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TSUNAMIS AND EARTHQUAKES*

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STRONG earthquakes occurring near an oceanic coast are sometimes followed by alternating advances and recessions of the sea, which may even rush inland several kilometers over beaches, carry ships ashore, crush houses, then recede far beyond the normal shore, and in repeated oscillations cause great damage and loss of life. In the open ocean, these waves are of so great length that they are not dangerous. In general, their period is between a quarter- and a half-hour; their velocity in an ocean of the constant depth h is approximately $\sqrt{gh}$. This gives about 220 m/sec. in water 5 km. deep, and about 70 m/sec. in water 500 m. deep; the corresponding lengths of waves with a period of 30 min. are about 400 km. and 130 km., respectively.

These waves are frequently called "tidal waves." However, as they have no connection with tides, it seems preferable to use another expression, for example, the Japanese word "tsunami."[1] The waves arise not only in connection with earthquakes, but also from submarine volcanic action and from strong storms.

In a remark in *Earthquake Notes* (vol. 10, no. 3 [December, 1938], p. 7) it was stated that "no instances have been observed where sea waves have been caused by earthquakes centering entirely on land." In a letter to the editor, the present writer expressed doubt that the statement as quoted is correct, and referred to the Atacama earthquake of November 11 (Greenwich time), 1922. In a second note following the letter (vol. 10, no. 4 [April, 1939]) the editor of *Earthquake Notes*, Mr. Bodle, remarked: ". . . the shock of November 10, 1922, is not conclusive evidence in support of the conclusion that seismic sea-waves may be caused by an earthquake centering entirely on land." It is because Mr. Bodle's comments contain several other statements which need modification, and because the correspondence discloses a wide difference in opinion concerning the origin of tsunamis, that the present paper is written.

* Manuscript received for publication July 17, 1939.

[1] The Japanese sometimes spell the word "tunami," but give it the same pronunciation as "tsunami." In English, the latter spelling should always be used, in order to avoid a wrong pronunciation.

In his comments Mr. Bodle states: "Seismologists are almost unanimous in the opinion that seismic sea-waves originate in vertical displacements of the sea floor." In fact, however, a notable fraction of the few who have investigated tsunamis have reached the conclusion that submarine landslides are to be considered at least as one of the chief causes, if not indeed the major cause, of tsunamis. Some of these opinions can be found in the following statements of Montessus de Ballore.[2]

"Tsunamis can originate only from phenomena which are indirectly seismic; for example, slides (*éboulements*). According to Verbeck,[3] such was the origin of the waves by which many people were drowned after the earthquake in Ceram in 1899, the origin of which was incontestably tectonic and on land, not submarine. In the Assam earthquake of 1897, large landslides occurred, and there is nothing hypothetical about the idea that large waves will result from submarine slides. Thus, this is not only a possible but even a sure cause of the production of tsunamis. Milne[4] applies this same point of view to the tsunamis which are produced by the earthquakes on the slope of the Tuscarora deep, east of Japan, and thus is in agreement with Forster,[5] who thinks that the breakage of several cables near Greece must be attributed to submarine slides which were caused by earthquakes."

The statements of Montessus de Ballore and Milne are especially important, as both had had experience of earthquakes as well as of tsunamis. The conclusion that submarine slides must produce tsunamis, and therefore are one certain cause of the large waves, seems to the present author to be unavoidable, and it should be added that submarine slides may be expected to occur more readily than slides on land. In this connection, reference is made to Imamura's[6] mention of "the great landslide from the side of the volcano Unzendake near Nagasaki, which occurred in 1792 and which discharged an enormous quantity of débris into the bay, resulting in a gigantic tsunami that caused the death of 12,000 people."

Tsunamis are relatively frequent in Japan and have been studied in detail, but apparently no definite conclusion concerning the direct cause of them has been reached. In the Kwanto earthquake of September 1, 1923, a large area was found to have suffered vertical displacements amounting to 100 meters and more. While there can be no doubt that such large changes must produce tsunamis, it is still to be learned how the changes were produced. The vertical changes along the coast at distances of the order of 10 mi. from the points on

[2] F. de Montessus de Ballore, *La Science Séismologique* (Paris, 1907), p. 220. The sentences given are a somewhat shortened translation.

[3] R. D. M. Verbeck, "Kort verslag over de aard- en zeebeving op Ceram, den 30. September 1899," *Natuurkund. Tijdschr. voor Ned.-Indie*, 60:218 (1900).

[4] Third report of the Committee on Seismological Investigation, Brit. Assoc. for the Adv. of Sci., Bristol meeting, 1898.

[5] W. G. Forster, "Earthquake Origin," *Trans. Seism. Soc. Japan*, 15:73 (1890).

[6] A. Imamura, *Theoretical and Applied Seismology* (Tokyo, 1937), p. 126.

the ocean bottom where large differences were observed did not exceed $2\frac{1}{2}$ m.[7] On the other hand, the depth of the ocean was found to be about 100 m. greater in some regions, and a like amount less in others closely adjoining.[8] As a consequence, the conclusion has been drawn independently by many scientists that "submarine landslides appear to account for the phenomena more satisfactorily."[9] This is the more probable because in this "earthquake thousands of conspicuous landslides took place in the Miura and Idu peninsulas, in the southern part of Bô-Sô Peninsula, and in the mountainous district of southwestern Sagami. . . . [One] landslip swept down a narrow ravine about 150 m. wide, 6 km. long. [At Hakone Volcano, avalanches] united on their way to grow into a volume of at least one million cubic meters, and run down the whole course within five minutes."[10] It would be very curious indeed if the landslides had been restricted to the visible land while large vertical tectonic displacements had occurred only on the invisible bottom of the sea.

Another region of frequent destructive tsunamis is the coast of Chile.[11] There are several instances of their occurrence in connection with earthquakes for which the observations indicate an epicenter on land. As an example one may mention the shock of May 9, 1877, which was accompanied by a large tsunami. According to Montessus de Ballore, the intensity of this earthquake was high far inland, and decreased toward the coast.

The Atacama earthquake of November 11, 1922, is another example. As has been mentioned, Mr. Bodle has doubted the conclusions of the present author, and of A. Sieberg and others, concerning this shock. For this reason the data and conclusions are presented more fully here. This earthquake has been studied from various points of view.[12] Detailed measurements on original seismograms and copies have been made by Gutenberg[13] and by Macelwane and

[7] For a summary see, for example, Ch. Davison, *The Japanese Earthquake of 1923* (London, 1931), chap. xi.

[8] Davison, *op. cit.*, p. 95, mentions one region in which "the bed has sunk by more than 1312 feet, and this closely adjoins one in which the uplift is as much as 755 feet."

[9] F. P. Shepard, "Depth Changes in the Sagami Bay During the Great Japanese Earthquake," *Jour. Geol.*, 41:527 (1933). In another paper—"Investigations of Submarine Valleys," *Trans. Am. Geophys. Union*, 1933, p. 172—Shepard writes: "The deepening of Sagami Bay . . . was evidently due to a landslide. . . . Other cases such as those along the east coast of North America at the time of the Grand Banks earthquake are less certainly established."

[10] Imamura, *op. cit.*, p. 70.

[11] See, for example, C. Bobillier, "Historia de los maremotos acaecidos en Chile desde el año 1562 hasta el año 1932," *Bol. Servicio Sismológico Universidad de Chile*, no. 23, pp. 34–41 (1933).

[12] A. Sieberg and B. Gutenberg, "Das Erdbeben in der chilenischen Provinz Atacama am 10. November 1922," *Veröff. Reichsanstalt f. Erdbebenforsch.* (Jena, 1924), Heft 3.

Bailey Willis, "Earthquake Conditions in Chile," Carnegie Inst. Washington *Publ.* no. 382 (1929).

Luis Sierra Vera, "Distribution of Intensities," *ibid.*, pp. 143–147.

[13] Sieberg and Gutenberg, *op. cit.*; B. Gutenberg, "Bearbeitung der instrumentellen Aufzeichnungen des Atacamabebens am 10. November 1922," *Veröff. Reichsanstalt f. Erdbebenforsch.* (Jena, 1925), Nachtrag.

Byerly.[14] In these published investigations, independent calculations of the epicenter have been made. Moreover, A. Mohorovičić has determined its location (written communication). And, finally, all reports from stations have been published, together with a special discussion of the epicenter by H. H. Turner.[15] The results of these calculations are as shown in table 1.

TABLE 1

CALCULATIONS OF THE EPICENTER OF THE ATACAMA EARTHQUAKE OF NOVEMBER 11, 1922

Author	Location of epicenter		Origin time	Travel-time curve used
	Long. W	Lat. S		
Gutenberg	70.2±0.7	28°.5±0.4	$4^h32^m37^s±4^s$	Mohorovičić
A. Mohorovičić	69.9	28.9	37	Mohorovičić
Gutenberg	70.4±0.6	28.4±0.5	36±3	Mohorovičić
Gutenberg	70.3±0.5	27.9±0.8*		
Turner	71.0	29.0	30	Zoeppritz
Macelwane and Byerly	69°59′±19′	29°00′±14′	33±2	Gutenberg, 1923

* Epicenter based on data from pairs of stations having about equal time of first movement.

Although the results based on different methods and in part on different data show very good agreement, a new calculation has been made. Data were used only from stations for which P had been measured either by Macelwane and Byerly or by Gutenberg. Furthermore, since the results of the measurements at most stations are available in the *International Seismological Summary*, two or three independent results concerning the times of arrival of P are available for the selected stations. In general, the differences are small, and the mean of the readings was taken. Where, as rarely happened, the calculated mean error of the results exceeded 2 sec., the data were rejected. From stations at distances between 95° and 104° only records with clear beginnings were used, and no records from distances of more than 104°. Table 2 exhibits the data and results of the calculations. The second column gives the geocentric distances of the stations from the point with the coördinates 70° W, 28°.5 S, which was taken as an approximation, using the earlier findings. The azimuths were taken from the *I.S.S.*, so far as they were available there. $P-O^*$ is the travel time of P under the assumption that $O^*=4^h\ 32^m\ 36^s$ is the origin time (from previous results). The observed values of $S-P$ were used to find $P-O$;[16] the column headed "O" gives the difference $(P-O^*)-(P-O)$. The average is −6 sec. The use of S−P in the determination of O gives too early an origin time, owing to

[14] J. B. Macelwane and P. Byerly, "Report on Seismograms . . . ," Carnegie Inst. Washington *Publ.* no. 382, pp. 137–139 (1929).

[15] *Internat. Seism. Summary for 1921* (University Observatory, Oxford, 1925), pp. 183–186.

[16] B. Gutenberg and C. F. Richter, "Materials for the Study of Deep-focus Earthquakes," *Bull Seism. Soc. Am.*, 26:375, table 45 (1936), for depth of focus of 25 km.

late readings of S. As this error is usually about −6 sec., the adopted origin time of $4^h\ 32^m\ 36^s$ may be considered the best approximation available. In the following column, distances Δ* are given; they correspond to P−O* for normal focal depth.[17] The last column contains the residuals between this "true" distance and the distance from the adopted point. These residuals have been plotted in figure 1 as a function of the azimuth of the stations. Twenty-two out of twenty-eight values are within ±0.7 deg. without evidence of any preference for certain values within a given range of azimuth. The figure confirms the previous calculations that the mean error of the adopted epicenter is about

TABLE 2

DATA FOR THE ATACAMA EARTHQUAKE OF NOVEMBER 11, 1922, $4^h32^m36^s$ GREENWICH TIME

Station	Δ	Azim.	P-O*	S-P	O	Δ*	Δ*-Δ
	deg.	deg.	m s	m s	s	deg.	deg.
Santiago	4.4	190	0:59	0:49	− 5	3.7	−0.7
Villa Ortuzar	11.5	100	2:45	2:15	− 7	11.2	−0.3
Rio de Janeiro	24.6	83	5:24	4:27	− 9	24.7	+0.1
Vera Cruz	53.8	351	9:26	7:37	− 1	54.0	+0.2
Tacubaya	55.5	328	9:40	7:41	+ 7	56.0	+0.5
Georgetown	67.5	355	11:01	8:55	− 5	67.6	+0.1
Washington	67.5	355	10:57	8:57	−12	67.0	−0.5
St. Louis	69.6	345	11:09	9:10	−15	68.9	−0.7
Ithaca	71.0	356	11:17	9:14	−11	70.3	−0.7
Chicago	72.1	348	11:25	9:08	+ 3	71.7	−0.6
Northfield	72.5	359	11:31	9:24	− 9	72.8	+0.3
Ottawa	73.9	357	11:34	9:32	−14	73.3	−0.6
Lick	81.5	321	12:21	....	....	81.8	+0.3
Berkeley	82.3	321	12:18	....	....	81.2	−1.1
Lisbon	87.8	40	12:48	....	....	87.2	−0.6
San Fernando	88.2	46	12:51	....	....	87.8	−0.4
Malaga	89.5	48	12:55	....	....	88.6	−0.9
Victoria	90.3	329	13:04	....	....	90.6	+0.3
Toledo	91.7	45	13:13	....	....	92.6	+0.9
Apia	93.6	254	13:22	....	....	94.5	+0.9
Algiers	94.5	50	13:27	....	....	95.6	+1.1
Oxford	100.3	37	13:49	....	....	100.6	+0.3
Uccle	102.6	39	13:58	....	....	102.6	0.0
Florence	103.5	47	14:04	....	....	103.9	+0.4
De Bilt	103.7	39	14:06	....	....	104.3	+0.6

[17] B. Gutenberg and C. F. Richter, "Materials for the Study of Deep-focus Earthquakes" (second paper), *Bull. Seism. Soc. Am.*, 27:161, table 1 (1937).

0°.5. Figure 1 does not suggest a change of the assumed coördinates. The fact that the residuals in a given azimuth do not change noticeably with distance indicates that the origin time assumed for the calculation is very closely correct. If the epicenter had been off the coast, the residuals should group around a sinusoidal curve with an ordinate of at least $+1\frac{1}{2}°$ near the azimuth of 90° and of below $-1\frac{1}{2}°$ near 270°. Although there are only three stations with

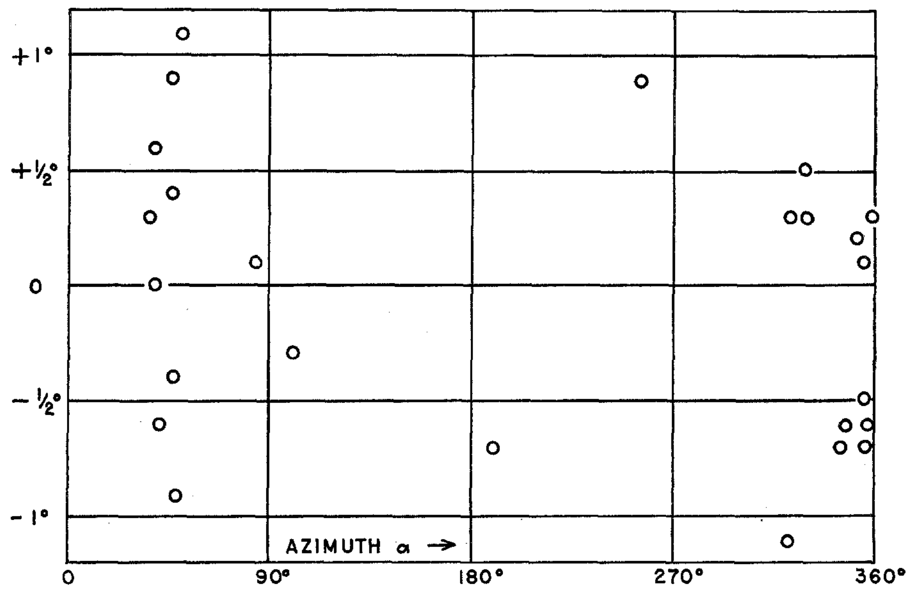

Fig. 1. Atacama earthquake, November 11, 1922. Residuals as given in the last column of table 1 as a function of the azimuth of the stations at the epicenter.

azimuths near 90° and 270°, the data of the stations with azimuths near 45° and 315° add sufficiently to the "longitude control" of the epicenter to practically exclude the possibility that the epicenter was off the coast. According to Willis,[18] during one of the aftershocks "telegraph operators at Vallenar communicating with those at Copiapó wired: 'It shakes.' And those at Copiapó perceived the shock a few seconds later." The epicenter of the main shock as calculated from the microseismic data would fit this observation (see fig. 2).

Mr. Bodle has mentioned the possibility that the focus of the shock was deeper than normal. However, all data point to a normal depth. The radius of the shaken area was about 1400 km. to the south and more than 1600 km. to the east. Taking 1600 km. as average radius and the maximum intensity as XI of the Mercalli-Sieberg scale, the Blake-Gassmann equation[19] gives a depth

[18] *Op. cit.*, p. 45.

[19] A. Blake, "On the Estimation of Focal Depth from Macroseismic Data," *Trans. Am. Geophys. Union*, 1937, p. 120.

of slightly more than 30 km. The surface waves of the shock were large, as may be seen from the seismograms reproduced in the article by Sieberg and Gutenberg referred to above.[20] Even W_4-waves could be studied.[21] All travel times of P′ indicate a shallow focus with most calculated depths between 0 and 30 km. (maximum of 30 km. from P′ at Batavia, $\Delta = 145°$, and Manila, $\Delta = 162°.5$).

The macroseismic data of the Atacama earthquake have been studied by Sieberg, Sierra Vera, Willis, and others.[22] The isoseismal lines drawn by Sieberg are reproduced in figure 2. In general, there is a good agreement among the results of the various authors. In comparing the results, it must be kept in

TABLE 3

INTENSITIES OF THE ATACAMA EARTHQUAKE OF NOVEMBER 11, 1922
(Grades Rossi-Forel reduced to Mercalli-Sieberg as indicated in text)

Locality	By Sieberg	By Sierra Vera
Taltal	VI	......
Chañaral	VI to VII	No damage
Caldera	VII	VI to VII
Carrizal	VII	VI to VII
Huasco	IX	VI to X
Coquimbo	VI	VI
Tongoi	VI	......
Coast near Illapel	V to VI	......

mind that Sieberg used the Mercalli-Sieberg scale, whereas the others preferred the use of the scale of Rossi-Forel. The grades VI to IX of Rossi-Forel are about 1 deg. higher than those of Mercalli-Sieberg; the grade X of Rossi-Forel corresponds about to the grades IX to XII of Mercalli-Sieberg, without further discrimination between them.

All locations to which Sieberg has assigned an intensity of XI (Vallenar) or X are rated about equally high by Sierra Vera and Willis. For places along the coast, the intensities given in table 3 have been considered correct.

Figure 2 is in agreement with the conclusion of Chilean seismologists[23] that the intensity decreased considerably in the coastal region. Thus, it can safely be concluded that the macroseismic as well as the microseismic data point to a source on land and that neither agrees with the assumption of a submarine source for the main shock.

The problem of the tsunamis that did severe damage after the earthquake was first discussed by Sieberg.[24] Unfortunately, he only had data on their amplitudes, none on their travel times. He concluded that the waves started at two different locations: (*a*) 17¾° W, 29° S, and (*b*) 71½° W, 26½° S, and that

[20] See note 12.
[21] Gutenberg, *op. cit.*
[22] See note 12.
[23] See note 11.
[24] *Op. cit.*

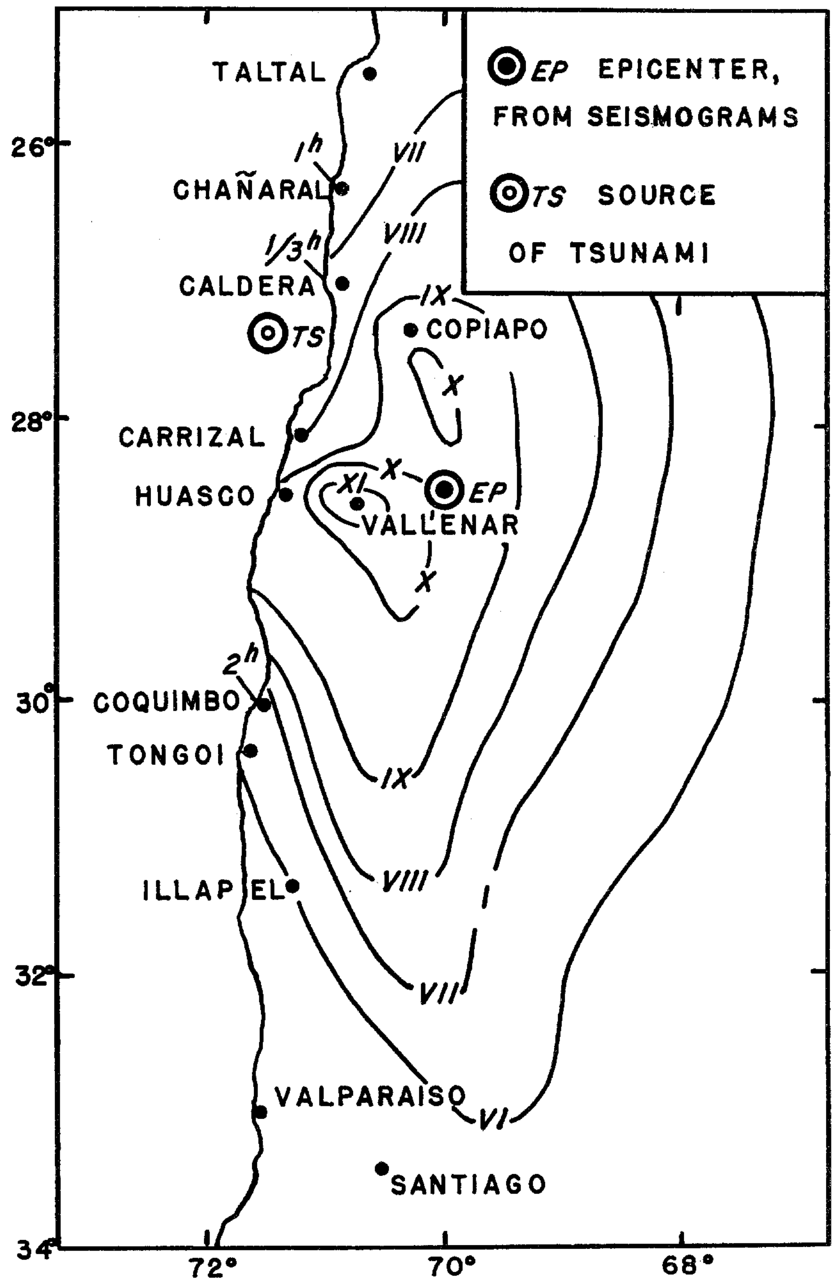

Fig. 2. Isoseismal lines of the Atacama earthquake, November 11, 1922, after Sieberg, and travel times of tsunamis in hours.

they were produced by large submarine slides on the very steep slopes of the ocean bed. He considers his paper as the first proof that tsunamis are sometimes produced by submarine slides which are started by an earthquake on land with an epicenter more than 100 km. from the coast.[25]

Fortunately, Willis has reproduced some reports in which travel times were mentioned. At Chañaral (see fig. 2) "the earthquake was not alarming. . . . The maremoto began an hour after the shock."[26] Damage was done only by the maremoto.[27]

At Caldera, four witnesses gave the time of the tsunami.[28] The first observed it 45 minutes after the shock; the second, after the shock, "got up and ran to the playa to see the maremoto"; the third, on board of a steamer, "went ashore, and 15 minutes after the beginning of the terremoto he observed close at hand the initial rise of the maremoto, being at the time in the boat"; the last reported that "after the earthquake the sea remained completely tranquil . . . but after 30 minutes began to advance." From the data there is no doubt that the tsunami reached Caldera after a fraction of an hour, probably closer to 15 than to 30 minutes. The difference between the time noted by the observer in the boat and that noted by the first witness is easily explained by the fact that the one was "close at hand," whereas the other probably missed the first wave; "the several advances of the sea which followed were greater than the first." The maximum occurred about 4 hours after the shock. Most observers at Caldera reported "no damage" from the earthquake, but the tsunami destroyed many buildings.[29]

At Coquimbo, the maremoto started about 2 hours after the earthquake and did much damage.[30]

From the times as given above and the theoretical velocity of the waves it is possible to calculate the approximate location of the origin of the tsunami. The assumption of the source in the region of 71½° W, 27½° S (marked "TS" in fig. 2) would well explain all reports. In this region, the ocean bottom descends by about 5 km. in a horizontal distance of 50 km. As may be seen from the data given in figure 2, the evidence plainly contradicts the assumption that the tsunami was produced by tectonic movements in connection with the main shock. Bodle suggests[31] the possibility that, in addition to the main shock, some seismic activity might have occurred under the sea to cause the tidal wave. However, a tectonic vertical displacement large enough to produce a tsunami of the observed dimensions would be accompanied by earthquake movements of at least grade X, and probably even XI, according to the investigations which led to the establishment of earthquake scales. The observed in-

[25] In his article in B. Gutenberg, *Handbuch der Geophysik*, vol. 4 (Berlin, 1932), p. 983, he gives additional references. See also *ibid.*, p. 671.

[26] *Op. cit.*, p. 35.

[27] *Ibid.*, p. 143.

[28] *Ibid.*, p. 34.

[29] Sieberg and Gutenberg, *op. cit.*

[30] Willis, *op. cit.*, p. 31.

[31] *Op. cit.*, p. 12.

tensities in the critical region, especially near Caldera, are extremely unfavorable to this hypothesis. From all data available the conclusion seems unavoidable to the present writer that the tsunami was not produced by tectonic displacements, but by submarine slides.

The present author, after investigating reports and records of tsunamis, has for many years[32] shared with others who have worked in this field the belief that submarine slides are among the most important sources of tsunamis. The fact that large tsunamis are observed most frequently along coasts with steep slopes is in favor of this hypothesis. This does not exclude the generation of waves by submarine faulting. The relatively small tsunamis observed on gently sloping coasts, as for example in California, are very likely produced in this way.

Summary

Tsunamis ("tidal waves," "maremotos") may be produced by submarine volcanic eruptions, submarine slides started by earthquakes, submarine faulting, and atmospheric conditions. The hypothesis that at least some of the largest tsunamis have been produced by submarine slides with earthquake waves as a trigger force has been advanced by a notable number of those seismologists who have studied tsunamis. The macroseismic as well as the microseismic data of the Atacama earthquake of November 11, 1922, indicate clearly that the fault movement occurred inland; the tsunamis originated from a submarine slide near a relatively feebly shaken stretch of the coast where the surface slopes steeply to a considerable depth. On gently sloping coasts, such as those of California, large tsunamis are rare and the relatively small tsunamis there are probably produced by faulting at the bottom of the ocean.

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California Institute of Technology, contribution no. 281.]

[32] See, for example, B. Gutenberg, *Grundlagen der Erdbebenkunde* (Berlin, 1927), p. 30.