Tsunamis of Volcanic Origin: Summary of Causes, with Particular Reference to Krakatoa, 1883

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ABSTRACT

Known tsunamis of volcanic origin are reviewed and classified according to their causes. Earthquakes accompanying eruptions (excluding tectonic events which apparently triggered eruptions), pyroclastic flows, and submarine explosions have each accounted for about 20% of cases. Ten causes of volcanic tsunamis are discussed. From the risk point of view, those due to landslides are particularly dangerous. Eruptions at calderas are more likely to generate tsunamis than eruptions elsewhere. Of those killed directly by volcanic eruptions, nearly a quarter have died as a result of tsunamis. By transfer of energy to sea waves, a violent eruption, which would be comparatively harmless on land, extends greatly the radius over which destruction occurs.

Krakatoa, 1883, is the only eruption sequence for which sufficient data exist for a detailed study of tsunamis. The times at which air and water waves generated by this sequence were recorded have been reread, and new origin times have been calculated and compared with observations made at the time. Origin times of successive pairs of air and water waves agree closely, except in some cases in which the tsunami arrived up to 15 minutes early, thus giving an apparent origin time 15 minutes before that of the corresponding air wave. This is explained by postulating that these tsunamis did not originate at the focus of the explosions, but at distances along the path towards the tide gauge, equivalent to those which would be covered by a tsunami in the time interval observed.

The calculated point at which the largest recorded tsunami originated coincides with the outer edge of a bank of volcanic debris laid down during the eruption. This is interpreted as part of an unwelded ignimbrite deposit, the violent emplacement of which, within a minute or so of the explosion, generated the tsunami. A satisfactory correlation is established between explosions and deposits laid down by the eruptions, as described from a geological section close to the source vent.

An outline is given of a proposed numerical index to define tsunamigenic potential at a given volcano. Such an index could be used to calculate the expected amplitudes of tsunamis at particular places in the vicinity, and hence could serve as a basis for tsunami risk contingency planning.

INTRODUCTION

Many different sorts of events, with a multiplicity of causes, can be grouped under the term «tsunami». IMAMURA (1937, p. 123) states that the word comes from a combination of the Japanese *tsu* meaning a port and *nami* a long wave, hence «long wave in harbour». He goes on to say that the meaning might also be defined as «seismic sea-wave. Hardly recognizable out at sea, these waves, upon reaching the head of a bay or harbour, attain extraordinary heights, and on occasion cause great damage». At the same time as acquiring an «s» in the plural (the Japanese word is the same in plural as in singular), the term has gradually been extended to cover waves other than those caused by earthquakes, so that it now includes waves due to volcanic eruptions, as well as those resulting from landslides, many of which have no relationship to either seismicity or volcanism.

The purpose of this paper is to examine the causes of tsunamis of volcanic origin, or of those closely associated in time and space with volcanic eruptions, more precisely than has been done before, with the ultimate aim, not realised in this paper, of

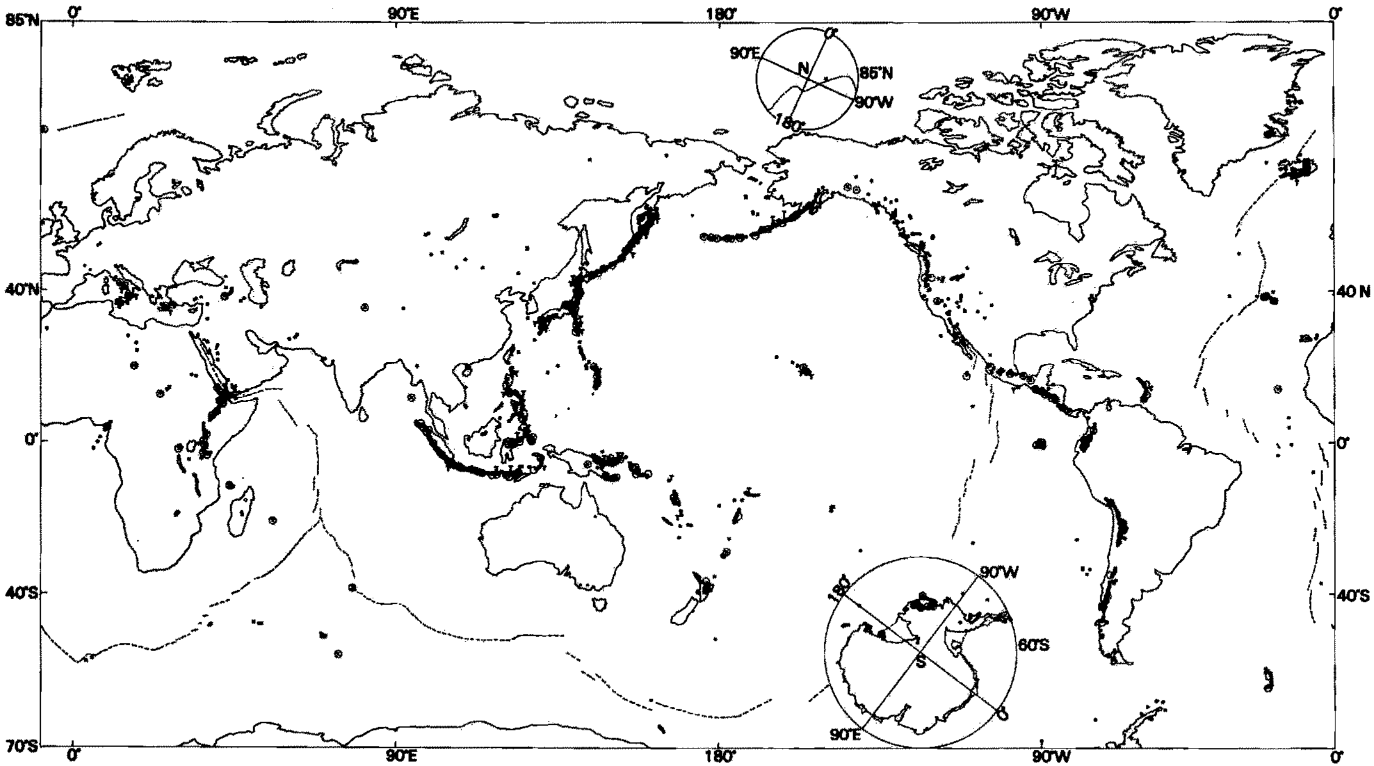

FIG. 1 - Active and potentially active volcanoes of the world. The letters T mark volcanoes at which the 92 cases of volcanic tsunamis investigated have occurred. Prominent calderas are marked by small circles. Dashed and dotted lines represent mid-ocean ridges, and fine dots the edge of the Antarctic ice shelves. Differences in the symbols used for the volcanoes may be ignored. Adapted from LATTER (1980).

assessing the likelihood and probable scale of future tsunamis at specific volcanoes. With this intention, I have reviewed as many historic cases of supposed «volcanic tsunamis» as I have been able to find in the catalogues of HECK (1947), BERNINGHAUSEN (1966, 1968, 1969), IIDA *et al.* (1967), COX *et al.* (1976), PARARAS-CARAYANNIS *et al.* (1977), and HÉDERVÁRI (in press), and where practicable have also read the original reports.

Although volcanic tsunamis are much less frequent than those associated with tectonic earthquakes, they are very often highly destructive. Most of those known to have been killed as a result of volcanic eruptions since 1000 A.D. have died through the indirect effects of eruptions, starvation and disease, as in Iceland and Sumbawa after the great eruptions of 1783 and 1815. However, of those killed directly during eruptions, by events related to the eruptive process, 20-25% have died because of tsunamis. This proportion is similar to the combined total of those killed by pyroclastic flow and airfall ejecta, and much larger than the number killed by lahars and landslides.

The principal cause of the large number killed by volcanic tsunamis is the extension of the distance over which destructive processes such as nuées ardentes, lahars, landslides etc., are able to operate, through the direct transfer of part of their energy to sea waves, which can then propagate for great distances. Thus the uninhabited island of Krakatoa, far removed from populated areas, was nevertheless able to inflict an enormous number of casualties on neighbouring coastlines, at distances of as much as 120 km, far greater than would have been the case had the eruption taken place with the same degree of intensity in a wholly terrestrial environment. In spite of their rarity, volcanic tsunamis have an extremely high potential for destruction, and are therefore among the phenomena, like the eruption of ignimbrites, which deserve careful consideration from the risk point of view. *Jokulhlaups*, similarly high risk phenomena, are ignored in this paper.

VOLCANIC TSUNAMIS IN HISTORIC TIMES

Historic time, the time over which an adequate record has been kept of important events, varies widely in different parts of the world, extending back 3000 years or more in the Mediterranean, and a mere few hundred, or less, in some regions of the Pacific and South Indian and Atlantic Oceans. Thus no summary of recorded tsunamis can be of much value for statistical purposes, and indeed amounts to hardly more than a random sample of events. Subject to this limitation, however, 106 cases of supposed tsunamis of volcanic origin have been examined. Eruptions at certain submarine volcanoes, which habitually generate small tsunamis each time an explosion takes place, have been included only once in this total for every eruptive episode. Tsunamis at Krakatoa in 1883, on the other hand, have been individually included, because, as discussed below, not all appear to have had the same origin or cause.

Of these 106 cases, 14 have been rejected: 10 because they were clearly tsunamis due to tectonic earthquakes (1), including earthquakes that appear to have triggered eruptions, three because they were straightforward errors or misprints, and one, attributed to a submarine volcano in the North Atlantic in 1894, which amounts to nothing more than a guess. The 92 remaining cases are provisionally considered to have been genuine tsunamis of volcanic origin, although there is insufficient evidence to deduce the cause of 23 of them. The volcanoes at which these 92 originated are identified in Fig. 1 by a «T». Over half took place at

(1) These are: 1946 April 1 attributed to Pavlof, 1856 September 25 at Komagatake, 1737 October 17 at Avachinsky, two tsunamis attributed to Oshima in 1703 and 1716, 1897 September 21 at Jolo, 1913 March 14 at Awu, 1968 September 6 at Banua Wuhu, 1975 November 29 near Kilauea, and the 1918 September 2 event near Simushir Island. The errors are the 1827 supposed Fisher tsunami, the 1050 Santorin event, and 1742 at Fuss Peak.

calderas or cones within calderas. Accordingly, the prominent calderas of the world are also identified in Fig. 1: see discussion below concerning the risk of future tsunamis.

Leaving aside the 23 cases [2] for which more research on the field evidence or original reports is necessary before any clear idea as to their causes can be obtained, the most probable causes for the remaining 69 have been determined. The commonest, accounting for 22% of the events, is found to be earthquakes accompanying eruptions (tectonic earthquakes preceding eruptions and apparently triggering them are excluded, however, as mentioned above). Pyroclastic flows (nuées ardentes and ignimbrites), impacting on water, account for 20% of cases, and submarine explosions for 19%. Caldera collapse or subsidence is the cause of about 9%. Avalanches of cold rock, in solid form, and base surges with accompanying shock waves, have each produced about 7%, and avalanches of hot material 6% of volcanic tsunamis. Lahars impacting on water, and air waves of explosions, have each generated 4½% of cases, and a single eruption in which tsunamis were formed by lava avalanching into the sea makes up the final 1%. These 10 types of volcanic tsunami are described in more detail below.

DETAILED INFORMATION

Unfortunately, even within the 69 cases of tsunamis for which causes can be fairly confidently identified, little detailed information is available. Accurate times at which both tsunamis and their attendant eruptions were observed are for the most part lacking, and in very few cases are there tide gauge records to which reference can be made for the determination of origin times and other characteristics of tsunamis.

STEHN (1929) has published a short, but detailed account of small waves associated with submarine eruptions at Anak Krakatoa, and MIYOSHI *et al.* (1954), NAKANO *et al.* (1954), and MORIMOTO *et al.* (1955) have described in detail the mode of generation of small to medium tsunamis generated by submarine explosions at the Bayonnaise Rocks. For the latter, a continuous tide gauge record is available from Hachijo Island, at a distance of about 125 km. For a few other events, such as the Augustine eruption of 1883, and the eruption of Vulcan in Rabaul caldera in 1937, times and accurate descriptions have been given. By far the best source of information, however, is the great eruption of Krakatoa in 1883, for which not only numerous eyewitness accounts have been published, but also tide gauge and air pressure records, albeit of a somewhat primitive kind, exist. Furthermore, the tsunamis produced by this eruption were exceptionally large and destructive, being exceeded, if at all, only by the inferred, but still rather controversial tsunamis associated with the Minoan eruption of Santorin, Accordingly, a special effort has been made to reinterpret the Krakatoa eruption, with a view to establishing, more precisely than has been done previously, the causes of the several tsunamis that resulted.

THE 1883 KRAKATOA ERUPTION AND ITS ATTENDANT TSUNAMIS

VERBEEK (1886) interviewed survivors of the climactic eruptions of 26-27 August 1883 at Krakatoa, and wrote his findings in a comprehensive report, published in Dutch and French. JUDD, STRACHEY, WHARTON, and RUSSELL *et al.* followed this up in 1888 with the Royal Society

(2) These represent tsunamis at the following volcanoes: Mt Pelée (1902 May 5 23 h L.T.), a submarine volcano (?) off the coast of Mexico (1931 February 3), Torishima (1664), Gamalama (1673 August 12, and 1763 September 1), Makian? (1858 November 13), Gamkonora (1673 May 20), Assongsong (1786?), Hatizyozima Nisiyama (1606 January 23), Sakurajima (766 July), Bulusan (1933 December 25), Serua (1859 September 25), Krakatoa (416?, and 1883 October 10) Santorin (Minoan eruption), Mauna Loa (1872 August 23, 1877 February 24, 1903 October 8, 1919 October 2, and 1935 November 21), and Kilauea (1877 May 4, 1919 April 9, and 1924 May 30).

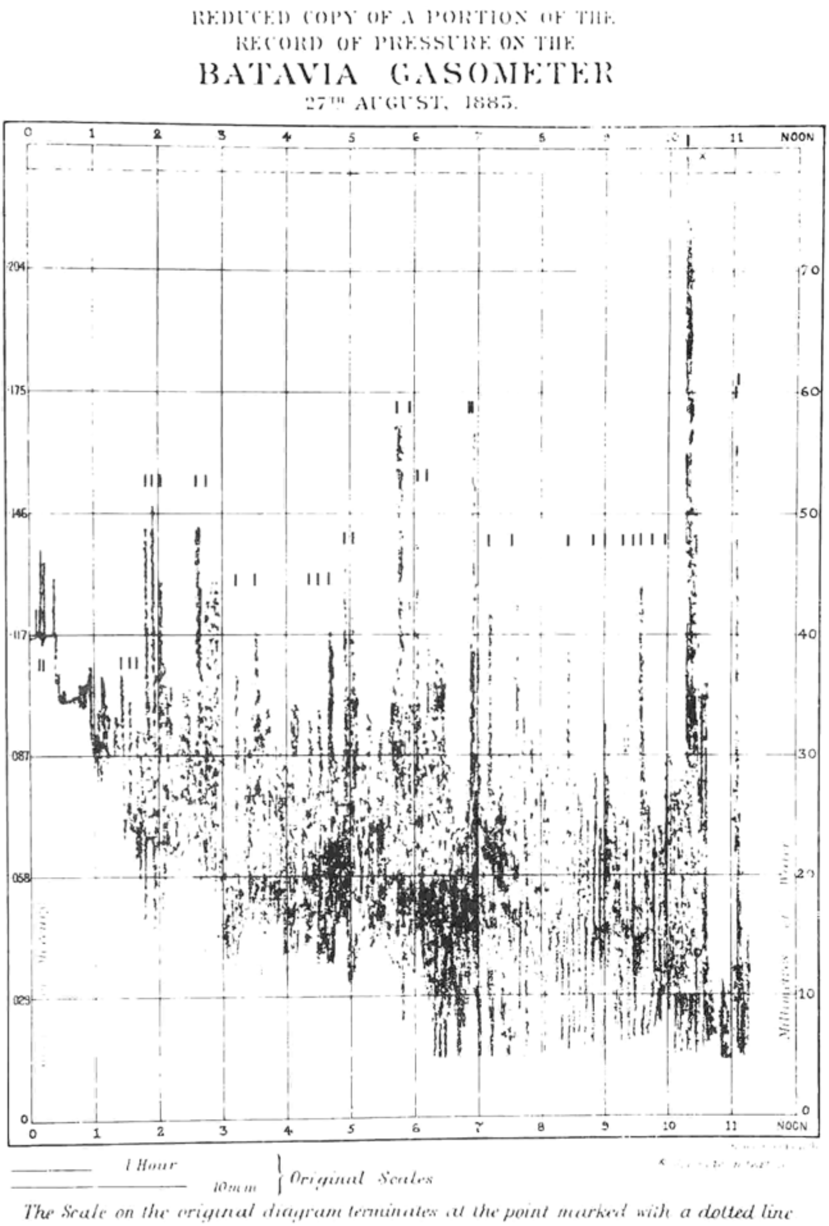

FIG. 2 - Record of pressure gauge at the Batavia gasworks, 1883 August 27, Batavia Time (approximate). Short dashes mark the arrival times of air waves (as recorded) which have been read; these are listed, converted to origin times at Krakatoa, in Table 1. Note that the largest pulse shown overloaded the record (the limit is marked by a horizontal dashed line). The right hand scale gives the indicated pressure on the gasometer in millimetres of water, and the left hand scale the equivalent pressure in inches of mercury: these figures must be doubled in order to get the absolute pressure on the gasometer. For comments on the variation of the baseline, see Fig. 3. Adapted from STRACHEY (1888), and reproduced by permission of The Royal Society, London.

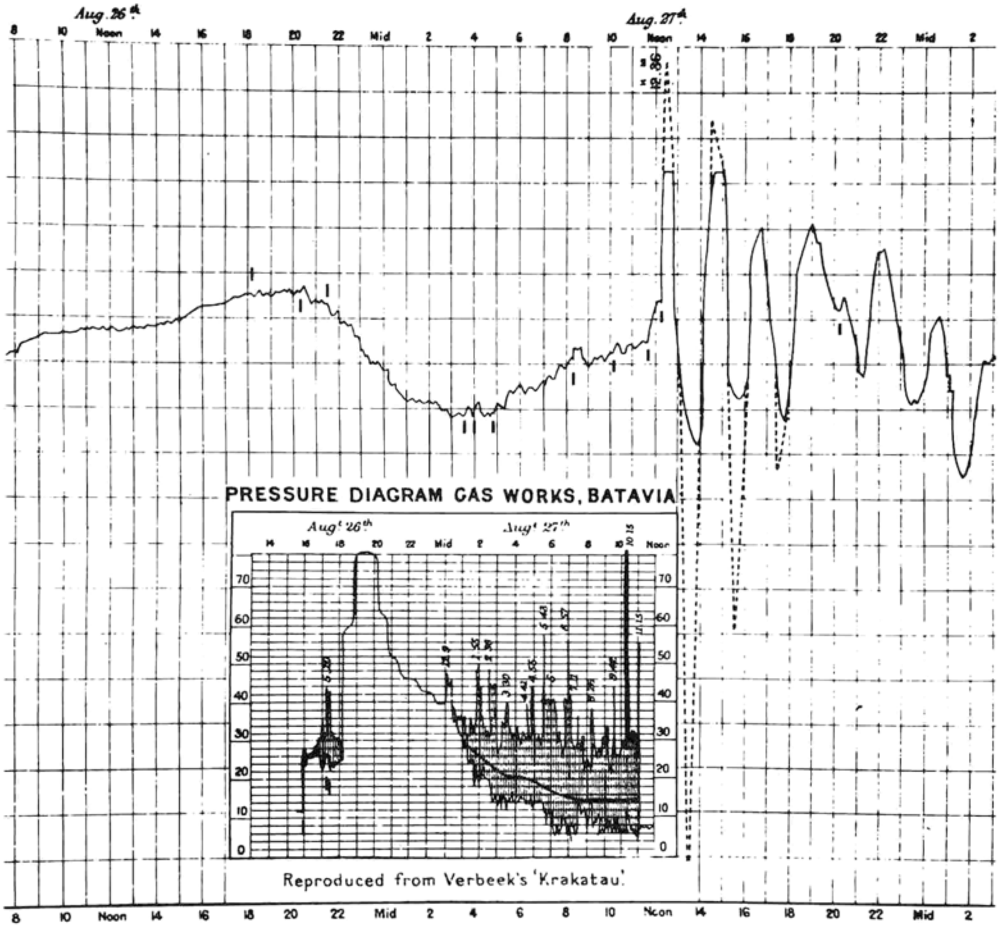

FIG. 3 - Record of tide gauge at Tandjong Priok, 1883 August 26-28, Batavia Time (approximate); with inset showing record of pressure gauge at the Batavia gasworks (the right hand half is the same diagram as in Fig. 2, on a reduced scale: the left hand half shows the pressure variation from mid-afternoon, 1883 August 26). The horizontal divisions on the tide gauge record represent one foot intervals of water level: the scales on the pressure gauge record are as in Fig. 2. Short dashes mark the arrival times read and listed in Table 1: those above the trace indicate a negative (downwards) onset, and those below a positive (upwards) onset: three onsets read on the pressure gauge record for August 26 are also marked. The thin continuous line on the pressure gauge record represents the base line pressure to which the gasometer was regularly adjusted on an hourly basis (VERBEEK, 1886, p. 367). Note that the largest increase on the tide gauge record overloaded the recorder. The sinusoidal waves that follow are due to seiches set up in the bay near Tandjong Priok (YOKOYAMA, 1981). Adapted from WHARTON (1888), and reproduced by permission of the Royal Society, London.

report in English. In addition, WATSON, who was captain of the ship «CHARLES BAL» which approached Krakatoa more closely than any other during the climax of the eruptions, published an account in 1883: METZGER (1884), VERBEEK (1884), and JUDD (1889) are also valuable early sources. YOKOYAMA (1981) has discussed the eruption and tsunamis from the geophysical point of view: STEHN (1929) and WILLIAMS (1941) remain the best sources of geological data. FURNEAUX (1964) has written a good popular account of the eruption, with a wealth of details derived from newspapers of the time. SELF *et al.* (1980) have recently made a field study of the deposits laid down by the 1883 eruption.

VERBEEK (1886) included in his report reproductions of the continuous record of pressure in the gasometer at the Batavia [3] gas works, and of the tide gauge at Tandjong Priok, 9 km. east of Batavia (Figs. 2 and 3). He read the times of 14 peak deflections on the pressure gauge record, and 18 on the tide gauge record, correlating the former with arrival times of air waves generated by explosions at Krakatoa, and the latter with arrivals of sea waves from the volcano. He assumed the times to be accurate to the minute, converted them to Krakatoa time by subtracting five minutes, and obtained origin times at Krakatoa by subtracting eight minutes for the travel time of the air wave, 151 minutes for that of the largest sea wave, and 173 minutes for the smaller sea waves. He discussed at some length the inertia of the pressure gauge resulting from its complicated design, and pointed out that the tide gauge was established in an unsatisfactory place near the mouth of a navigation canal. At both instruments, therefore, there may have been a delay in recording the arrival of the waves. He deduced an origin time at Krakatoa of 10 h 2 m, Krakatoa time, for the largest air wave, by adopting a velocity which fitted best the arrival times at Batavia and Sydney: for the largest sea wave, he obtained an origin time of 10 h 0 m: this is equivalent to 02 h 58 m G.M.T.

STRACHEY (1888) determined the origin time of the largest air wave as 09 h 58 m, Krakatoa time, by analysing the six closest observatory barographs, at distances ranging from 33° to 51° from Krakatoa: at Batavia, apart from the gasometer pressure gauge, only hourly observations of a barometer were made. He compared this with the largest arrival at the Batavia gasometer, which he read as «some time between 10 h 15 m and 10 h 20 m, local time», corresponding to an origin time at Krakatoa, in Krakatoa time, between 10 h 2 m and 10 h 7 m. He concluded that it agreed «as exactly... as could be expected from the somewhat rough character of the trace, the inertia of the recorder, and the possible error of the clock at a non-scientific establishment».

I have read onset times for all deflections on the pressure gauge of $\geqslant$ 6 mm above noise level (in mm of water, as marked on the right hand scale in Fig. 2): these, amounting to 39, are identified in Fig. 2, or, for events on August 26, on the inset in Fig. 3. On the tide gauge record, I have read arrival times of all ten waves of amplitude $\geqslant$ 2.7 cm (0.09 ft), zero to peak, up to and including the arrival of the largest wave, together with a single possible wave after this time, during the period when seiches were being recorded. These arrivals are marked in Fig. 3. Both sets of times are listed, after conversion to origin times at Krakatoa in Krakatoa time, together with a summary of observations of the air and water waves, in Table 1. Travel times of the tsunamis to the various places mentioned have been estimated from YOKOYAMA's (1981) refraction diagram (Fig. 4).

VERBEEK's (1886) estimate of 151 minutes for the travel time of the largest tsunami to Tandjong Priok has been accepted, a figure with which YOKOYAMA (1981) is in close agreement (Fig. 4), and has been deducted from the *onsets* of all the waves recorded at the tide gauge, rather than, as VERBEEK did, from the *peak* time of the largest wave only. The

[3] The old name has been deliberately used, instead of the modern Jakarta, in order to facilitate reference to the original accounts. The same applies to other names throughout this paper.

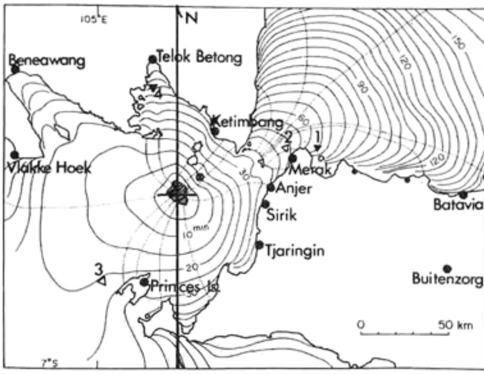

FIG. 4 - Locality map of the Sunda Straits and refraction diagram, showing travel times in minutes for tsunamis originating at Krakatoa Caldera (hatched area). The vent at which the largest explosion is inferred to have taken place is marked by the intersection of the horizontal dash on the north-south line. Filled triangles represent ships at anchor, and open triangles ships underway; 1 = «W. H. BESSE», 2 = «CHARLES BAL», 3 = «BERBICE», 4 = «G. G. LOUDON»; 1, 2 and 4 represent the ships' positions at 10 h on 27 August 1883; position 3 is at 15 h on the same day. The point marked with a small x in a circle represents the position at which the largest tsunami recorded at Tandjong Priok is thought to have been generated. Note that «Batavia» marks the port of Tandjong Priok and not the city proper. Adapted from YOKOYAMA (1981), and reproduced by permission of Elsevier Scientific Publishing Co.

uncertainties due to bathymetry and the amplitude of the waves in deep water are each thought to amount to 2 or 3% of the travel time (G. J. WEIR, personal communication, 1981), i.e. to between six and ten minutes for the two effects combined.

As for the air waves, eight minutes, as used by VERBEEK, has been adopted as a reasonable estimate for the travel time to the Batavia gasworks, which lie at a distance of between 152 km and 155½ km from the vents which are believed to have been active. With the air heavily contaminated by dust and volcanic gases, and heated by previous eruptions, conditions must have been vastly different to the propagation of sound in still air at constant temperature and humidity. However, there are insufficient data for a more accurate estimate of velocity. At Batavia, the air wave of the largest explosion was probably of very low frequency: it caused some damage, but was not heard. Closer to the volcano, at Tjaringin, Anjer, Ketimbang, Telok Betong, and on board the ships at points 1 and 2 in Fig. 4, it was both heard, and, at the last three locations, was accompanied by a violent wind blowing outwards from Krakatoa (VERBEEK (1886); WATSON (1883)).

All previous investigators have assumed, while admitting the possibility of error, that the clocks at the gasworks and tide gauge were correct. However, there is evidence to suggest otherwise. The Director of the Batavia Observatory, J. P. VAN DER STOK, noted 08 h 20 m as the time of the loudest explosion at Batavia (VERBEEK, 1886, pp. 36, 94, 342), whereas the arrival is 08 h 26 m on the pressure gauge record (Fig. 2). Others stated that the time was a few minutes later, and a newspaper, evidently quoting J. P. VAN DER STOK, gave the time as 8⅓ h, implying some uncertainty. However, it seems reasonable to accept the Observatory Director's time as accurate, particularly since he also timed to the minute the explosion heard in Batavia at 13 h 6 m on August 26, which initiated the climax of the eruptions. Unfortunately, VERBEEK (1886) did not publish the pressure gauge record covering this earlier period, nor did he list J. P. VAN DER STOK's observations in full. Provisionally, however, a correction of −6 minutes, for the combined inertia and time correction, has been applied to the arrival times, yielding the origin times given in Table 1.

A time correction to the tide gauge records has also been applied. It seems likely that the wave onset at 10 h 8 m on August 27 (Table 1, column 7) was generated by the arrival of the largest air wave at Tandjong Priok, rather than by a genuine tsunami propagating from Krakatoa. In the latter case, it should have originated at 07 h 32 m, a time which does not correlate well with other observations, the great wave which destroyed Tjaringin «at about 8 h» being more likely to have been the same as that which destroyed Anjer and originated at the volcano at about 6¾ h.

TABLE 1

*Numbered strata after Stehn (1929, plate II)	AIR WAVES						WATER WAVES										REFERENCES
	RECORDED AT BATAVIA		HEARD ELSEWHERE				RECORDED AT TANDJONG PRIOK					EXPERIENCED ELSEWHERE					
				GREATEST DISTANCE													
Layer in Geological Section* Suggested equivalent	ORIGIN TIME AT KRAKATOA (KRAKATOA TIME)	RELATIVE TRACE AMPLITUDE	ORIGIN TIME AT KRAKATOA (KRAKATOA TIME)	DISTANCE	WHERE HEARD AND REMARKS		ONSET OF WAVE L.T. UN-CORRECTED	+ OR -	PERIOD OF WAVE	MAX. AMPLI-TUDE, ZERO TO PEAK	APPARENT ORIGIN TIME AT KRAKATOA (KRAKATOA TIME)		WHERE WAVE EXPERIENCED AND REMARKS	TIME SEEN (L.T.)	MAX. AMPLI-TUDE ZERO TO PEAK	EFFECTS	(see Verbeek(1886, pp342-359 and notes) for air waves)
	h m	mm	h m (or h)	degrees			h m		mins	cm	h m	h		h	m	C = Casualties D = Damage	
	1883 AUGUST 26				* Timed by Director Batavia Observatory												
22	No record till 15 14		12 53*	3.3	Palembang (Sumatra)							13–13¼	Anjer(telegraphist's account)	13¾–14	1.5		Furneaux(1964, pp56–59)
			14½	7.7	Siak (Sumatra)												
			15	10.6	Cocos Is.												
23	15 34	16					18 30	–	27	3	17 57						
			16	12.7	Penang (Malaya)							16¾–17¼	Beneawang(Pajoeng)	17–18		(D)	Verbeek(1886,p59)
			16½	9.9	Bali							17	Anjer	17½	1–2	(D)	" " p43
24	16 54	18															
			17	26.1	Batticaloa (Ceylon)												
	17 05	17															
25			17½	29.2	Daly Waters (Australia)							17½	Ship 'MARIE', Telok Betong	18½		(D)	" " p505
			18	7.2	Pontianak (Borneo)							17½	Telok Betong: wharf flooded	18½		(D)	Metzger(1884)
												17½	Tjanti(N of Ketimbang)	18¼		(D)	Verbeek(1886, pp52–53)
	No record				NB earthquake(s) felt 1950 at First Point Java (SE of Princes Is) (Verbeek (1886) p555)							17¾–19¼	Ketimbang	18½–19		(D)	" "
												18–18¾	Merak : Chinese camp destroyed	19–19½		C	Wharton(1888, pp90,95)
							20 16	+	31	5	17 45	17¼–18½	Tjaringin	19–19		C?	(" "
	17 52						21 33	–	22	3	19 00						(Verbeek(1886,p46)
26	till 11		20	28.2	Victoria Plains (Australia)							19¼–20¼	Tjaringin : houses set alight	19–21		C?	" " "
	23 40		20⅓	21.8	Port Blair (Andaman Is)							20¼–21¼	Ketimbang : preceeded by recession of sea (Furneaux (1964) p68)	21–22		C?	" " p53, Metzger(1884)
			21		Increased activity seen Anjer	(telegraphist's account)											Furneaux(1964,p61)
			21½	6.1	Ship 'AIRLIE' near Lingga												

TABLE 1 (*con'd*)

			22	24.3	Geraldton (Australia)											
27			23	26.1	Batticaloa (Ceylon)											
	2350	7														
	2354	6														
	AUGUST 27										0½	Sirik partly submerged (no wave Anjer)	1		D	Metzger(1884)
											0½	Kankoeng, Telok Betong	1½		D	Wharton(1888,p90)
											0½	Vlakke Hoek 'high water'	1			Verbeek(1886, pp56,62)
	0107	6														
	0113	9			NB possible earthquake felt(c.0130) at First Point, Java (SE of Princes Is)											Verbeek(1886,p49)
	0121	7														
	0131	21				0333	+	28	5	0100						
											1-1½	Ketimbang	2		D	" " p53)
28-29	0136	25	1½	7.9	Sinkawang (Borneo)	(0400)	+	(36)	9	(0127)						
	0143	18														
30	0218	25	2	1.1	Sukadana (Sumatra)	0454	+	32	6	0221						
	0226	21			NB 2 earthquakes(?) felt Anjer between 2 and 3h, and possibly a shock at First Point at 3h.											Verbeek(1886, pp43, 49)
	0254	14														
	0312	18	3	5.2	Ambarawa (Cent. Java)											
	0402	12			NB possible earthquake felt at First Point at 4h.											Verbeek(1886,p49)
	0413	12														
	0420	20	4	1.1	Sukadana (Sumatra)											
31	0435	25														
	0443	22														
			5	1.2	Goenoeng Soegi (Sumatra)											
32	0528	40	0525	32.2	Alice Springs (Australia)											
										NB no wave at Tjaringin(Verbeek(1886)p409)						

TABLE 1 (*con'd*)

33–34	0534	26									5¼–6	Anjer (Pilot's account)	6–6½	>10	C	Verbeek(1886,pp43,45)
						(*possibly related to 0528 explosion)										
35–36	0543	30				0819	+	?	6	0546*	5½	Telok Betong, Kankoeng: 'BEROUW' and 'MARIE' stranded	6½		C	" " p56
37–38	0553	26	6	25.6	Hambantota (Ceylon)											
	0634	24														
39	0636	41	6½	27.9	Bogawantalawa (Ceylon)						just after 6¼	Beneawang(Pajoeng): Bimangan	just after 7*		C	(Metzger(1884) (Verbeek(1886,p59)
												* NB Water low c.1h earlier				
	0650	26									6¾	Telok Betong	7¾		?	" " p57
40	0713	28	7?	29.7	Dutch Bay (Ceylon)						6¾	Anjer(not large a short distance N)	7½	>>10	C	" " p44–45
	0807	24	0807*	7.3	Padang (Sumatra)						(7¼)	Tjaringin : 9 villages destroyed (700 dead)	8		C	" " p48
		*	Timed by Director Batavia Observatory (Verbeek(1886)pp36,94,342)								(8¼)	Merak*	9	>>10	?	Metzger(1884,p242)
	0831	14										* but Verbeek(1886, p42) refers this to the great wave at c. 10h.				
	0841	16	8½	3.3	Bandar (Sumatra)											
	0859	18	9	3.9	Benkulen (Sumatra)											
	0908	9														
41	0916	29	9½	8.2	Bengkalis (Sumatra)	1139	+	60	24	0906	(9¼)	Possibly wave seen at Vlakke Hoek (where HAMWYK reported 3 waves,- he thought, within the space* of ½h)				
	0927	12														Verbeek(1886,p62)
	0939	15										* Wrongly reported by Wharton(1886,p91) as 3 waves at intervals of c. ½h: however it is very likely that HAMWYK, who was seriously injured, had no clear memory of the time which elapsed between events.				
		*	Water wave produced by interaction of air wave at water surface													
42	0958½	>67	10	42.8	Rodriguez Is	(1008	+	35	6	0958*	10	Tjaringin	Soon after 10			Verbeek(1886,pp46–47)
						(1216	+	70	>>161	0943	10	Sangkanila (near Merak)				" " pp412,398)
											(10)	Ship 'CHARLES BAL' near Merak				(" " pp73: (Watson(1883)
											(10)	Probably Vlakke Hoek HAMWYK's account), see above				Verbeek(1886,p62)
	1044	13														
43–44	1045 ↑	41	11	28.8	Mullivavalei (Ceylon)											

TABLE 1 (*con'd*)

No record after 1050										(14)	Telok Betong, ship 'MARIE'	(15)			Verbeek(1886,pp421,506)
										(14¾)	Ship 'BERBICE' near Princes Is : (considered by Verbeek to have been a freak sea wave unconnected with Krakatoa).		6		" " pp74–75, 102
		1625	1.7	Kroe (Sumatra)	correlated by Verbeek(1886,p420) with suppression of expected minimum at 1930, in seiches caused by the great wave at c. 10h.										Verbeek(1886,p64)
					(2014	+	?	11	1741	onset of wave may represent a discrete arrival from Krakatoa, but the record is obscured by the seiches mentioned above).					

VERBEEK (1886, p. 414) thought that the 10 h 24 m wave (his peak time at Tandjong Priok) was a reflection of the wave which arrived at the tide gauge at 08 h 19 m, giving a two hour periodicity similar to that of the seiches which followed the arrival of the largest wave. This, however, seems unlikely, as the amplitude of the earlier wave was small (Table 1). Interpreted as due to the arrival of an air wave, it would yield an origin time at Krakatoa of 09 h 55 m, Krakatoa time, in close agreement with the figure of 09 h 58½ m deduced from the pressure gauge record, which is itself almost identical to STRACHEY's (1888) estimate. Accordingly, a correction of +3½ minutes has been applied to the arrivals read on the tide gauge, yielding the origin times given in Table 1 (Column 11).

A comparison of origin times in Table 1, estimated as above, shows close agreement between those calculated for the air waves and tsunamis in some cases, but a wide divergence in others. Tsunamis appear to have been generated three minutes after the explosions at 15 h 34 m on August 26, and 02 h 18 m and 05 h 43 m on August 27. This difference is negligible within the limits of error. For three of the waves, however, the origin times are between nine and 15 minutes earlier than the explosions with which they are almost certainly correlated. The largest anomaly corresponds to the largest explosion, with its accompanying tsunami apparently preceding it by 15 minutes. The most reasonable explanation for the anomaly in these three cases, the explosions at 01 h 36 m, 09 h 16 m, and 09 h 58½ m, would seem to be that the tsunamis were not generated at the focus of the eruptions but at distances from the volcano equivalent to the time anomaly observed.

For the largest explosion of all, the tsunami that travelled to Tandjong Priok would then have been produced at the point marked in Fig. 4, which, shown on an enlarged scale in Fig. 5, is found to coincide with the outer edge of Calmeyer Island, built up by volcanic ejecta during the climactic eruptions in water that was

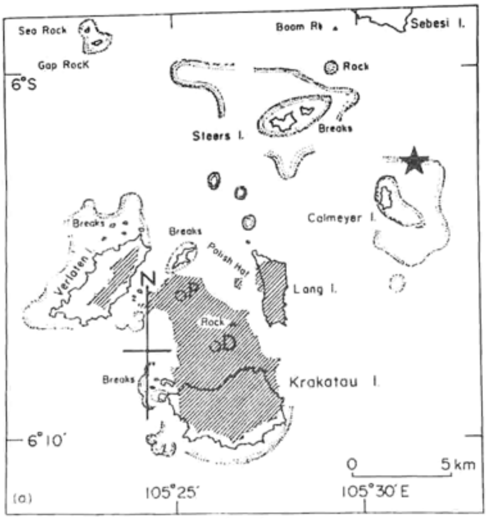

FIG. 5 - Locality map of the Krakatoa Islands. The hatched areas show the outlines of the islands before the climax of the 1883 eruptions; other outlines show the islands as they were soon after the climax. Steers and Calmeyer Islands were quickly eroded to below sea level. The vent at which the largest explosion is inferred to have taken place, marking the deepest part of the caldera, is the cross on the north-south line: the other two principal vents of the eruption are marked P (Perboewatan) and D (Danan). The heavy star corresponds to the point marked with an x in a circle on Fig. 4, and represents the position at which the largest tsunami recorded at Tandjong Priok is thought to have been generated. Adapted from YOKOYAMA (1981), and reproduced by permission of Elsevier Scientific Publishing Co.

previously 45 to 50 m deep (JUDD (1888); WHARTON (1888); YOKOYAMA (1981)). This is strong evidence that the tsunami was generated by the violent impact of a huge mass of unwelded ignimbrite, erupted at the instant of the largest explosion, and emplaced at a distance of the order of 10 to 15 km, probably at a low angle trajectory, within a minute or so of the explosion. Following YOKOYAMA (1981), I have assumed that the eruption took place at what is now the deepest part of the caldera (Fig. 5): it is likely that the ignimbrite now forming Calmeyer Bank, and Steers Bank to the northwest, impacted at some intermediate distance between Lang Island and its final resting place, rolling forward across the sea floor to its present position, and generating the tsunami as it did so.

A suggested correlation is given in Table 1 between the explosions and the products of the eruptions described by STEHN (1929, plate II) from a geological section on north west Lang Island. The correlation has been made by equating the thickest stratum of the deposit, a lens of up to 11 m thickness of black pumice with a strongly eroded upper surface, with the most powerful explosion at 09 h 58½ m, and two beds lower down in the section, which are described as containing pumice bombs, with the two previous most powerful explosions, at 05 h 28 m and 06 h 36 m. The lower metre, or less, of the deposit, resting on soil and charred vegetation, predates the August 26-27 climactic eruptions. Above this lies white pumice, passing upwards into pale pink pumice. This represents the Plinian stage of the eruption, lasting from 12 h 53 m till about 18 h on August 26, the upper pink part being due probably to eruption of pumice at a higher temperature, from deeper in the magma chamber, as the Plinian phase drew gradually to a climax. Subsidence of part of the island seems to have taken place as early as the explosion at 15 h 34 m, since this was accompanied by a wave with a negative onset at Tandjong Priok. From the beginning of the climactic period of the eruption, small waves were observed at Anjer, due probably to minor pyroclastic flows from Perboewatan (Fig. 5) impacting into the sea: activity of this kind was observed by WATSON (1883) ([4]).

The tsunami generated with an apparent origin time of 17 h 45 m was the first large one in the series, and is known to have propagated in all directions from north through east towards south east.

([4]) Note that 1 h should be subtracted from WATSON's times, in order to bring them into line with his observations of the principal eruption.

Although explosions were heard in Australia, with an origin time of about 17½ h at Krakatoa, no large explosion was recorded at the Batavia gasworks before 17 h 52 m, Krakatoa time, when the record became unreadable (Fig. 3). It is therefore likely that the corresponding explosion occurred after this time, and thus at least seven minutes after the apparent origin time of the tsunami. In line with the reasoning above, this tsunami may therefore have been generated by the emplacement of a pyroclastic flow or small ignimbrite, at a distance of the order of five to ten kilometres from the volcano, or, if unconnected with an explosion, may have been due to a large landslide. This eruption probably correlates with STEHN's pumice lapilli bed No. 25, which marks the first of a series of discrete explosions which occurred sporadically until the climax at 09 h 58½ m on August 27.

A marked recession of the sea, interpreted as due to subsidence, possibly of the northern part of the island, seems to have begun at Krakatoa at about 19 h 0 m. This was observed both on the tide gauge and at Ketimbang (Table 1). One or more powerful explosions, heard in Australia and the Andaman Islands, took place between 20 h and 20½ h, and it is likely that the largest of these blasted a new vent and deposited the distinctive cinnabar-red pumice lapilli and ash bed, which was described by STEHN (1929) as originating in a submarine eruption just west of the islet of Polish Hat (Fig. 5). A notable feature of the rocks a little higher in the section is the alternation of pumice lapilli and overlying ash beds; for example, the paired beds correlated with explosions between 01 h 36 m and 05 h 53 m in Table 1. It is likely that all these were erupted from beneath the sea.

A tsunami with apparent origin at about 0½ h seems to have had a different cause to others in the sequence. It was accompanied by no conspicuous explosion, and was, in addition, markedly directional in that it caused damage at Sirik (Fig. 4), but was not noticed at neighbouring Anjer, although it also caused damage in the opposite azimuth at Telok Betong and nearby Kankoeng ([5]). Possibly its origin is to be sought in a massive rock fall from the slowly subsiding island. VERBEEK (1886, p. 411) interpreted the local nature of waves of this kind as due to ejecta falling in different places. Several of the waves which caused damage within the Straits failed to propagate outside. Thus the two great waves, with origins at 05 h 46 m and about 6¾ h, which together destroyed Anjer, were only slightly smaller there than the wave accompanying the largest eruption at 09 h 58½ m, yet both were comparatively insignificant at Tandjong Priok. Indeed, the 6¾ h wave, though read by VERBEEK (1886, p. 413), had an amplitude below my chosen threshold, and thus does not appear in the tide gauge readings in Table 1.

Little can be said about the wave which originated at 01 h 0 m: it also failed to correlate with a significant explosion, and may equally have been due to a rockfall. The 02 h 21 m wave accompanied an explosion and was probably due to a localised pyroclastic flow, whereas the 01 h 36 m eruption, like the later 09 h 16 m and 09 h 58½ m eruptions, appears to have emplaced an ignimbrite, and generated a tsunami (destructive at Ketimbang) at a considerable distance, perhaps of the order of ten kilometres from the volcano. There is insufficient information as to whether a tsunami was generated by the final large explosion at 10 h 45 m: all survivors of the earlier waves had by then fled as far as possible from the sea, and once the largest wave had arrived at Tandjong Priok it, and the seiches that followed, effectively masked any later movements that may have taken place. This final eruption, however, is marked by a blocklayer, with overlying pumice, at the top of STEHN's (1929) section.

The collapse, rather than explosion, of the greater part of the island, inferred by VERBEEK (1886), STEHN (1929), and WILLIAMS (1941) from the scarcity of old rock in the ejecta, may have taken place gradually. VERBEEK (pp. 407, 412) assumed that it was a sudden process, and

([5]) A village a short distance from Telok Betong.

that it gave rise to the largest tsunami; but the evidence cited above makes it clear that the latter was due to the emplacement of an ignimbrite, erupted radially from a vent, formed probably at the instant of the explosion, at what is now the deepest part of the caldera. Prior to this, from the fact that mud only began to fall in large quantities soon after 10 h, it may be concluded that the principal vents were on land (VERBEEK (p. 409), although, as mentioned above, some submarine eruptions had occured, which have left recognisable deposits close to the volcano. The principal eruption at 09 h 58½ m formed a deposit up to 100 m thick (STEHN (1929, p. 24) on the southern part of Krakatoa Island and on Verlaten Island, but seems likely to have largely jumped Lang Island, eroding the surface of its basal black pumice before coming to rest in the area of the new banks.

Evidence of the timing of the final large-scale subsidence at Krakatoa comes from the observation, soon after 10 h on August 27, at position 1 in Fig. 4, that water was flowing «at about 10 knots» (18 km/h) towards the volcano (VERBEEK (1886, p. 503)). For this negative movement to have propagated the 85 km or so outwards to the entrance of the Straits indicates that it began considerably earlier at the volcano. It did not, however, reach Tandjong Priok, being overtaken, presumably, by the largest tsunami. Within broad limits, it probably originated at Krakatoa between about 02 h 45 m and 07 h 30 m on August 27. As to the cause of the largest explosion, there is no direct evidence. It was probably deep-seated and effectively emptied the magma chamber, because the eruption came to an end soon afterwards. It was clearly exceptionally violent. There was no accompanying earthquake felt on neighbouring coasts. Further geological work is required to decide the extent to which sea water flashing to steam contributed to its violence [6]. The long period nature of the sea waves suggests a large source size (several km^3: G. J. WEIR, personal communication, 1981): however, both the pressure gauge and tide gauge records of the climax of the eruption (Figs. 2 and 3) should be interpreted with caution, since both records overloaded, and it is possible that the pens became stuck for a while before commencing to fall back. VERBEEK (1886, p. 74) pointed out that the sea waves were clearly of long period since they were not noticed by ships, with the exception of the vessel close to shore at position 4 in Fig. 4, except insofar as they were seen to run up on land. WATSON (1883) reported that the wave train consisted of at least four major peaks: these may have been comparatively short period perturbations on a single long period tsunami, as the tide gauge seems to suggest. Later during the day, about 15 h, a ship under way at position 3 in Fig. 4 reported a wave 6 m high which struck the ship and stopped the chronometers: VERBEEK (pp. 74, 102), however, thought that this was merely a freak sea wave, unconnected with Krakatoa. Finally it should be noted that a moderate tsunami occurred on 10 October 1883, possibly due to a secondary steam explosion, such as continued for several months in the submarine banks formed of hot ejecta, and in the Krakatoa caldera itself (VERBEEK, pp. 81, 125).

[6] SELF *et al.* (1980), who appear to have reached similar conclusions to mine, although their evidence is not given, have studied this question.

CLASSIFICATION OF VOLCANIC TSUNAMIS: TYPE EXAMPLES

Tsunamis Due to Earthquakes Accompanying Eruptions

Apart from very large tectonic earthquakes apparently triggering volcanic eruptions, which are excluded from the discussion, there are 15 clear cases of earthquakes closely associated with eruptions in time and space, which have been accompanied by tsunamis or similar disturbances. Most seem to have been earthquakes felt only locally close to the volcano, often at the culmination of a swarm of felt shocks, and therefore probably of the type normally called «volcanic». Only four, however, have occurred since 1900, during the instrumental period of seismology, and of these only one, a destructive earthquake of magnitude about 7 at Kagoshima on 12 January 1914, nine hours after the beginning of a very violent eruption at nearby Sakurajima Volcano, was widely recorded by seismographs. A small tsunami was observed at Kagoshima an hour or an hour and a half after the earthquake (KOTO (1916, p. 69)), but it seems likely that this was a seiche effect rather than a true tsunami.

A good example of a tsunami due to an earthquake associated with an eruption is that of 1930 September 11 at Stromboli. This shock was felt on Lipari and on the Calabrian coast (RITTMANN, 1931), at a distance of more than 50 km, and was recorded at some Italian seismograph stations. It took place (RITTMANN, 1962) an instant before the climactic explosions, nearly two hours after the eruption had begun, and was accompanied by a sharp uplift of the island by about a metre, with immediate rebound to its previous position: this was interpreted by RITTMANN (1931, p. 76) as due either to a magma intrusion in a new radial fissure in the interior of the volcano, or to a submarine eruption from the flank of the cone. The tsunami reached a maximum height of 2 m, and caused some damage.

A similar, but larger tsunami accompanied the explosive destruction of a lava-dome at Severgin Volcano in the Kurile Islands on 8 January 1933: three earthquakes were felt, each with an accompanying tsunami, the largest reaching a height of about 9 m above sea level (TANAKADATE, 1934). The earthquakes were not mentioned in the International Seismological Summary, and, like that of 1930 September at Stromboli, were probably of shallow volcanic origin: a characteristic of such earthquakes is that their energy usually fails to propagate to great distances although they may be strongly felt close to source.

Possibly the largest tsunami of this type occurred on 10 January 1878 in association with an eruption of Yasour Volcano in the New Hebrides; formation of a new crater and marked uplift accompanied a strong earthquake, with an attendant tsunami 17 m high (FUCHS, 1879); a second earthquake and eruption, with a smaller tsunami, occurred a month later, but little is known in detail either about the earthquakes or the eruptions (see CARNEY *et al.*, 1979). Other tsunamis due to earthquakes accompanying eruptions are: – 1878 August 29 Okmok?, 1971 September 6 Tinakula, 1741 August 29 Osima-o-Sima (7), 1640 July 31 Komagatake, 1827 August 9 Avachinsky, 1889 September 6 Banua Wuhu, 1845 February 8 Soputan?, 46 A.D.? and 1650 September 29 Santorin, and 1693 February 13 Hekla. At Rabaul, a severe, but very local earthquake, on the day before the Vulcan eruption of 1937 May 29, was followed within about an hour by seiches of up to 2 m above sea level (FISHER, 1939).

Tsunamis Due to Submarine Explosions

Submarine eruptions in water less than about 500 m deep (MACHADO, 1964) usually disturb the water surface, and may give rise to small tsunamis. STEHN (1929) described waves accompanying the early submarine eruptions at Anak Krakatoa in January 1928: «waves arose in two different ways; firstly by the collapse of the water-cone ..., and secondly by the falling ejecta. The former waves are the higher».

NIINO (1953) and MORIMOTO *et al.* (1955) gave vivid descriptions of submarine eruptions near Bayonnaise Rocks in 1952, in which tsunamis, 2 m in height, with a wave length of 50 m, were formed by the collapse of water domes formed by the explosions. These waves did not propagate to a tide gauge about 125 km away, and are considered by MIYOSHI *et al.* (1954) to have been Cauchy-Poisson waves which were «caused by a local impulse and had not much energy to travel the long distance. The real

(7) HATORI *et al.* (1977) report that the earthquake which generated this tsunami had a magnitude of at least M = 6.9. According to I. YOKOYAMA (personal communication, 1981) a nuée ardente caused the 1640 Komagatake event.

tsunami» (which *was* recorded at the tide gauge) «is inferred to be a phenomenon of a larger scale, which the witnesses near the origin would not have found». Similar tsunamis were reported from Bayonnaise Rocks on 19 June 1915, and in March and April 1953.

Activity of this kind is common at submarine volcanoes, and indeed probably almost always accompanies substantial eruptions. Such waves, however, are nearly always of comparatively low amplitude, although they are capable of causing damage and casualties. Examples have been described by BEST (1956) from Tuluman in 1953, and by OMORI (1914) and KOTO (1916) from the Sakurajima eruptions of 1779-1781. One of the latter eruptions, on 9 September 1780, generated waves up to 6 m in height; in another, on 11 April 1781, three boats were overturned and 15 people were drowned (OMORI, 1914, pp. 66-67).

Seiches were set up in Rabaul harbour once submarine eruptions on 29 May 1937 had actually begun (FISHER, 1939), and either a tsunami or a seiche caused damage during the previous eruption of Vulcan in February 1878 (BROWN, 1908, p. 243). According to SAPPER (1927), a submarine eruption in Unimak Strait, Alaska, on 26 July 1856, was accompanied by a tsunami. A report that three people were drowned in March 1969 on the coast of north east Luzon should, it appears, be attributed to a small tsunami generated at Didicas Island, about 70 km away (SMITHSONIAN INSTN., 1969).

Tsunamis Due to Pyroclastic Flows (Ignimbrites and Nuées Ardentes)

Krakatoa, as described above, is the type example for tsunamis generated by pyroclastic flows. During the climax of the 1883 eruptions, on August 26-27, it is inferred that four tsunamis were generated by ignimbrites emplaced violently at distances of the order of 10-15 km, and at least a further four by smaller pyroclastic flows (nuées ardentes?) comparatively close to the vents.

ANDERSON *et al.* (1903) reported small tsunamis in the Grenadines, St. Lucia and Barbados after nuées ardentes were erupted on 7 May 1902 at St. Vincent, and similarly at St. Pierre, the nuée ardente from Mt. Pelée, which destroyed the city on 8 May 1902 (8), generated a tsunami by its impact into the sea (JAGGAR, 1949). This propagated a distance of about 20 km to Fort de France. NEUMANN VAN PADANG (1959) identified the cause of the very destructive tsunami, 25 m high, which accompanied an eruption of Ruang on 5 March 1871 (MEYER, 1871), as a nuée ardente due to the destruction of a lava dome. Similar tsunamis at nearby Awu volcano, on 2 March 1856 and 7 June 1892, seem also to have been produced by nuées ardentes entering the sea.

KIENLE *et al.* (1980) have interpreted the tsunami, eight or nine metres high, which caused damage at English Bay 25 minutes after a violent eruption of Augustine Volcano, as due to the impact of «a large hot pyroclastic flow... into the shoal waters surrounding Augustine Island. The sudden displacement of large volumes of sea water probably gave rise to the waves that crossed Cook Inlet to English Bay», a distance of 87 km from the volcano (9). This is a good example of how an eruption which would only have caused destruction within 10 to 20 km of the volcano, if it had been at least that far from the sea, was destructive at far greater distances through the efficient transfer of energy to a tsunami.

Tsunamis Due to Caldera Collapse or Subsidence

The disappearance by subsidence of Ritter Island on 13 March 1888 gave rise to a tsunami 12 to 15 m high on neighbour-

(8) Small tsunamis were also observed following subsequent eruptions in May, June and July (ANDERSON *et al.* 1903).

(9) This eruption occurred on 6 October 1883 at 8 h, Local Time. FUCHS (1884) reports a second wave on 8 October 1883, 6 m high, and an earthquake associated with each wave: the times, however, are confused.

ing coasts. A caldera 2½ km in diameter formed, and only a small remnant, about 100 m high, was left above sea level of the previously c. 780 m high volcano. COOKE *et al.* (1978) concluded from the available evidence that only very minor eruptions had accompanied this subsidence. In 1972 and 1974 local earthquake swarms took place at Ritter Island, accompanied by very small submarine eruptions and minor tsunamis, caused, it is thought, by a continuation of submarine caldera subsidence: COOKE *et al.* (1976).

Another example of a tsunami which was probably due to subsidence was the event described by PLINY (20, lines 36-38) on the morning of 25 August 79 A.D., during the great eruption of Vesuvius: «then we beheld the sea sucked back, and as it were repulsed by the convulsive motion of the earth; it is certain at least the shore was considerably enlarged, and now held many sea animals captive on the dry sand».

The minor tsunami during the 1815 April eruption of Tambora, in which a summit caldera was formed and the island's shoreline subsided by five to six metres, may also have been due purely to subsidence: JAGGAR (1949, p. 60) speaks of the «inrush rather than outrush of a tidal wave, which accompanied the phenomena of land subsidence». Finally, attention has already been drawn to the tsunami due to subsidence which took place at the time of the 15 h 34 m explosion at Krakatoa on 26 August 1883.

Tsunamis Due to Landslides and Avalanches of Cold Rock

Several highly destructive tsunamis have been caused by the collapse and impact into the sea of large masses of rock from volcanoes, either through the shaking of earthquakes, through fumarolic alteration, or by means of simple gravitational collapse. Landslides of this sort are comparatively common events at volcanoes, although they only rarely reach water in sufficient quantity and with sufficient velocity to generate a tsunami. They are distinguished here from avalanches of hot rock ejected during an eruption; see below.

The disaster at Simabara, Japan, and neighbouring coasts on 21 May 1792, which killed more than 15000 people, was caused by the collapse of nearly 0.5 km^3 of one of the lava domes on Unzen Volcano, Mayeyama, situated some 4 km from vents which had been active a month or two previously. The collapse was caused either by an explosion at Mayeyama, or by a strong swarm of volcanic earthquakes (KUNO, 1962). The landslide [10] generated waves which reached «a height of 20 to 30 feet»(6 to 9 m), «causing devastations... for a distance of 77 km» (OMORI, 1907). A similar disaster at Paluweh Island, Indonesia, on 4 August 1928 was caused by a large landslide which took place at about the same time as the beginning of a very violent eruption. Three waves, 5 to 10 m high, killed at least 160 people (NEUMANN VAN PADANG, 1930).

A massive landslide at Ili Werung Volcano seems to have been the cause of the tsunami, up to 9 m high, which caused destruction and more than 500 deaths at Iomblen Island on 18 July 1979 (PARARAS-CARAYANNIS, 1979). Finally, as mentioned above, the waves which originated at Krakatoa between 0 h and 1 h on 27 August 1883 are likely to have been caused by large landslides.

Landslides and rockfalls generating tsunamis constitute a serious element of risk at steep sided volcanoes close to the sea or lakes, especially when the volcano's structure is cut by faults or fumarolically altered, and where there has been a history of subsidence or signs of incipient caldera formation. A good example of a massive landslide, which, however, evidently took place sufficiently gradually for no tsunami to be formed, is shown in Fig. 6.

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(10) CLARK (1977) believes this to have been a lahar.

Tsunamis Due to Base Surges, with Accompanying Shock Waves

Large waves, two to five metres in height, are characteristically formed on Lake Taal, Philippines, during violent phreatomagmatic eruptions with base surges from vents on Volcano Island. MOORE *et al.* (1966) considered that they were generated by the shock waves of explosions. PRATT (1911) ascribed them to «the explosive rush of gases down the volcano slopes», and MASÓ (1911), describing the violent winds which accompanied the 1911 January 30 eruption, wrote «To the descent of these winds (upon the lake) are probably due, at least in part, the tremendous waves which formed...». Such waves have formed in at least five major eruptions at Taal, those of 1716 September 24, 1749 August 11, 1754 November 28, 1911 January 30, and 1965 September 30. All have caused casualties. MASÓ attributes waves formed on 15 November 1754 to a violent earthquake. The initial impact of such waves on the shores of Lake Taal may fairly be called tsunamis: subsequent waves, reflected from the opposite shores of the lake, are better described as seiches.

Tsunamis Due to Avalanches of Hot Rock

Small tsunamis are occasionally generated at Stromboli by gravitational sliding of masses of hot ejecta down steep slopes into the sea [11]. This only takes place following large eruptions, when a great thickness of hot ejecta accumulates on the upper slopes. Tsunamis of this sort are distinct from those due to the impact of nuées ardentes, which have also occurred at Stromboli (CAPALDI *et al.*, 1978). As mentioned above, the very large tsunami formed on 11 September 1930 was due to an earthquake, with accompanying displacement of the island.

Tsunamis Due to Lahars Entering the Sea

The largest, most destructive tsunami supposed due to a lahar, triggered by a

(11) For example, on 20 August 1944.

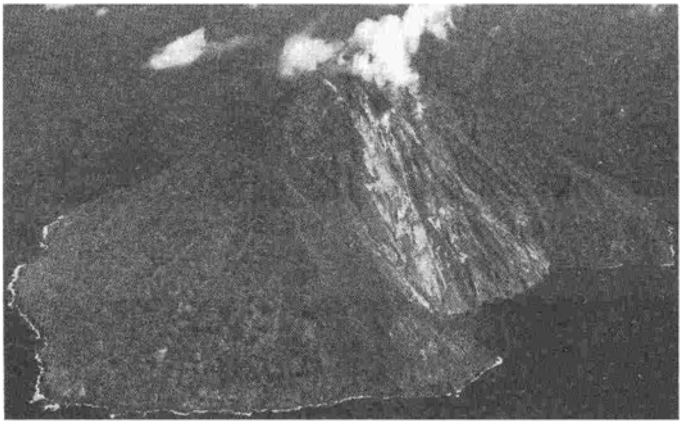

FIG. 6 - Tinakula Volcano, Santa Cruz Islands, Solomons. The large bay, of area about 1.6 km^2, and steep cliffs on the right formed, at about the same time as a substantial eruption, as a result of a huge submarine landslide in April or May, 1966, which destroyed the north west side of the cone: apparently no tsunamis were formed, and it is assumed that the collapse occurred gradually. A sudden collapse on this scale, however, would certainly generate a tsunami. Reproduced by permission of the Ministry of Natural Resources, Solomon Islands.

very large earthquake on 2 April 1868 in Hawaii (PARARAS-CARAYANNIS *et al.*, 1977; OMORI, 1907) was in fact due directly to earthquake faulting offshore. The «lahar», a destructive landslide, did not reach the sea (J. BUCHANAN-BANKS, R. W. DECKER, J. P. LOCKWOOD, personal communications, 1981).

A small tsunami formed when a gigantic lahar swept down the Rivière Blanche, Martinique, on 5 May 1902, three days before the violent eruption of Mt. Pelée: a yacht capsized offshore, but no other damage was caused (JAGGAR, 1949). At Vesuvius, it is likely that the event described by PLINY, a sudden ebbing or shallowing of the sea due to a «landslip», was caused by a lahar reaching the sea (16, lines 48-49). This took place on the day before the recession of the sea mentioned above.

Tsunamis Due to Air Waves of Explosions

The 1955-1956 eruption of Bezymianny, Kamchatka, culminated with a tremendous explosion on 30 March 1956, and the eruption of unwelded ignimbrites. A small tsunami, widely recorded on tide gauges in the Pacific, with a maximum amplitude of 30 cm at Attu Island (IIDA *et al.*, 1967), was probably generated by the air waves of the explosion (P. HÉDERVÁRI, personal communication, 1980) in the manner first suggested by EWING *et al.*, 1955, and elaborated by HARKRIDER *et al.* (1967). GORSHKOV (1959) described how the blast resulted in seiches which were recorded on a tide gauge at the mouth of the Kamchatka River, at a distance of about 118 km. These small standing waves had a maximum amplitude, zero to peak, of 5-6 cm, and a period of about 18½ minutes. By comparison, the wave formed at Tandjong Priok, 164 km from Krakatoa, by the air wave accompanying the largest eruption at 09 h 58½ m on 27 August 1883 had an amplitude of 6 cm, zero to peak, and a period of 35 minutes (Table 1).

Sea waves were generated during the violent eruption of St. Vincent, by nuées ardentes entering the sea. Because they were not observed at St. Vincent itself, but only on neighbouring islands, ANDERSON *et al.* (1903) considered that the shock wave of the explosion might have contributed to their formation.

Tsunamis Due to Lava Avalanching into Water

Towards the end of 1906, and during 1907, when large volumes of lava from Matavanu Volcano, Samoa, had reached the sea, many small tsunamis formed as a result of avalanching of large blocks of cooled lava, carried forward by underlying molten lava. These tsunamis caused little or no damage and travelled only for short distances (SAPPER, 1927).

CONCLUSIONS: RISK OF FUTURE VOLCANIC TSUNAMIS

Ten mechanisms for the formation of tsunamis at volcanoes have been reviewed. Of these, the most violent and destructive are due to the impact of ignimbrites and nuées ardentes into the sea, or to large landslides of the kind illustrated in Fig. 6. Ignimbrites are fortunately rare events, and besides, like the comparatively common nuées ardentes, occur only at the climax of very large eruptions, when people are already alerted to the fact that a major eruption is in progress. Landslides, on the other hand, can occur suddenly without warning; and, even when triggered by volcanic earthquakes or explosions, such activity need not be conspicuous. All too often, they are set in motion by heavy rainfall, or simply by the culmination of a long-continued process of fumarolic alteration. It is of vital importance, for accurate assessment of volcanic risk, to assess slope stability, particularly where steep-sided volcanoes stand close to the sea or to lakes, and particularly where fumarolic alteration is already far advanced.

Large tsunamis, commonly destructive, are also often generated by earthquakes directly associated with volcanic eruptions, frequently due, as in the case described by RITTMANN (1931), to inherently unpredictable processes of magmatic intrusion. Other large and destructive tsunamis are due to phreatomagmatic eruptions and accompanying shock waves: for these the risk continues to be highest at Taal, but is not limited to this volcano.

Tsunamis which have been of lesser importance to date, but which could well prove very destructive in future, are those due to lahars, avalanching of hot ejecta, and submarine explosions. Tsunamis due to air waves and lava flows are probably always minor, but those due to caldera subsidence present a problem, similar to that posed by large landslips. More research is required to determine the speed with which caldera formation proceeds. Normally, it may progress sufficiently slowly for tsunamis not to be formed, but Ritter Island in 1888 provides a dramatic exception.

The larger tsunamis are generally due to destructive processes such as subsidence, disruption of lava domes and emplacement of pyroclastic flows, rather than to constructional processes such as cone-building by submarine eruptions, or the extrusion of lava flows. They are, therefore, in turn, often related to caldera formation, which is an essentially destructive process, frequently extending over a long series of eruptions. Therefore, eruptions at calderas carry a heightened risk of tsunami generation, and areas in which calderas are concentrated close to the sea, such as the Aleutian and Kurile Islands, the Izu-Mariana arc, Indonesia and New Guinea, have a greater risk of volcanic tsunamis than areas such as the Tonga-Kermadec arc, where calderas are few (Fig. 1).

Because the factors that determine tsunami generation can be quantified to a great extent, it ought to be possible to characterise the risk of future tsunamis at individual volcanoes numerically, both for the maximum tsunami likely, and for smaller tsunamis in accordance with eruptions and related events of a given size. A quantity called *Tsunami Capacity* is proposed, defining the volume of water which is considered likely to be involved at the source of a tsunami. This will contain terms for every mechanism of tsunami generation which is considered appropriate for a given volcano. In any large eruption, as demonstrated for Krakatoa, tsunamis are likely to be formed through a variety of causes. Only the one that is expected to generate the largest tsunami need be considered for the definition of *Tsunami Capacity*. Inherent also in the definition of this quantity is the distance of a volcano from water, together with other unchanging (static) factors such as the volume of potential landslides.

Another quantity, *Tsunami Likelihood*, would take account of changing (dynamic) factors. For the term concerned with tsunami generation by ignimbrites, for example, it would increase greatly once a substantial eruption of acid magma had commenced. So long as the volcano remained inactive, this quantity would depend on the periodicity of violent, potentially tsunamigenic eruptions. *Tsunami Capacity* × *Tsunami Likelihood* would together define *Tsunami Potential*, which could be expressed as the risk of a tsunami of given size within a given period, and would therefore define the time-related source function of a tsunami.

By adopting this source function, and calculating from bathymetry and shoreline profiles how a given amplitude would propagate to a particular place, it would be possible to define *Tsunami Intensity*, in a manner analogous to that proposed by SOLOVIEV (1970) for tsunamis due to earthquakes. *Tsunami Intensity* combined with data on population distribution, and the whereabouts and vulnerability of assets such as buildings and agricultural land, would define *Tsunami Risk*, which could be used as a basis for contingency planning. A start has been made on defining these quantities for selected volcanoes, beginning with White Island in New Zealand. This will be reported in a future paper.

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REFERENCES

ANDERSON, T. and FLETT, J. S., 1903, *Report on the Eruptions of the Soufrière, in St. Vincent, in 1902, and on a Visit to Montagne Pelée, in Martinique. Part 1.* Phil. Trans. Roy. Soc., Ser. A, *200*, p. 353-553, plates.

BERNINGHAUSEN, W. H., 1966, *Tsunamis and Seismic Seiches Reported from Regions Adjacent to the Indian Ocean.* Bull. Seism. Soc. Amer., *56* (*1*), p. 69-74.

———, 1968, *Tsunamis and Seismic Seiches Reported from the Western North and South Atlantic and the Coastal Waters of Northwestern Europe.* Naval Oceanographic Office, Washington D.C., Report, IR 68-85, 48 pp.

———, 1969, *Tsunamis and Seismic Seiches of Southeast Asia.* Bull. Seism. Soc. Amer., *59* (*1*), p. 289-297.

BEST, J. G., 1956, *Investigations of Recent Volcanic Activity in the Territory of New Guinea.* Proc. 8th Pac. Sci. Congr. (1953), Manila, *2*, p. 180-204.

BROWN, G., 1908, *George Brown, D. D., Pioneer Missionary and Explorer. An Autobiography.* Hodder and Stoughton, London, 536 pp.

CAPALDI, G., GUERRA, I., LO BASCIO, A., LUONGO, G., PECE, R., RAPOLLA, A., SCARPA, R., DEL PEZZO, E., MARTINI, M., GHIARA, M. R., LIRER, L., MUNNO, R. and LA VOLPE, L., 1978, *Stromboli and Its 1975 Eruption.* Bull. Volcanol., *41-3*, p. 259-285.

CARNEY, J. N. and MACFARLANE, A., 1979, *Geology of Tanna, Aneityum, Futuna and Aniwa.* Geological Survey, New Hebrides, Regional Report, 71 pp.

CLARK, R. H., 1977, *Volcanic Disasters in the Japanese Main Islands and New Zealand.* J. Fac. Sci., Hokkaido Univ., Ser. IV, *17-3*, p. 541-552.

COOKE, R. J. S., MCKEE, C. O., DENT, V. F. and WALLACE, D. A., 1976, *Striking Sequence of Volcanic Eruptions in the Bismarck Volcanic Arc, Papua New Guinea, in 1972-75.* In: *Volcanism in Australasia.* Editor, R. W. Johnson. Elsevier, Amsterdam, p. 149-172.

——— and JOHNSON, R. W., 1978, *Volcanoes and Volcanology in Papua New Guinea.* Geological Survey of Papua New Guinea, Report, *78/2*, 40 pp.

COX, D. C., PARARAS-CARAYANNIS, G. and CALEBAUGH, J. P., 1976, *Catalog of Tsunamis in Alaska, Revised 1976.* World Data Center A for Solid Earth Geophysics, Report, *SE-1*, 43 pp.

EWING, M. and PRESS, F., 1955, *Tide-gage Disturbances from the Great Eruption of Krakatoa.* Trans. Amer. Geophys. Un., *36-1*, p. 53-60.

FISHER, N. H., 1939, *Geology and Vulcanology of Blanche Bay and the Surrounding Area, New Britain.* Territory of New Guinea, Geological Bulletin, *1*, 68 pp.

FUCHS, C. W. C., 1879, *Die Vulkanischen Ereignisse des Jahres 1878.* Tschermaks Mineralog. und Petrogr. Mittheil., *2*, p. 97-125.

———, 1884, *Die Vulkanischen Ereignisse des Jahres 1883.* Tschermaks Mineralog. und Petrogr. Mittheil., *6*, p. 185-231.

FURNEAUX, R., 1964, *Krakatoa.* Prentice-Hall, Inc., Englewood Cliffs, N. J., 224 pp.

GORSHKOV, G. S., 1959, *Gigantic Eruption of the Volcano Bezymianny.* Bull. Volcanol., ser. 2, *20*, p. 77-109, plates.

HARKRIDER, D. and PRESS, F., 1967, *The Krakatoa Air-sea Waves: an Example of Pulse Propagation in Coupled Systems.* Geophys. J. R. Astr. Soc., *13*, p. 149-159.

HATORI, T. and KATAYAMA, M., 1977, *Tsunami Behavior and Source Areas of Historical Tsunamis in the Japan Sea.* Bull. Earthq. Res. Inst., Tokyo Univ., *52*, p. 49-70, in Japanese with English abstract.

HECK, N. H., 1947, *List of Seismic Sea Waves.* Bull. Seism. Soc. Amer., *37-4*, p. 269-286.

HÉDERVÁRI, P., *Tsunamis Related to Volcanic Activity.* In: *« Volcanoes and Volcanology »*, encyclopaedia. R. FAIRBRIDGE and J. GREEN, Eds., Dowden, Hutchinson and Ross, Inc., California, Series of Earth Sciences, *16*, (in press).

IIDA, K., COX, D. C. and PARARAS-CARAYANNIS, G., 1967, *Preliminary Catalog of Tsunamis Occurring in the Pacific Ocean.* Hawaii Inst. Geophys., Data Report 5, HIG-67-10.

IMAMURA, A., 1937, *Theoretical and Applied Seismology.* Maruzen and Co., Tokyo, 358 pp.

JAGGAR, T. A., 1949, *Steam Blast Volcanic Eruptions: a Study of Mount Pelée in Martinique as Type Volcano.* Hawaiian Volcano Observatory, 4th Special Report, 137 pp.

JUDD, J. W., 1888, *On the Volcanic Phenomena of the Eruption, and on the Nature and Distribution of the Ejected Materials.* Part 1, p. 1-46. In *« The Eruption of Krakatoa, and Subsequent Phenomena »*, Report of the Krakatoa Committee of the Royal Society, G. J. SYMONS, Ed., Harrison and Sons (Printers), Trübner and Co., (Publishers), London, 494 pp.

———, 1889, *The Earlier Eruptions of Krakatoa.* Nature, London, *40*, p. 365-366.

KIENLE, J. and SWANSON, S. E., 1980, *Volcanic Hazards from Future Eruptions of Augustine Volcano, Alaska.* Geophys. Inst. Univ. of Alaska, Fairbanks, Report UAG R-275, 122 pp., appendix, maps.

KOTO, B., 1916, *The Great Eruption of Sakura-jima in 1914.* J. Coll. Sci., Imp. Univ. Tokyo, *38-3*, p. 1-237, plates.

KUNO, H., 1962, *Catalogue of the Active Volcanoes and Solfatara Fields of Japan, Taiwan and Marianas.* Int. Volcanol. Assoc., Rome, *Catalogue of the Active Volcanoes of the World, 11*, 332 pp.

LATTER, J. H., 1980, *Volcanoes in New Zealand.* N. Z. Dept. Sci. Indust. Res., Alpha Extension Inf. Leaflet, *6*, 6 pp.

MACHADO, F., 1964, *Sobre a ocorrência de erupções submarinas.* Bol. Soc. Geol. Portugal, *15*, p. 211-218.

MASÓ, M. S., 1911, *The Eruption of Taal Volcano, January 30, 1911.* Philippines Dept. Interior, Weather Bureau, 45 pp.

METZGER, E., 1884, *Gleanings from the Reports Concerning the Eruption of Krakatoa.* Nature, London, *29*, p. 240-244.

MEYER, A. B., 1871, *Volcano near Celebes.* Nature, London, *4*, p. 286.

MIYOSHI, H. and AKIBA, Y., 1954, *The Tsunamis Caused by the Myôjin Explosions.* J. Oceanogr. Soc. Japan, *10-2*, p. 49-59.

MOORE, J. G., NAKAMURA, K. and ALCARAZ, A., 1966, *The 1965 Eruption of Taal Volcano.* Science, *151*, p. 955-960.

MORIMOTO, R. and OSSAKA, J., 1955, *The 1952-1953 Submarine Eruption of the Myôjin Reef Near the Bayonnaise Rocks, Japan (I).* Bull. Earthq. Res. Inst., Tokyo Univ., *33-2*, p. 221-250, plates.

NAKANO, M., UNOKI, S., HANZAWA, M., MARUMO, R. and FUKUOKA, J., 1954, *Oceanographic Features of a Submarine Eruption That Destroyed the Kaiyo-Maru No. 5.* J. Marine Res., *13-1*, p. 48-66.

NEUMANN VAN PADANG, M., 1930, *Het Vulkaaneiland Paloeweh en de uitbarsting van den Rokatinda in 1928.* Dienst van den Mijnbouw in Nederlandsch-Indie, Vulkanol. en Seism. Med., *11*, p. 1-92, plates.

———, 1959, *Changes in the Top of Mount Ruang (Indonesia).* Geol. en Mijnbouw (NW. Ser.), *21-4*, p. 113-118.

NIINO, H., 1953, *Observations on the Eruption of Myôjin-sho: a) Phenomena of the Eruption*, p. 9-15. In: Report on the Submarine Eruption of Myôjin-sho, J. Tokyo Univ. Fisheries, *40-2*, (special number), 43 pp., plates: and *Part II. The Second Survey of Myôjin-sho*, p. 33-43. In: *ibid.*

OMORI, F., 1907, *Note on the Eruptions of the Unsendaké in the 4th Year of Kansei (1792).* Bull. Imp. Earthq. Inv. Comm., *1*, p. 142-144.

———, 1914, *The Sakura-jima Eruptions and Earthquakes. II.* Bull. Imp. Earthq. Inv. Comm., *8*, 35-179.

PARARAS-CARAYANNIS, G., 1979, *Tsunamis in Indonesia.* Tsunami Newsletter, *12-2*, p. 32.

——— and CALEBAUGH, J. P., 1977, *Catalog of Tsunamis in Hawaii, Revised 1977.* World Data Center A for Solid Earth Geophysics, Report, *SE-4*, 78 pp.

PLINY, C., *Letters*, Book *6*, *16* and *20*, with English transl. by W. Melmoth, William Heinemann Ltd, London, 1961.

PRATT, W. E., 1911, *The Eruption of Taal Volcano, January 30, 1911.* Philippine J. Sci., *6-2*, p. 63-86, plates.

RITTMANN, A., 1931, *Der Ausbruch des Stromboli am 11. September 1930.* Zeitschr. f. Vulk., *14-1*, p. 47-77.

———, 1962, *Volcanoes and Their Activity.* Transl. from 2[d] German Edition by E. A. Vincent, Interscience Publishers (John Wiley and Sons), New York, 305 pp.

RUSSELL, F. A. R. and ARCHIBALD, E. D., 1888, *On the Unusual Optical Phenomena of the Atmosphere, 1883-1886, Including Twilight Effects, Coronal Appearances, Sky Haze, Coloured Suns, Moons, etc.* Part 4, p. 151-463. In: *The eruption of Krakatoa, and Subsequent Phenomena*, Report of the Krakatoa Committee of the Royal Society, G. J. SYMONS Ed., Harrison and Sons (Printers), Trübner and Co. (Publishers), London, 494 pp.

SAPPER, K., 1927, *Vulkankunde*. J. Engelhorns Nachf. Stuttgart, 424 pp.
SELF, S. and RAMPINO, M. R., 1980, *Krakatau, West of Java: a Reappraisal of the 1883 Eruption*. EOS, *61-46*, p. 1141.
SMITHSONIAN INSTITUTION, 1969, *Didicas Volcano*. Event Information Report, *1*, 1 April 1969.
SOLOVIEV, S. L., 1970, *Recurrence of Tsunamis in the Pacific*. p. 149-163. In: *Tsunamis in the Pacific Ocean*. W. M. ADAMS Ed., East West Center Press, Honolulu, Hawaii.
STEHN, C. E., 1929, *The Geology and Volcanism of the Krakatau Group. Part 1*, p. 1-55, plates. In: 4th Pac. Sci. Congr., Batavia, Guidebook, 118 pp.
STRACHEY, R., 1888, *On the Air Waves and Sounds Caused by the Eruption of Krakatoa in August 1883*. Part 2, p. 57-88, plates. In: *The Eruption of Krakatoa, and Subsequent Phenomena*, Report of the Krakatoa Committee of the Royal Society, G. J. SYMONS, Ed., Harrison and Sons (Printers), Trübner and Co (Publishers), London, 494 pp.
TANAKADATE, H., 1934, *Volcanic Activity in Japan During the Period Between June 1931 and June 1934*. Japan J. Astr. Geophys., *12*, p. 89-108.
VERBEEK, R. D. M., 1884, *The Krakatoa Eruption*. Nature, London, *30*, p. 10-15, and p. 335-336.
———, 1886, *Krakatau*. Govt. Press, Batavia, 567 pp. (French edition).
WATSON, W. J., 1883, *The Java Disaster*. Nature, London, *29*, p. 140-141.
WHARTON, W. J. L., 1888, *On the Seismic Sea Waves Caused by the Eruption of Krakatoa, August 26th and 27th, 1883*. Part. 3, p. 89-150, plates. In: *The Eruption of Krakatoa, and Subsequent Phenomena*, Report of the Krakatoa Committee of the Royal Society, G. J. SYMONS Ed., Harrison and Sons (Printers), Trübner and Co. (Publishers), London, 494 pp.
WILLIAMS, H., 1941, *Calderas and Their Origin*. Univ. Calif. Publ. *25-6*, p. 239-346.
YOKOYAMA, I., 1981, *A Geophysical Interpretation of the 1883 Krakatau Eruption*. J. Volc. Geoth. Res., *9*, p. 359-378.

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