy); 2: Vesuvio (Italy); 3: Lipari Islands (Italy); 4: Etna (Italy); 5: Methana (Greece); 6: Santorino (Greece); 7: Monte Nuovo (Italy); 8: Isola Ferdinandea (Neptune); 9: Tenedus (Bozcaada) (Turkey); 10: Malta; 11: Nisiros (Greece).


375 a.C.-1399
1
2
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4
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A
1400-1499
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C
1600-1699
2
3
4
8
6
D

OBSERVATION OF SEISMIC GAPS IN ASIA AND AMERICAS

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ABSTRACT

Seismic gaps observed with the help of Seismic Grid Method in India, Indonesia, Philippines, Mexico, USA and Venezuela are reported. Based on this method a few earthquakes have occurred in the past, the most significant being the 19th September, 1985 Mexican earthquake of magnitude 8.1. The paper discusses the Seismic Grid Method, past cases of successful predictions and the predicted seismic gaps.

INTRODUCTION

During the last couple of decades, research in earthquake prediction has advanced to a considerable degree of reliability. The long-term and intermediate term earthquake predictions have reached an admirable state of reliability. However, short-term prediction, about 100 - 200 hours before the occurrence of an earthquake, is undergoing teething troubles. Rikitake (1982) has discussed the state of art on earthquake prediction and has given details of successful predictions. At times there have been failures in earthquake prediction, which have resulted in unexpected socio-political embarrassments. The case of drop in tourist revenue from a Latin American country, due to the prediction of a major seismic event, in quite well known. At times social, political and administrative constraints have prevented research seismologists from publishing their research findings on earthquake prediction. In order to avoid any sort of embarrassing situation and also not losing credit for successful prediction, prediction oriented research findings are either not published in leading research journals or are sent as personal communications or as research reports to a limited number of researchers or published in the form of news in local newspapers. The author had undergone similar experience, wherein the prediction findings were not communicated to any journal but were kept at personal level. This philosophy has stemmed from the fact that earthquake prediction is long term optimism and short term escapism. Until and unless the predicted seismic event occurs, there is always some element of statistical uncertainty in prediction invariably associated with it. The author has developed a method known as Seismic Grid Method for prediction of seismic gaps and it is observed that at about seven locations predicted in the past, earthquakes have occurred in the vicinity of predicted locations and they have had the predicted magnitude. On seeing these encouraging results it is thought proper to communicate some more seismic gaps observed by author in Asia and Americas.

SEISMIC GRID METHOD

Seismic Grid Method for prediction of seismic gap has been reported by Bapat and Kulkarni (1984) wherein the authors have observed a seismic gap in northeast India. This method is briefly described here. For this purpose the initial requirement is useful and reliable seismic data over a long time. For this analysis, instrumentally recorded seismic events are used. The advantage of using these data and excluding historical seismic data, is that these data are uniform and homogeneous and are more accurate than the historical seismic data. The study area is divided into grids of size 1.0° Latitude x 1.0° Longitude. The area of this grid is approximately 10,000 Km^2 for latitudes falling approximately within 40.0°N to 40.0°S and it would decrease with increasing values of latitudes. The earthquake magnitude is divided into four different ranges viz. 1) $M > 5.0$, 2) 5.0 - 5.9, 3) 6.0 - 6.9 and 4) $M \geq 7.0$. The time window is taken as ten years. Seismic Grid Method consists of observing number of earthquakes per grid per magnitude range per decade. This method is further supported by a model which envisages various stages of seismic gap. The first stage is 'Establishment Stage' of gap, wherein occurrences of two earthquakes of comparable magnitude, M, separated by a distance 2L or more are observed, where L (Km) is the rupture length associated with magnitude M. In the establishment stage, the seismic gap is seen in a grotesque form. These two or sometimes more than two events are associated with a known tectonic or geological feature. During the next stage, the 'Development Stage', few earthquakes of magnitude M - 1 occur in between the two epicenters of establishment stage and seismic gap emerges in an observable form indicating the likely area of highest isoseismal. The next stage is 'Maturity Stage', where there are occurrences of large number of earthquakes of magnitude M - 2 and the seismic gap is seen very clearly. The last stage is 'Closing Stage' during which the gap is closed as a result of occurrence of a seismic event of magnitude equal to or more than M. Broadly speaking the first, second and third stage indicates the long term, intermediate term and short term behaviours of seismic gap.

The author has been applying this method for various seismic regions of the world. The method has been tried for prediction of earthquakes of magnitude greater than or equal to 6.0. It is thought that there is no point in predicting smaller magnitude earthquakes where there is little or no damage. This statement is somewhat risky keeping in view the destructive effects of the recent earthquake of 10th October, 1986 in El Salvador, where the observed magnitude was around 5.4 as reported by Tiedemann (1987). Using the Seismic Grid Method it is observed that quite a few seismic gaps predicted by Bapat (1983) have been filled up with the occurrences of earthquakes of predicted magnitude and locations within the predicted grid. Table 1 gives list of earthquakes which were predicted by Bapat (1984) and which have occurred afterwards.

Occurrences of these earthquakes are somewhat encouraging and keeping the past cases of successful prediction, the method was extended to some other areas in American and Asian continents for observation of seismic gaps. In all total nine seismic gaps have been observed. It would therefore be seen that there would be 288 plots (8 decades x 4 magnitude ranges x 9 locations) for nine locations and made the paper unnecessarily lengthy.

The observed seismic gaps are presented in Table II. It is expected that these gaps could experience earthquakes of predicted magnitudes in the near future, say the next 2 - 4 years. If these predicted seismic events do not occur within the projected period this may be taken as a false alarm only on time scale. The observation of seismic gap, the magnitude range and location could be taken as reliable. It is seen that the first five gaps are confined within a seismic grid, while the remaining gaps have been given locations with ±25 Km. In the latter case the likely epicenter of the predicted seismic event was falling almost on the boundary of two grids as evidenced from plots of all seismic events for the entire period, 1900 - 1986. It was somewhat difficult to assign any of the two grids as such the likely location of the predicted epicenter is given with tolerance of ±25 Km.

DISCUSSION

From the data shown in Table 1 it appears that the method has good potential for prediction of medium to large earthquakes. The biggest success was observed in the case of the Mexican earthquake of magnitude 8.1 on September 19, 1985, see Bapat (1985. Some of the events in Table II such as Alaska, California, Indonesia and Philippines could generate damaging tsunamis and its effect could be more severe. The event in Venezuela is of moderate size but due to shallow depth of focus it is likely to be somewhat destructive. The main aim of earthquake prediction is to mitigate the seismic disaster. As a matter of fact the author was happy to see that the Mexican seismic event had occurred as per his prediction but felt extremely sorry to see the destruction caused by the event. It is, therefore suggested with great humility that fellow seismologists may examine these gap areas from various angles and make efforts to ascertain the existence of these gaps from different approaches and mitigate the seismic disasters.

TABLE I

No.	Geographical Co-ordinates	Area	Probable Magnitude
1.	34.0 N - 35.0 N, 117.0 - 118.0 W	California	M 6.0
2.	35.0 N - 36.0 N, 121.0 - 122.0 W	California	6.0 6.5
3.	17.0 N - 18.0 N, 102.0 - 103.0 W	Mexico	around 8.0
4.	27.0 N - 28.0 N, 62.0 - 63.0 E	Iran	around 6.5
5.	13.0 N - 14.0 N, 94.0 - 95.0 E	Andaman	around 6.5 - 7.0
6.	36.0 N - 37.0 N, 73.0 - 74.0 E	India/Pakistan border	around 6.5
7.	34.0 N - 35.0 N, 71.0 - 75.0 E	Pakistan	around 6.0

Table I: These earthquakes were predicted in 1983 and have occurred. See Bapat (1983)

TABLE II

No.	Geographical Co-ordinates	Area	Probable Magnitude
1.	26.5 - 27.5 N, 94.0 - 95.0 E	Assam	7.0 - 7.5
2.	37.0 - 38.0 N, 122.0 - 123.0 W	California	about 7.5
3.	16.0 - 17.0 N, 98.0 - 99.0 W	Mexico	about 7.5
4.	17.0 - 18.0 N, 100.0 - 101.0 W	Mexico	about 7.5
5.	19.0 - 20.0 N, 105.0 - 106.0 W	Mexico	7.0 - 7.5
6.	Within ±25 Km of 56.0 N & 158.0 W	Near Alaska Peninsula	7.0 - 7.5
7.	Within ±25 Km of 7.0 S & 108.0 E	Indonesia	about 7.5
8.	Within ±25 Km of 11.25 N & 123.0 E	Philippines	about 7.5
9.	Within ±25 Km of 10.0 N & 71.0 W	Venezuela	6.5 - 7.0

Table II: The above locations of earthquake are predicted with the help of seismic grid method. These events are likely to occur within near future, say next 2 - 4 years.

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Shelf tsunami and trench tsunami
-one dimensional model

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Abstract

Applying Laplace transform to box-type tsunami generations on one-dimensional three-step model of sea bottom, we analytically obtained waveforms and spectra for shelf and trench tsunamis, respectively. Time histories of sea level and spectra of these were calculated at coast and outer sea, using parameters of the 1964 Niigata Tsunami as a shelf tsunami and the 1933 Sanriku Tsunami as a trench tsunami. The results were compared with the observed waveforms and spectra. Particularly the predominant frequency components were reasonably explained with this model in the 1964 Niigata Tsunami. The reason is attributed to a good approximation of the shelf structure. Characteristic properties of shelf and trench tsunamis were also discussed.

§1 Introduction

Laplace tranceform is useful to solve an initial value problem of tsunami wave motion. Nakamura and Suzuki(1964) and Noiseux(1985) applied it to one-dimensional linear wave equation on a linearly sloping sea bottom and studied the effect of slope for propagation of the wave.It is also important to study wave trains in order to deepen an understanding of behavior of tsunamis. Discontinuities of the slope have important roles in making wave trains. As a first approximation we assume three-step model of sea bottom and apply Laplace transform to the model. We can investigate two typical tsunamis using the model, namely, trench tsunami and shelf tsunami. The trench tsunami is accompanied with a sinking slab under the trench and a shelf tsunami is generated by the earthquake having epicenters near land. Honshu Island in Japan was invaded by both kinds of tsunami in the past. The typical one of the former is the 1933 Sanriku Tsunami and the latter is the 1964 Niigata Tsunami. The location of the sources is shown in Fig.1. Since the long axes of these are parallel to general trend of Honshu Island, one dimensional model of tsunami propagation is a good approximation. On the model we will explore characteristic properties of both trench and shelf tsunamis.

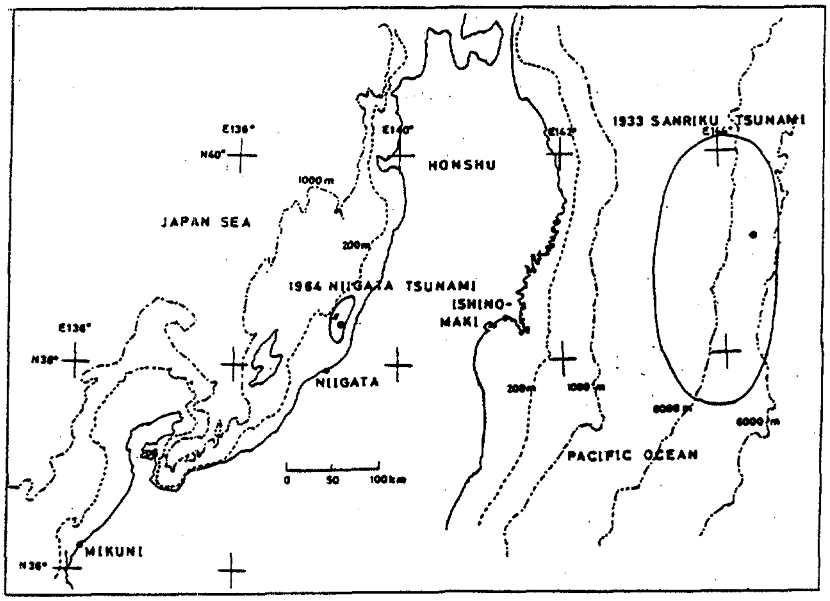

Fig.1 Source regions of the 1964 Niigata Tsunami (Aida et.al.,1964,Modified by author), the 1933 Sanriku Tsunami(Abe,1978) and tide gauge stations

§2 Analytical expression

(1) Shelf tsunami

A three-step model is applied to a shelf tsunami as shown in Fig.2. A linear wave equation is assumed in the model. For each region the wave equation is written as follows.

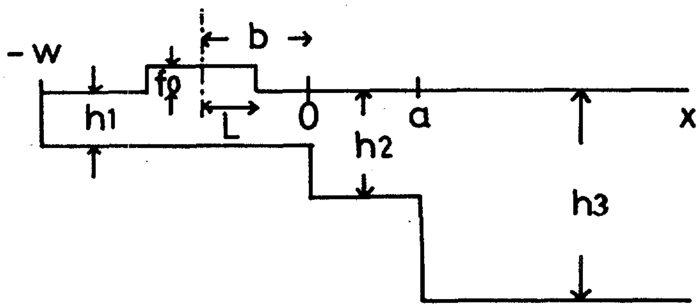

Fig.2 Shelf tsunami model

$$\frac{\partial^2 \zeta_i}{\partial t^2} = v_i^2 \frac{\partial^2 \zeta_i}{\partial x^2} \qquad (1)$$

$$v_i = \sqrt{g h_i} \qquad (i = 1,2,3)$$

Each step is expressed as i-th region. As a model of shelf tsunami the initial condition of

$$\zeta_1(x,0) = f(x), \quad \zeta_{2,3}(x,0) = 0$$

$$\left.\frac{\partial \zeta_{1,2,3}}{\partial t}\right|_{t=0} = 0 \qquad (2)$$

is assumed in which f(x) is the waveform generated in the shelf.
Using Laplace transform of

$$\overline{\zeta}_i(x,p) = \int_0^{\infty} \zeta_i(x,t)\, e^{ipt}\, dt \qquad (3)$$

wave equation of (1) is rewritten as

$$\frac{\partial^2 \overline{\zeta}_1}{\partial t^2} - \frac{p^2}{v_1^2}\overline{\zeta}_1 = -\frac{p^2}{v_1^2} f(x)$$

$$\frac{\partial^2 \overline{\zeta}_{2,3}}{\partial t^2} = \frac{p^2}{v_{2,3}^2}\overline{\zeta}_{2,3} \qquad (4)$$

Solving these equations

$$\overline{\zeta}_1(x,p) = A_1(x)\, e^{q_1 x} + B_1(x)\, e^{-q_1 x}$$

$$\overline{\zeta}_2(x,p) = A_2 e^{-q_2 x} + B_2 e^{q_2 x} \qquad (5)$$

$$\overline{\zeta}_3(x,p) = A_3 e^{-q_3(x-a)}$$

are obtained by the use of

$$q_i = p/v_i \quad (i=1,2,3) \qquad (6)$$

Taking an initial condition of

$$f(x) = 1 \qquad -b-L \leqq x \leqq -b+L$$

$$= 0 \qquad x<-b-L,\ x>-b+L \qquad (7)$$

and boundary conditions of

$$\overline{\zeta}_1(0,p) = \overline{\zeta}_2(0,p)$$

$$h_1 \left.\frac{\partial \overline{\zeta}_1(x,p)}{\partial x}\right|_{x=0} = h_2 \left.\frac{\partial \overline{\zeta}_2(x,p)}{\partial x}\right|_{x=0}$$

$$\overline{\zeta}_2(a,p) = \overline{\zeta}_3(a,p) \qquad (8)$$

$$h_2 \left.\frac{\partial \overline{\zeta}_2(x,p)}{\partial x}\right|_{x=a} = h_3 \left.\frac{\partial \overline{\zeta}_3(x,p)}{\partial x}\right|_{x=a}$$

$$\left.\frac{\partial \overline{\zeta}_1(x,p)}{\partial x}\right|_{x=-w} = 0$$

we obtain $A_1(x), B_1(x)$ by the method of variation of constants(Nakamura and Suzuki,1965) as follows:

$$\overline{\zeta}_1(-w,p) = 2A_1(-w)\, e^{-q_1 w}$$

$$= \frac{-e^{-q_1w}\left[(I+J)K_1 + (I-J)\right]\left[(1+K_2)e^{q_2a} - (1-K_2)e^{-q_2a}\right]}{\Delta} \qquad (9)$$

in which

$$\Delta = pe^{q_2a}(1+K_1)(1+K_2)\left[1 - \frac{1-K_1}{1+K_1}e^{-2q_1w} - \frac{1-K_2}{1+K_2}e^{-2q_2a-2q_1w} + \frac{1-K_1}{1+K_1}\,\frac{1-K_2}{1+K_2}e^{-2q_2a}\right] \qquad (10)$$

$$I = e^{q_1(b-L)} - e^{q_1(b+L)} \qquad (11)$$

$$J = e^{-q_1(b-L)} - e^{-q_1(b+L)}$$

and $K_1 = \sqrt{h_2/h_1}$, $K_2 = \sqrt{h_3/h_2}$

At the same time

$$\begin{aligned} \overline{\zeta}_3(2a,p) &= A_3\,e^{-q_3a} \\ &= 2e^{-q_3a}(J - Ie^{-2q_1w})/\,\Delta \end{aligned} \qquad (12)$$

Inverses of the denominators in (10) and (12) are expanded into an exponential series and the following relations are obtained after inversely transforming these equations. These are

$$\begin{aligned} \zeta_1(-w,t) = {} & H(t-\frac{w-b-L}{V_1}) - H(t-\frac{w-b+L}{V_1}) \\ & +R_{12}\left[H(t-\frac{w+b-L}{V_1}) - H(t-\frac{w+b+L}{V_1})\right] + R_{12}\left[H(t-\frac{3w-b-L}{V_1}) - H(t-\frac{3w-b+L}{V_1})\right] \\ & +R_{12}^2\left[H(t-\frac{3w+b-L}{V_1}) - H(t-\frac{3w+b+L}{V_1})\right] + R_{12}^2\left[H(t-\frac{5w-b-L}{V_1}) - H(t-\frac{5w-b+L}{V_1})\right] \\ & +R_{12}^3\left[H(t-\frac{5w+b-L}{V_1}) - H(t-\frac{5w+b+L}{V_1})\right] \\ & + T_{12}T_{21}R_{23}\left[H(t-\frac{w+b-L}{V_1}-\frac{2a}{V_2}) - H(t-\frac{w+b+L}{V_1}-\frac{2a}{V_2})\right] \\ & +T_{12}T_{21}R_{23}^2R_{21}\left[H(t-\frac{w+b-L}{V_1}-\frac{4a}{V_2}) - H(t-\frac{w+b+L}{V_1}-\frac{4a}{V_2})\right] \\ & + R_{23}T_{12}T_{21}\left[H(t-\frac{3w-b-L}{V_1}-\frac{2a}{V_2}) - H(t-\frac{3w-b+L}{V_1}-\frac{2a}{V_2})\right] \\ & +2R_{12}R_{23}T_{12}T_{21}\left[H(t-\frac{3w+b-L}{V_1}-\frac{2a}{V_2}) - H(t-\frac{3w+b+L}{V_1}-\frac{2a}{V_2})\right] \\ & + \cdots\cdots \end{aligned} \qquad (13)$$

and

$$\begin{aligned} \zeta_3(2a,t) = \frac{1}{2}T_{12}T_{23}\Big[& \Big\{H(t-\frac{b-L}{V_1}-\frac{a}{V_2}-\frac{a}{V_3}) - H(t-\frac{b+L}{V_1}-\frac{a}{V_2}-\frac{a}{V_3}) \\ & + H(t-\frac{2w-b-L}{V_1}-\frac{a}{V_2}-\frac{a}{V_3}) - H(t-\frac{2w-b+L}{V_1}-\frac{a}{V_2}-\frac{a}{V_3})\Big\} \\ & + R_{12}\Big\{H(t-\frac{2w+b-L}{V_1}-\frac{a}{V_2}-\frac{a}{V_3}) - H(t-\frac{2w+b+L}{V_1}-\frac{a}{V_2}-\frac{a}{V_3}) \\ & + H(t-\frac{4w-b-L}{V_1}-\frac{a}{V_2}-\frac{a}{V_3}) - H(t-\frac{4w-b+L}{V_1}-\frac{a}{V_2}-\frac{a}{V_3})\Big\} \\ & +R_{12}^2\Big\{H(t-\frac{4w+b-L}{V_1}-\frac{a}{V_2}-\frac{a}{V_3}) - H(t-\frac{4w+b+L}{V_1}-\frac{a}{V_2}-\frac{a}{V_3}) \\ & + H(t-\frac{6w-b-L}{V_1}-\frac{a}{V_2}-\frac{a}{V_3}) - H(t-\frac{6w-b+L}{V_1}-\frac{a}{V_2}-\frac{a}{V_3})\Big\} \\ & + R_{21}R_{23}\Big\{H(t-\frac{b-L}{V_1}-\frac{3a}{V_2}-\frac{a}{V_3}) - H(t-\frac{b+L}{V_1}-\frac{3a}{V_2}-\frac{a}{V_3}) \\ & + H(t-\frac{2w-b-L}{V_1}-\frac{3a}{V_2}-\frac{a}{V_3}) - H(t-\frac{2w-b+L}{V_1}-\frac{3a}{V_2}-\frac{a}{V_3})\Big\} + \cdot\Big] \end{aligned} \qquad (14)$$

in which reflection coefficient R_{mn} , transmission coeficient T_{mn} are given as

$$R_{12}=\frac{1-K_1}{1+K_1}\ ,\ R_{23}=\frac{1-K_2}{1+K_2}\ ,\ R_{21}=-R_{12}\ ,\qquad T_{12}=\frac{2}{1+K_1}\ ,\ T_{23}=\frac{2}{1+K_2}\ ,\ T_{21}=\frac{2K_1}{1+K_1} \qquad (15)$$

These expressions of reflection and transmission coefficients are the same as ones derived by Cochrane and Arthur(1948). In the derivation an relation of

$$\overline{\zeta}(x,p)=\frac{Ae^{-cp}}{p} \qquad \zeta(x,t)=AH(t-c)\ ,\quad H(t-c)=1\ \ t>c,\ =0\ \ t<c \qquad (16)$$

between transformed and inversely transformed conditions was used(Nakamura and Watanabe, 1961). In the latter H(t-c) is Heaviside step function.

The formulas (13) and (14) show that wave train is expressed as a summation of pair of step function and the amplitude is represented by the use of reflection and transmission coefficients. Each phase of the wave is followed from the expression of travel time c. For example, the first pair in the formula (13) is a direct wave, the second one is a reflected wave at the shelf margin after starting from the source toward outer sea and the third one is two times reflected wave at the coast and shelf margin after starting toward coast from the source.

(2) Trench Tsunami

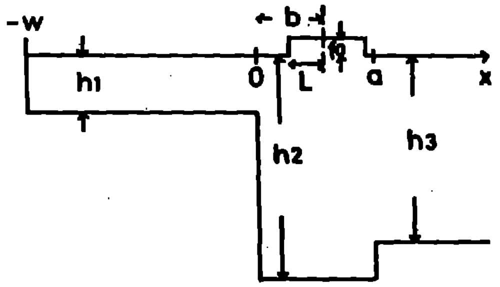

Fig.3 Trench tsunami model

In the next step a trench structure, as shown in Fig.3, is dealt with and the same equations as that of (1) are assumed for each region. The initial condition of

$$\zeta_2(x,0)=F(x),\ \ \zeta_{1,3}(x,0)=0 \qquad \left.\frac{\partial \zeta_{1,2,3}(x,t)}{\partial t}\right|_{t=0}=0 \qquad (17)$$

is given in which F(x) is assumed to take the wave form of

$$F(x)=-1 \quad b-L\leqq x\leqq b+L \qquad =0 \quad x<b-L,\ x>b+L \qquad (18)$$

Amplitudes A_1 and B_1 are determined under the same boundary conditions as those of (8). Thus we obtain the coastal amplitude as

$$\begin{aligned}\overline{\zeta}_1(-w,p) &= A_1e^{-q_1w}+B_1e^{q_1w}\\ &= 2A_1e^{-q_1w}\\ &= 2K_1e^{-q_1w}\left[I'(1-K_2)e^{-q_2a}-J'(1+K_2)e^{q_2a}\right]/\Delta \end{aligned} \qquad (19)$$

in which I' and J' are given as

$$I'=e^{q_2(b+L)}-e^{q_2(b-L)}$$

$$J'=e^{-q_2(b+L)}-e^{-q_2(b-L)}$$

In addition the outer sea amplitude is

$$\overline{\zeta}_3(2a,p) = A_3 e^{-q_3 a}$$

$$= e^{-q_3 a} \lbrack I' \{(1+K_1)-(1-K_1)e^{-2q_1 w}\} + J' \{(1-K_1)-(1+K_1)e^{-2q_1 w}\} \rbrack / \Delta \quad (20)$$

Next expressions are derived using the same method as one in the shelf tsunami.They are

$$\begin{aligned}
\zeta_1(-w,t)=T_{21} \lbrack & H(t-\frac{w}{v_1}-\frac{b-L}{v_2}) - H(t-\frac{w}{v_1}-\frac{b+L}{v_2}) \\
&+R_{21} \{H(t-\frac{3w}{v_1}-\frac{b-L}{v_2}) - H(t-\frac{3w}{v_1}-\frac{b+L}{v_2})\} \\
&+R_{12}^2 \{H(t-\frac{5w}{v_1}-\frac{b-L}{v_2}) - H(t-\frac{5w}{v_1}-\frac{b+L}{v_2})\} \\
&+R_{21}R_{23} \{H(t-\frac{w}{v_1}-\frac{2a+b-L}{v_2}) - H(t-\frac{w}{v_1}-\frac{2a+b+L}{v_2})\} \\
&+R_{23} \{H(t-\frac{w}{v_1}-\frac{2a-b-L}{v_2}) - H(t-\frac{w}{v_1}-\frac{2a-b+L}{v_2})\} \\
&+R_{12}R_{23} \{H(t-\frac{3w}{v_1}-\frac{2a-b-L}{v_2}) - H(t-\frac{3w}{v_1}-\frac{2a-b+L}{v_2})\} \\
&+R_{12}^2R_{23} \{H(t-\frac{5w}{v_1}-\frac{2a-b-L}{v_2}) - H(t-\frac{5w}{v_1}-\frac{2a-b+L}{v_2})\} \\
&+R_{23} \{H(t-\frac{w}{v_1}-\frac{4a-b-L}{v_2}) - H(t-\frac{w}{v_1}-\frac{4a-b+L}{v_2})\} \\
&+\cdot\cdot\cdot\cdot\cdot\cdot\cdot \rbrack
\end{aligned} \quad (21)$$

$$\begin{aligned}
\zeta_3(2a,t)= \frac{1}{2} T_{23} \lbrack & \{H(t-\frac{a-b-L}{v_2}-\frac{a}{v_3}) - H(t-\frac{a-b+L}{v_2}-\frac{a}{v_3})\} \\
&+ R_{21} \{H(t-\frac{a+b-L}{v_2}-\frac{a}{v_3}) - H(t-\frac{a+b+L}{v_2}-\frac{a}{v_3})\} \\
&+ R_{21}R_{23} \{H(t-\frac{3a-b-L}{v_2}-\frac{a}{v_3}) - H(t-\frac{3a-b+L}{v_2}-\frac{a}{v_3})\} \\
&+ R_{21}^2R_{23} \{H(t-\frac{3a+b-L}{v_2}-\frac{a}{v_3}) - H(t-\frac{3a+b+L}{v_2}-\frac{a}{v_3})\} \\
&+ R_{21}^2R_{23}^2 \{H(t-\frac{5a-b-L}{v_2}-\frac{a}{v_3}) - H(t-\frac{5a-b+L}{v_2}-\frac{a}{v_3})\} \\
&+ R_{21}^3R_{23}^2 \{H(t-\frac{5a+b-L}{v_2}-\frac{a}{v_3}) - H(t-\frac{5a+b+L}{v_2}-\frac{a}{v_3})\} \\
&+T_{12}T_{21} \{H(t-\frac{2w}{v_1}-\frac{a+b-L}{v_2}-\frac{a}{v_3}) -H(t-\frac{2w}{v_1}-\frac{a+b+L}{v_2}-\frac{a}{v})\} \\
&+R_{23}T_{21}T_{12} \{H(t-\frac{2w}{v_1}-\frac{3a-b-L}{v_2}-\frac{a}{v_3}) -H(t-\frac{2w}{v_1}-\frac{3a-b+L}{v_2}-\frac{a}{v_3})\} \\
&+2R_{21}R_{23}T_{21}T_{12} \{H(t-\frac{2w}{v_1}-\frac{3a+b-L}{v_2}-\frac{a}{v_3}) -H(t-\frac{2w}{v_1}-\frac{3a+b+L}{v_2}-\frac{a}{v_3})\} \\
&+T_{21}R_{12}T_{12} \{H(t-\frac{4w}{v_1}-\frac{a+b-L}{v_2}-\frac{a}{v_3}) -H(t-\frac{4w}{v_1}-\frac{a+b+L}{v_2}-\frac{a}{v_3})\} \\
&+R_{23}T_{21}R_{12}T_{12} \{H(t-\frac{4w}{v_1}-\frac{3a-b-L}{v_2}-\frac{a}{v_3}) -H(t-\frac{4w}{v_1}-\frac{3a-b+L}{v_2}-\frac{a}{v_3})\} \\
&+\cdot\cdot\cdot\cdot\cdot\cdot\cdot \rbrack
\end{aligned} \quad (22)$$

§3 Spectra and the waveforms

Spectra are obtained replacing p by $i\omega$ in (9),(12) and (19),(20). In the expression ω is an angular frequency and i is a pure imaginary number. Spectra and waveforms were calculated in both the cases. Parameters representative of two typical tsunamis, which are the 1964 Niigata tsunami as a shelf tsunami and the 1933 Sanriku tsunami as a trench tsunami, were chosen and shown in Fig.5,7. The results are shown in Fig.4,5,6 and 7. In the shelf tsunami it is shown that both the spectra have the same peak frequencies between coast and outer sea but in the trench tsunami it is shown that both the spectra have complimentary peak frequencies particularly in low frequency. It is noticed in the wave-forms that the width of first pulse d is controled by the source length along x

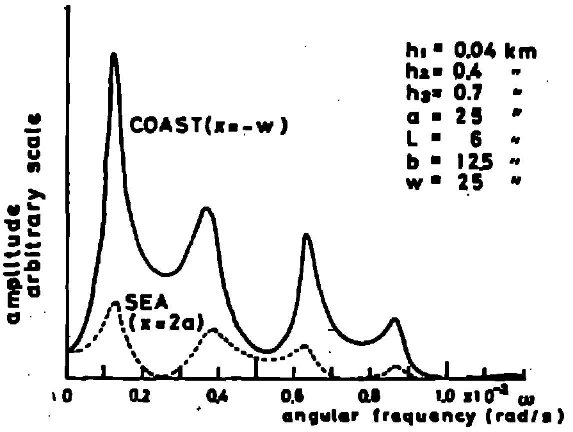

Fig.4 Amplitude spectra of shelf tsunami

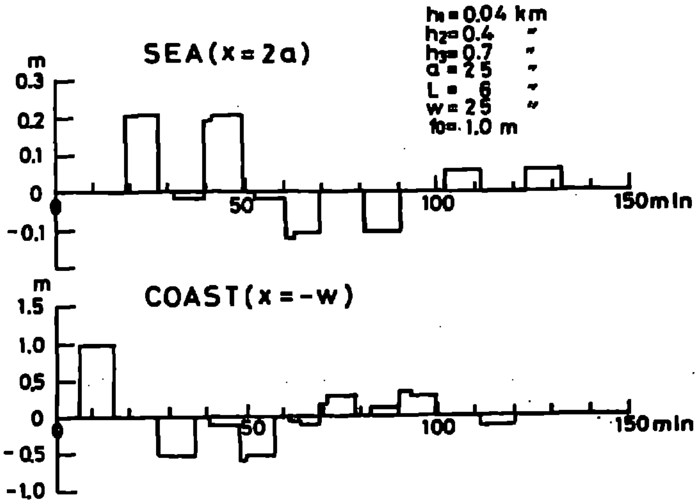

Fig.5 Waveforms of shelf tsunami

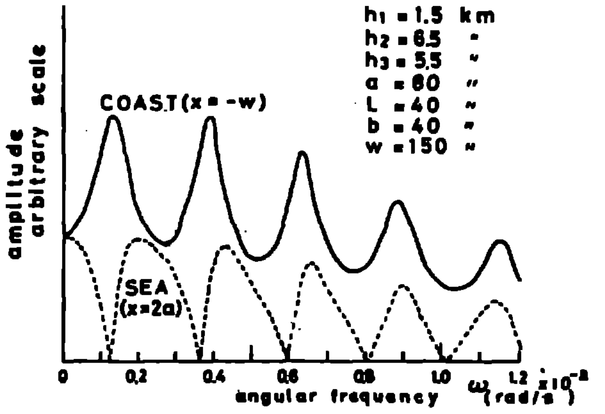

Fig.6 Amplitude spectra of trench tsunami

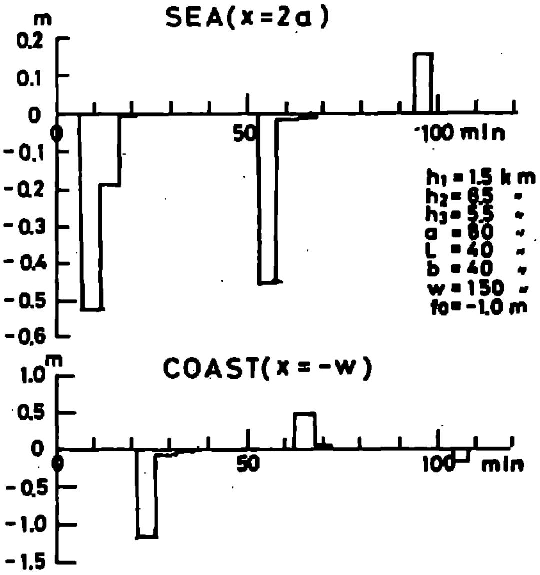

Fig.7 Waveforms of trench tsunami

axis, 2L and the long wave velocity, v_i, and the relation is represented as $d = 2L/v_i$ in which i is the number of source region. The pulse width is proportional to source width 2L and inversely proportional to wave velocity v. We can point out an importance of sea depth h through the latter one in formula (1) to the pulse width.

The shelf tsunami is characterized with a large pulse width and a short time interval between two waves in comparison with the trench tsunami.

§4 Comparison with the observation

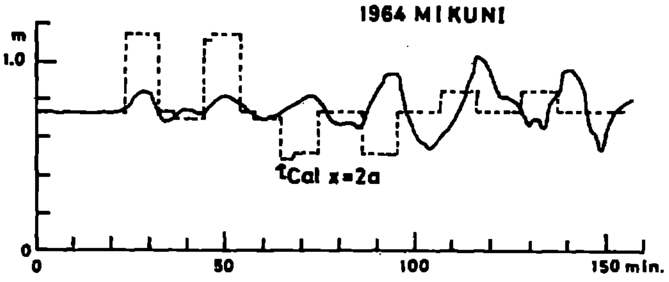

Fig.8 Comparison of waveform in calculation(x=2a) with one in observation(Mikuni) for the 1964 Niigata Tsunami. Scale of calculated amplitude is arbitrary.

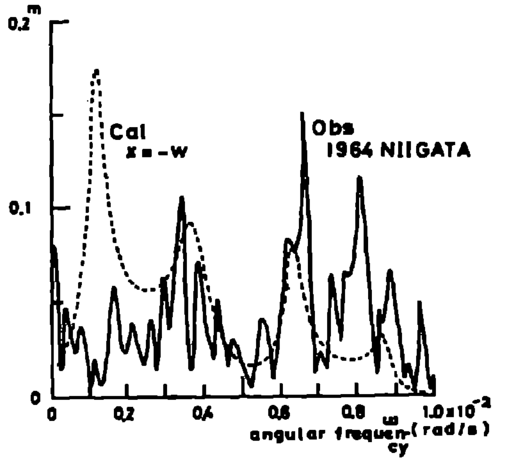

Fig.9 Comparison of amplitude spectrum in calculation(x=-w) with one in observation(Niigata) for the 1964 Niigata Tsunami.Scale of calculated amplitude is arbitrary.

We collected tide gauge records including the 1964 Niigata Tsunami and the 1933 Sanriku Tsunami. For the former we referred the record at Mikuni which is located in Fukui Prefecture, Central Japan, as the observation at outer sea for the shelf tsunami and one at Niigata city as the observation at coast. For the later we did the record at Ishinomaki in Miyagi Prefecture,North-east Japan as the observation at coast in the trench tsunami. The locations are shown in Fig.1.After digitizing the records we removed ordinary tide and obtained tsunami wave forms.

For the waveforms we calculated Fourier coefficients on Goertzel's method by the use of micro-computer.

The waveform observed at Mikuni in case of the 1964 Niigata Tsunami are shown in Fig.8 with one calculated at outer sea for the shelf tsunami.

A record observed at a long distant coast is employed for wave form comparison because of no record at outer sea.Therefore,origin time is arbitrary for the calculation.The second wave in the observation is a reflected wave from the comparison with the calculation. But we cannot identify the third arrival of pulling phase, instead find a regular oscillation in the observation. The regular oscillation is possibly attributed to an excitation of natural oscillation. The spectrum

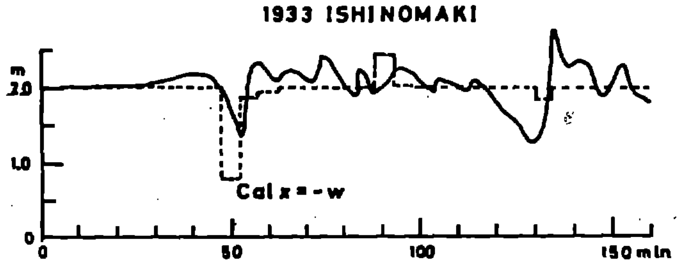

Fig.10 Comparison of waveform in calculation(x=-w) with one in observation(Ishinomaki) for the 1933 Sanriku Tsunami.Same comments as Fig.8.

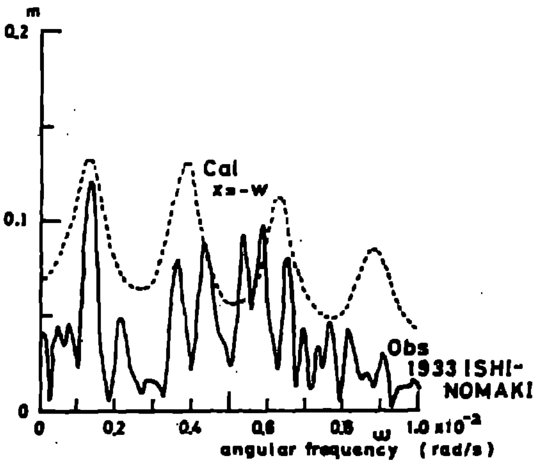

Fig.11 Comparison of amplitude spectrum in calculation(x=-w) with one in observation(Ishinomaki) for the 1933 Tsunami. Same comments as Fig.9.

observed at the estuary of the Agano River in Niigata City is shown in Fig. 9 with one calculated at coast(x=-w) for the 1964 Niigata Tsunami model. The two main peaks (ω=0.67x10^{-2}, 0.34x10^{-2}rad/s) observed are explained with the model. An amplitude corresponding to the predominant spectral peak with the longest period in the calculation is smaller for observation. For the trench tsunami model we compared the record observed at Ishinomaki in the 1933 Sanriku Tsunami with the waveform calculated. The result is shown in Fig.10. Origin times are also taken to be arbitrary. By superposing the calculated one on the observed one we find an agreement of the third pulling wave. We cannot find a reasonable explanation to no definite arrival of second wave.

In the comparison of spectrum we can describe a large excitation of the longest period component as shown in Fig.11. This fact is consistent with a difinite arrival of the third wave described before. Comparing two spectra for the shelf tsunami and trench tsunami, we find a difference in explanation of the predominant periods. In the trench tsunami model we succeeded in explaining the longest period component. On the other hand in the shelf tsunami model we succeeded in explaining the second and third longest period component. This difference is reflected with degree of approximation. This shows that the trench tsunami model is a good approximation for the long period components and the shelf tsunami model is a good approximation for wider range of period components.

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TSUNAMI CLIMBING A BEACH AND TSUNAMI ZONATION

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ABSTRACT

Investigations of tsunami waves climbing a beach and tsunami zonation of the Pacific coast performed by the Soviet scientists are reviewed.

The problems dealing with determining "tsunami-risk" coastal regions, erection and protection of coastal and hydrotechnical constructions in the area that experiences tsunamis can be hardly solved without methods for calculating tsunami waves climbing a beach and their effect on constructions. Up to 1980 tsunami zonation was performed using empirical methods of estimating the run-up height which were not reliable enough. Now due to the refinement of numerical methods the situation has changed drastically; and what is more there have appeared various competing methods. The methods for studying tsunami climbing a beach are being developed now in many institutions of the USSR. A special working group "Tsunami Effect on Beaches and Constructions" has been organized in the frames of the All-Union Committee on Tsunami which is to solve the following problems: analysis of the evidence of the tsunami climbing a beach, creating adequate numerical models of the phenomenon, estimation of the tsunami hazard for hydrotechnical and coast protecting constructions. We give a summary of the results of investigations of tsunami climbing a beach and tsunami zonation.

1. TSUNAMI CLIMBING A BEACH

To choose adequate concepts on physics of tsunami propagation, a statistical analysis of evidence of the character of tsunami waves climbing a beach was performed which permitted to estimate the probability of tsunami waves breaking in the basin of the Pacific Ocean [1]:

$$p = 0{,}5 + \Phi(z), \quad z = 3.1(\log R - 1.1) \qquad (1)$$

where R is the run-up height and Φ is the probability integral. Thus, waves of more than 10-m height on the average break and the coast is reached by waves with a sharp depth drop and flow velocity. Waves of less than 10-m height do not collapse on the average and in this case a quiet flooding of the coast occurs. Upon the whole almost 75% of the tsunami considered climb the coast without breaking. Therefore a model of long waves climbing a flat slope without breaking is adopted as the basic physical model. In its frames exact solutions for the case of the constant slope and one-dimensional propagation are found 2,3 . In particular, the following formula for the run-up height is found

$$R / H = m\sqrt{l / \lambda}\,, \qquad (2)$$

where λ is the tsunami wave length at the distance of l from the water edge, H is the wave amplitude at the same distance, m is the coefficient of the form. For the case of a monochromatic wave in the open ocean $m = 8.9$. For a monopolar pulse of a Lorentz type m equals 4.4, and for a sinusoidal one m equals 3.9 (here the wave length is determined by the level 0.1). This yields an important conclusion: the run-up height, generally speaking, depends on the wave form, which has not been unambiguously defined. Usually it is assumed to be in the form of a monopolar pulse, but the instrumental record of a tsunami far from the coast on the shelf of the Shikotan Island shows that it is most likely in the form of a monochromatic wave [4]. This problem has not been solved yet, that is why for rough calculations it is expedient to use a mean value $m = 5$ (the deviation ± 1.1). The analogous formula is for the depth of desiccation after a tsunami wave leaves the coast. For a monochromatic wave $|R_-| = R_+ \ (m_- = -m_+)$. Even if a monopolar pulse runs up, the desiccation takes place all the same, being equal to -1.2 for a Lorentz pulse and to -1.4 for a sinusoidal one, i.e. the desiccation depth constitutes approximately 30% of the run-up height. Exact solutions yield also a formula for the maximal velocity of the water flow

$$U = \omega R / \alpha, \tag{3}$$

where ω is the frequency of the monochromatic wave and the parameter of breaking (α is the angle of the slope inclination)

$$Br = \omega^2 R / g \alpha^2. \tag{4}$$

The case $Br < 1$ corresponds to a quiet flooding of the coast and $Br > 1$ corresponds to the tsunami climbing in the form of a bore. Estimates of the value Br (see below) testify that tsunami waves usually do not break.

It is obvious that exact solutions can be obtained only in exceptional cases. Among approximate methods we mention only one, the so-called linear approach, when a real run-up height is identified with the wave height at the water edge, calculated on the basis of the linear theory. For this approach, which has found an active application abroad, substantial grounds have been found [5]. We give only one solution corresponding to the wave climbing a slope when the bottom is even [3]

$$R/H = \begin{cases} 2 & \ell < 0.16\lambda \\ 5\sqrt{\ell/\lambda} & \ell > 0.16\lambda \end{cases} \tag{5}$$

Note that the formula becomes more exact with the decrease of a relative amplitude of the falling wave (nonlinearity parameter $H(h)$). Note also that (5) is in a good agreement with the data of laboratory experiments [6].

2. TSUNAMI ZONATION

The schemes of the tsunami zonation of the Pacific coast of the USSR were intensely developed in a number of papers using hydrodynamic calculations [7-9]. Having on the average equal orders of the run-up value, various schemes have considerable deviations for concrete points. It is obvious that under such conditions the role of the natural facts of tsunami effect on the coast increases, which are not widely used in "hydrodynamic" schemes of tsunami zonation. Where as the standard method of the application of natural information is plotting curves of the phenomena recurrence for every settlement, in particular, such a method was used in [10] to analyze the tsunami hazard for Village Tofino (west coast of Canada), where during 71 years (1906-1976), 33 cases of tsunami were registered by the sea-level recorder. This method is not effective for the tsunami zonation of the Far-Eastern coast of the USSR in view of poor data on tsunami aftereffects, although sometimes estimates for some points can be made [11,12]. Thus, for such a great region as Kamchatka, during the period 1737-1976 only 20 tsunamis were registered [13], the tsunami records by a tide gauge are available only for Petropavlovsk and Village Zhupanovo, reliable visual data on tsunami heights are for the Bay Morzhovaya, for the rest points only single data are at hand [11]. It seems at a glance that the natural material in Kamchatka available is insufficient to make concrete curves of recurrence. However, taking into account that the coastal relief exerts the main influence on the tsunami run-up, and in the open ocean the tsunami characteristics are more uniform (these assumptions lie essentially in the basis of all tsunami zonation schemes), the recurrence curves can be presented in the generalized form [11]

$$N/T = A \cdot 10^{-R/K} \tag{6}$$

where N is the quantity of tsunamis with run-up heights larger than R per time period T, A is the frequency of strong tsunami occurrence and K is the coefficient of the tsunami wave transformation from the centre to the coast. This formula can be verified for all points of the Pacific Ocean basin, where reliable data of observation are available. A good coincidence occurs for 29 points of the Pacific coast of the USSR, when transformation coefficients are used from the preliminary schemes of tsunami zonation [9], the deviation variance does not exceed 0.5.

Table 1 gives the data on the flooding level for the points of the Pacific coast of the USSR, calculated by the formula (6) for the period 100 years [11-14]. This time period corresponds to the typical recurrence of one event per 100 years.

The introduction of the time interval, for which a long range forecast of tsunami is given, is of principle value and a new stage in the Soviet practice. The theory of waves climbing a beach permits to make tsunami zonation with respect to the flow velocities and the breaking parameter [14]; however, to construct such schemes one should not only know the run-up heights but also the periods of tsunami waves with adeguate security. Therefore the schemes of tsunami zonation with respect to the flow velocities and the breaking parameter are less reliable.

TABLE

100-YEARS FORECAST FOR THE LEVELS OF FLOODING OF THE SOVIET PACIFIC COAST

Point	Height m	Point	Height m
the Komandorskiye Islands		the Kunashir Island	
Mednyi Isl.	2.5	Vil. Yuzhno-Kuril'sk	4.5
Bering Isl.	8.0	Vil. Golovnino	2.5
Kamchatka		Shikotan Island	
Vil. Ust'-Kamchatsk	9.5	Vil. Malokuril'skoye	7.0
Vil. Zhupanovo	8.0	Vil. Krabozavodsk	7.0
Bay Morzhovaya	18.0	Bay Dimitrova	8.0
Cape Shipunskii	21.0	Bay Tserkovnaya	13.0
Cape Mayachnyi	11.0	Malaya Kuril'skaya Ridge	
Petropavlovsk	2.5	the Polonskii Island	5.0
Cape Lopatka	17.5	the Zelyonyi Island	7.0
the Shumshu Island		the Tanfil'ev Island	3.5
Vil. Babushkino	9.0	the Yurii Island	3.5
Vil. Baikovo	17.0	Sakhalin	
the Paramushir Island		Kholmsk	1.0
Severo-Kuril'sk	18.0	Nevel'sk	1.0
Vasil'ev Cape	11.0	Korsakov	2.0
Sredniye Kuril Islands		Pervomaisk	1.5
the Onekotan Island	12.0	Vil. Katangli	1.0
the Shiashkotan Island	13.5	Primor'e	
the Matua Island	10.0	Vil. Ternei	1.0
the Simushir Island	8.5	Vil. Rudnaya Pristan'	1.5
the Urup Island		Nakhodka	1.0
Cape Kastrikum	8.0	Vladivostok	1.0
Vil. Podgornoye	8.0	Vil. Pos'et	0.5
Cape Van-der Linda	17.0		
the Uturup Island			
Vil. Kuril'sk	1.0		
Vil. Sentyabr'skii	10.5		
Vil. Burevestnik	7.5		

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CUMULATIVE INDEX FOR VOLUMES 1 THRU 7

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All items published to date are presented below in chronological order. In the next issue, a complete subject and author index will be published.

Type code: P = Scientific Paper; R = Review; N = Note, Editorial, or Report

YEAR	AUTHOR(S)	TITLE	VOL. NO. P.	TYPE
1982	Adams, W. M.	GUEST EDITORIAL	Vol. 1 No. 1 P. 1	N
1982	Mirchina, N. P. Pelinovsky, E. N. Shavratsky, S. Kn.	PARAMETERS OF TSUNAMI WAVES IN THE SOURCE	Vol. 1 No. 1 P. 3	P
1982	Mader, Charles L. Tangora, Robert E. Nicols,B.D.	A MODEL OF THE 1975 HAWAII TSUNAMI	Vol. 1 No. 1 P. 10	P
1982	Mirchina, N. R. Pelinovsky, E. N.	NONLINEAR AND DISPERSIVE EFFECTS FOR TSUNAMI WAVES IN THE OPEN OCEAN	Vol. 1 No. 1 P. 19	P
1982	Adams, W.M.;Lewis III, C.H.;	NUMERICAL MODELING OF TSUNAMI FLOODING	Vol. 1 No. 1 P. 29	P
1982	Pelinovsky, E. N. Stephanyants, Yu. A.	CYLINDRICAL SOLITONS PASSING THROUGH A FOCUS	Vol. 1 No. 1 P. 44	P
1982	Curtis, George D.	ESTABLISHMENT AND OPERATION OF A TSUNAMI MONITORING PROGRAM	Vol. 1 No. 1 P. 49	P
1983	Lewis III, Carter H. Adams, W. M.	DEVELOPING OF A TSUNAMI-FLOODING MODEL HAVING VERSITILE FORMULATION OF MOVING BONDARY CONDITIONS	MONOGRAPH SERIES	P
1984	Morgan, Joseph	A TSUNAMI AVOIDABLE SUSCEPTABILITY INDEX	Vol. 2 No. 1 P. 3	P
1984	Lockridge, Patricia A.	NATIONAL GEOPHYSICAL DATA CENTER DATABASES SUPPORTING INVESTIGATIONS OF GEOLOGICAL HAZARDS	Vol. 2 No. 1 P. 13	R
1984	Soloviev, S. L. Ivanshchenko, A. I. Poplavsky, A. A.	THE ALL-UNION MEETING ON TSUNAMI IN YUZHNO-SAKHALINSK	Vol. 2 No. 1 P. 19	R
1984	Blackford, Michael E.	USE OF THE ABE MAGNITUDE SCALE BY THE TSUNAMI WARNING SYSTEM	Vol. 2 No. 1 P. 27	P
1984	Dupon, J. F.	LANDSLIDES AND MUDFLOWS IN A YOUNG VOLCANIC HAWAIIAN TYPE STRUCTURE	Vol. 2 No. 1 P. 31	P
1984	Nakamura, S.	A NUMERICAL TRACKING OF THE 1883 KRAKATOA TSUNAMI	Vol. 2 No. 1 P. 41	P
1984	Murty, T. S. El-Sabh, M. I. Gratton, Y.	HURST PHENOMENON IN TSUNAMI-GENIC EARTHQUAKE DATA	Vol. 2 No. 1 P. 55	P
1984	Cox, Doak C.	IMPORTANCE OF LOCAL CONTEMPORARY REPORTS OF EFFECTS OF HISTORICAL TSUANMIS IN TSUNAMI RISK ANALYSIS	Vol. 2 No. 2 P. 67	P
1984	Mader, Charles L.	LANDSLIDE MODEL FOR THE 1975 HAWAII TSUNAMI	Vol. 2 No. 2 P. 71	P
1984	Cox, Doak C.	PROBABLE ALEUTIAN SOURCE OF THE TSUNAMI OBSERVED IN AUGUST 1872 IN HAWAII, OREGON, AND CALIFORNIA	Vol. 2 No. 2 P. 79	P

YEAR	AUTHOR(S)	TITLE	VOL. NO. P.	TYPE
1984	Adams, W. M. Curtis, G. D.	DESIGN AND DEVELOPEMENT OF AN INTELLIGENT DIGITAL SYSTEM FOR COMPUTER-AIDED DECISION-MAKING DURING NATURAL HAZARDS	Vol. 2 No. 2 P. 95	P
1984	Adams, Wm. Mansfield	VERIFICATION, CALIBRATION AND QUALITY ASSURANCE FOR TSUNAMI MODELS	Vol. 2 No. 2 P. 101	P
1984	Zielinski, A.	MODELING OF TSUNAMI DIRECTIVITY	Vol. 2 No. 2 P. 113	P
1984	Carte, George W.	A TSUNAMI PREPAREDNESS ASSESSMENT FOR ALASKA	Vol. 2 No. 2 P. 119	P
1985	Chubarov, L. V. Gusiakov, V. K.	TSUNAMIS AND EARTHQUAKE MECHANISMS IN THE ISLAND ARC REGIONS	Vol. 3 No. 1 P. 3	P
1985	Sokolowski, Thomas J.	THE ALASKA TSUNAMI WARNING CENTER'S RESPONSIBILITIES AND OPERATIONS	Vol. 3 No. 1 P. 23	P
1985	Curtis, George D. Adams, William M.	NEEDS AND DEVELOPEMENTS IN TSUNAMI MONITORING	Vol. 3 No. 1 P. 34	P
1985	El-Sabh, M. I. Tessier, B. Murty, T. S.	FRACTAL DIMENSION AND LENGTH OF AN IRREGULAR COASTLINE: Application to the St. Lawrence Estuary	Vol. 3 No. 1 P. 41	P
1985	Adams, William M. Nakashizuka, N.	A WORKING VOCABULARY FOR TSUANMI STUDY	Vol. 3 No. 1 P. 45	P
1985	Houston, James R.	TSUANMI FLOOD LEVEL PREDICTIONS FOR AMERICAN SAMOA	Vol. 3 No. 1 P. 53	P
1986	Kajiure, Kinjiro	HEIGHT DISTRIBUTION OF THE TSUANMI GENERATED BY THE NIHONKAI-CHUBU EARTHQUAKE	Vol. 4 No. 1 P. 3	P
1986	Murty, T. S. Crean, P. B.	NUMERICAL SIMULATION OF THE TSUNAMI OF JUNE 23, 1946	Vol. 4 No. 1 P. 15	P
1986	Togashi, Hiroyoshi	WAVE FORCE OF TSUNAMI BORE ON A VERTICAL WALL	Vol. 4 No. 1 P. 25	P
1986	Koyama, Junji Suzuki, Ziro Zosuga, Masahiro	EXTREME VALUES OF TSUNAMI MAGNITUDES	Vol. 4 No. 1 P. 39	P
1986	Volt, S. S. Sebekin, B. I.	THE INFLUENCE OF THE EARTH'S ROTATION ON THE ENERGY CHARACTERISTICS OF TSUNAMI WAVES	Vol. 4 No. 1 P. 55	P
1986	VanDorn, W. G.	NEW TSUNAMI RECORDERS AT WAKE ISLAND	Vol. 4 No. 1 P. 61	N
1986	Adams, Wm. M.	STORM SURGES- METEOROLOGICAL OCEAN TIDE, by T. S. Murty	Vol. 4 No. 1 P. 62	R
1986	Iwasaki, Toshio	HYDROMATIC NATURE OF DISASTERS BY THE TSUNMIS OF THE JAPAN EARTHQUAKE OF MAY 1984	VOl. 4 No. 2 P. 67	P
1986	Mader Charles L.	THE GREAT WAVES, by Douglas Myles	Vol. 4 No. 2 P.	R
1986	Koyama, Junji Kosuga, Masahiro	TSUNAMIGENIC EARTHQUAKES IN THE PACIFIC AND THE JAPAN SEA	Vol. 4 No. 2 P. 83	P
1986	Tsuji, Yoshinobu	COMPARISON OF OBSERVED AND NUMERICALLY CALCULATED HEIGHTS OF THE 1983 JAPAN SEA TSUNAMI	Vol. 4 No. 2 P. 91	P

YEAR	AUTHOR(S)	TITLE	VOL. NO. P.	TYPE
1986	Shuto, Nobuo Suzuki, Takao Hasagawa, Kan'ichi Inagaki, Kazuo	A STUDY OF NUMERICAL TECHNIQUES ON TSUNAMI PROPAGATION AND RUN UP	Vol. 4 No. 2 P. 111	P
1986	Solovjev, S. L. Pelinovsky, E. N.	ALL UNION CONFERENCE ON TSUNAMI PROBLEM IN GORKY	Vol. 4 No. 2 P. 125	N
1986	Qinghai, Zhou Adams, William	TSUNAMIGENIC EARTHQUAKES IN CHINA 1831 B.C. TO 1980 A.D.	Vol. 4 No. 3 P. 131	P
1986	Galkin, V. M. Golinko, V. I. Malizhenkova, V. I. Mirchina, N. R. Pelinovsky, E. N.	PROPAGATION OF TSUNAMI WAVES GENERATED BY ELLIPTICAL SOURCES	Vol. 4 No. 3 P. 149	P
1986	Abe, Kuniaki	AN EXPLANATION OF CHARACTERISTICS DISTRIBUTION OF THE TSUNAMI MAXIMUM INUNDATION HEIGHTS OBSERVED AT SMALL ISLANDS	Vol. 4 No. 3 P. 153	P
1986	Holloway, Greg Murty, Tad Fok, Edmand	EFFECT OF BATHYMETRIC ROUGHNESS UPON TSUNAMI TRAVEL TIME	Vol. 4 No. 3 P. 165	P
1986	Curtis, George D.	DESIGN AND DEVELOPEMENT OF A COASTAL TSUNAMI GAGE	Vol. 4 No. 3 P. 173	P
1986	Iida, Kumizi	ACTIVITY OF TSUNAMIGENIC EARTHQUAKES AROUND THE PACIFIC	Vol. 4 No. 3 P. 183	P
1987	Farrera, Salvador F. Sanchez, Antonio J.	GENERATION, WAVE FORM, AND LOCAL IMPACT OF THE SEPTEMBER 19, 1985 MEXICAN TSUNAMI	Vol. 5 No. 1 P. 3	P
1987	Hamilton, T. S. Wigen, S. O.	THE FORESLOPE HILLS OF THE FRASER DELTA: IMPLICATIONS FOR TSUNAMIS IN GEORGIA STRAIT	Vol. 5 No. 1 P. 15	P
1987	Adams, William M.	THE NOVEL SEISMIC SOURCE MECHANISM OF THE 7 MAY 1986 TSUNAMI	Vol. 5 No. 1 P. 35	P
1987	Curtis, George Mader, Charles	REAL-TIME MONITORING AND MODELING FOR TSUNAMI THREAT EVALUATION	Vol. 5 No. 1 P. 49	P
1987	Soloviev, S. L. Kulikov, E. A.	SPECTRAL ANALYSIS OF MAREOGRAMS FROM URUP TSUNAMIS OF 13 AND 20 OCTOBER 1963	Vol. 5 No. 1 P. 57	P
1987	Whitmore, P. M. Sokolowski, T. J.	RAPID SIZING OF POTENTIALLY TSUNAMIGENIC EARTHQUAKES AT REGIONAL DISTANCES IN ALASKA	Vol. 5 No. 2 P. 67	P
1987	Kowalik, Zygmunt Bang, Inkweon	NUMERICAL COMPUTATION OF TSUNAMI RUN-UP BY THE UPSTREAM DERIVATIVE METHOD	Vol. 5 No. 2 P. 77	P
1987	Shokin, Yu. I. Chubarov, L. B. Novikov, V. A. Sudakov, A. N.	CALCULATIONS OF TSUNAMI TRAVEL TIME CHARTS IN THE PACIFIC OCEAN - Models, Algorithms, Techniques, Results	Vol. 5 No. 2 P. 85	P
1987	Curtis, George D.	TSUNAMI! HAWAII'S OWN DRAMATIC STORIES AND THE FACTS ABOUT THE GIANT WAVES, by Walt Dudley and Min Lee	Vol. 5 No. 2 P. 123	R
1987	Murty, T. S.	NUMERICAL MODELING OF WATER WAVES, by Charles L. Mader	Vol. 5 No. 2 P. 124	R

YEAR	AUTHOR(S)	TITLE	VOL. NO. P.	TYPE
1988	Tinti, S.	INTRODUCTION: TSUNAMIS GENERATED BY EARTHQUAKE AND VOLCANIC ERUPTIONS	Vol. 6 No. 1 P. 3	N
1988	Nakamura, S.	ON AUDIBLE TSUNAMI ON THE COAST	Vol. 6 No. 1 P. 5	P
1988	Guidoboni, E. Tinti, S.	A REVIEW OF THE HISTORICAL 1627 TSUNAMI IN THE SOUTHERN ADRIATIC	Vol. 6 No. 1 P. 11	P
1988	Tinti, S. Guidoboni, E.	REVISION OF THE TSUNAMIS OCCURED IN 1783 IN CALABRIA AND SICILY (ITALY)	Vol. 6 No. 1 P. 17	P
1988	Pararas-Carayannis, George	THE TSUNAMI GENERATED FROM THE ERUPTION OF THE VOLCANO OF SANTORIN IN THE BRONZE AGE	Vol. 6 No. 1 P. 23	P
1988	Dotsenko, S. F. Soloviev, S. L.	MATHEMATICAL SIMULTION OF TSUNAMI EXITATION BY DISLOCATIONS OF OCEAN BOTTOM	Vol. 6 No. 1 P. 31	P
1988	Moreira, Victor S.	HISTORICAL AND RECENT TSUNAMIS IN THE EUROPEAN AREA	Vol. 6 NO. 1 P. 37	P
1988	Adams, William Mansfield	BASIC IMPROVEMENT OF TSUNAMI WARNING SYSTEMS ON PREVIOUS EXPERIENCES	Vol. 6 No. 1 P. 43	P
1988	Koutitas, Christopher Laskaratos, Alexander	TSUNAMI INDUCED OSCILATIONS IN CORINTHOS BAY MEASUREMENTS AND 1-D vs 2-D MATHEMATICAL MODELS	Vol. 6 No. 1 P. 51	P
1988	Zetler, Bernard D.	SOME TSUNAMI MEMORIES	Vol. 6 No. 1 P. 57	N
1989	Dunbar, D. LeBlond, P. H. Murty, T. S.	MAXIMUM TSUNAMI AMPLITUDES AND ASSOCIATED CURRENTS ON THE COAST OF BRITISH COLUMBIA	Vol. 7 No. 1 P. 3	P
1989	Guidoboni, E. Tinti, S.	THE LARGEST HISTORICAL TSUNAMIS IN THE NORTHERN ADRIATIC SEA: A CRITICAL REVIEW	Vol. 7 No. 1 P. 45	P
1989	Soloviev, S. L. Larichev, V. D. Sebekin, B. I. Zmur, V. V.	MEMORIUM TO SERGEI SERGEEVICH VOIT(1920-1987)	Vol. 7 No. 1 P. 55	N
1989	Rafiq, M.	BIOPHYSICAL MARKERS FOR DELINEATION OF INUNDATION LIMITS OF TSUNAMIS AND STORM SURGES	Vol. 7 No. 2 P. 67	P
1989	Danard, M. B. Murty, T. S.	ON SOURCES OF ERROR IN CALCULATION OF TSUNAMI TRAVEL TIMES	Vol. 7 No. 2 P. 73	P
1989	Caputo, Michele Caputo, Riccardo	CONTRIBUTION FOR THE STUDY OF TECTONIC ACTIVITY ON THE MEDITERRANEAN SEA FROM VOLCANIC ACTIVITY AT SEA AND NEW ISLANDS EMERGED IN HISTORIC TIMES	Vol. 7 No. 2 P. 79	P
1989	Bapat, Arun	OBSERVATION OF SEISMIC GAPS IN ASIA AND AMERICAS	Vol. 7 No. 2 P. 103	P
1989	Abe, Kuniaki Ishii, Hiroshi	SHELF TSUNAMI AND TRENCH TSUNAMI - 1-D MODEL	Vol. 7 No. 2 P. 107	P
1989	Pelinovsky, E. N.	TSUNAMI CLIMBING A BEACH AND TSUNAMI ZONATION	Vol. 7 No. 2 P. 117	P

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