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The hazards of eruptions through lakes and seawater

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Abstract

Eruptions through crater lakes or shallow seawater, referred to here as subaqueous eruptions, present hazards from hydromagmatic explosions, such as base surges, lahars, and tsunamis, which may not exist at volcanoes on dry land. We have systematically compiled information from eruptions through surface water in order to understand the circumstances under which these hazards occur and what disastrous effects they have caused in the past. Subaqueous eruptions represent only 8% of all recorded eruptions but have produced about 20% of all fatalities associated with volcanic activity in historical time. Excluding eruptions that have resulted in about a hundred deaths or less, lahars have killed people in the largest number of historical subaqueous eruptions (8), followed by pyroclastic flows (excluding base surges; 5) tsunamis (4), and base surges (2). Subaqueous eruptions have produced lahars primarily on high (>1000 m), steep-sided volcanoes containing small (<1 km diameter) crater lakes. Tsunamis and other water waves have caused death or destroyed man-made structures only at submarine volcanoes and at Lake Taal in the Philippines. In spite of evidence that magma–water mixing makes eruptions more explosive, such explosions and their associated base surges have caused fewer deaths, and have been implicated in fewer eruptions involving large numbers of fatalities than lahars and tsunamis. The latter hazards are more deadly because they travel much farther from a volcano and inundate coastal areas and stream valleys that tend to be densely settled. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Of the 7900 eruptions that have been recorded on Earth since 8000 BC, about 610 have erupted through lakes or seawater (Simkin and Siebert, 1994). Mixing of magma with water during such eruptions has frequently produced explosions, base surges, lahars, floods, or tsunamis, which may not have been produced in the absence of external water, but the presence of surface water alone does not guarantee the occurrence of these phenomena. Eruptions through lake water at Soufriere of St. Vincent in 1979, for example, produced violent hydromagmatic explosions with base surges (Shepherd and Sigurdsson, 1982); but dome-building eruptions in 1971–1972 at the same volcano did not (Aspinall et al., 1973). Lahars, tsunamis, and floods have also been devastating during some eruptions through water but non-existent during others.

The variability in the occurrence and extent of these phenomena poses a problem for scientists and civic officials attempting to anticipate the hazards of future eruptions at such volcanoes. If eruptions through the crater lake at Ruapehu, New Zealand, for example, produced base surges and lahars in 1975, might similar hazards occur from eruptions at Crater Lake,

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Oregon (USA)? The differences in lake diameter (500 m for Ruapehu versus 5 km for Crater Lake) and depth (60–180 m versus 600 m) should strongly influence the types of hazards produced, as should the magma supply rate, magma type, gas content of magma, and numerous other factors. The effect of these factors on eruptive hazards is not intuitively obvious, nor has it been extensively studied.

The purpose of this paper is to address some basic questions regarding hazards of eruptions through surface water. For example: (1) Are eruptions through surface water generally more hazardous than eruptions of other types? (2) What specific hazards are most responsible for death and injury during eruptions through surface water? (3) Under what kinds of conditions have those hazards generally been produced? We have addressed these and other questions by a systematic compilation of published reports of eruptions through surface water. In doing so, we recognize the many limitations of published accounts: observations may be biased by the prejudices of observers; phenomena may have occurred but not have been recognized; water depth, lake size, magma-flux rate and other important features may not have been recorded, etc. In spite of these limitations, this compilation reveals some interesting insights.

2. Structure of the database

Several compilations have been made of volcanic eruptions on a worldwide scale (e.g. Sapper, 1927; the *Catalogue of Active Volcanoes of the World*, published between 1951 and 1999; Simkin and Siebert, 1994). Our database draws from original sources to the greatest extent that time and our own resources have thus far allowed; where original accounts have not yet been obtained we refer to these previous compilations. With one well-documented exception (Santorini, 1650 BC), we restrict our discussion to eruptions that occurred during recorded history or took place recently enough before written records that they were still remembered by oral accounts (e.g. Long Island, Papua New Guinea, 1660; Blong, 1982). Of 530 recorded, historical subaqueous eruptions, a significant fraction have never been described in detail in any publication. Others took place so early in recorded history (e.g. twelfth century Japan) that their descriptions are not especially useful and are difficult for us to obtain. We have obtained verbal descriptions of about 200 eruptions and continue to seek accounts of the remainder. Our compilation tabulates the eruptive characteristics shown in Table 1.

Table 1
A comparison of data tabulated in Simkin and Siebert (1994) ("S&S") and in our compilation

	S&S	Here
Volcano name	x	x
Country	x	x
Identification number[a]	x	x
Latitude	x	x
Longitude	x	x
Year(s) of the eruption	x	x
Physical setting[b]	x	x
Eruption type[c]	x	x
Lake diameter[d]		x
Lake elevation[d]		x
Water depth		x
Erupted volume	x	x
Magma type		x
Size[e]	x	x
Date(s)	x	x
Hazardous phenomena	x	x
Fatalities and damage	x	x
Verbal description[f]		x

[a] Number from the Catalog of the Active Volcanoes of the World (CAVW number).
[b] Categories tabulated by us include; submarine, new island, crater lake, caldera-forming, flank, ground-water, sub-glacial, submarine caldera-forming, submarine flank island, submarine vent, subaerial lavas entering water. Simkin and Siebert include only four of these categories (submarine, new island, subglacial, crater lake).
[c] Categories tabulated by us include; non-juvenile (i.e. phreatic), submarine, dome growth, lava flows, Surtseyan, Vulcanian, Strombolian, phreatomagmatic, plinian, phreatoplinian, caldera-forming. Simkin and Siebert's categories include explosive, pyroclastic flows, phreatic, fumarolic, lava flows, lava lake, dome, and spine.
[d] For eruptions through lakes.
[e] As measured by the volcanic explosivity index of Newhall and Self (1982).
[f] Observations excerpted or summarized from original sources.

3. Findings

Volcanoes included in this compilation are listed in Table 2 along with the number of eruptions recorded

Table 2
Summary of volcanoes included in this database

1. Lake eruptions

Volcano name	Country or region	year(s)	number of eruptions
Nyamuragira	Zaire	1920	1
Tarawera	New Zealand	1886	1
Ruapehu	New Zealand	1889-1996	50
Niuafo'ou	Tonga-SW	1814-1985	3
Long Island	Papua New Guinea	1660-1993	8
Rabaul	Papua New Guinea	1940	1
Kerinci	Sumatra	1937	1
Kaba	Sumatra	1833	1
Dempo	Sumatra	1905-1939	6
Anak Krakatau	Indonesia	1931-1959	16
Dieng	Java	1986	1
Kelut	Java	1586-1990	21
Tenger Caldera	Java	1842	1
Raung	Java	1593-1838	6
Ijen	Java	1796-1993	6
Rinjani	Lesser Sunda Is	1944-1994	2
Lokon-Empung	Sulawesi-Indonesia	1969-1986	2
Mahawu	Sulawesi-Indonesia	1977	1
Tongkoko	Sulawesi-Indonesia	1801	1
Taal	Luzon-Philippines	1716-1965	9
Pinatubo	Luzon-Philippines	1992	1
Kirishima	Kyushu-Japan	1716-1959	3
Aso	Kyushu-Japan	864-1992	47
Haku-San	Honshu-Japan	1579	1
Kusatsu-Shirane	Honshu-Japan	1882	6
Zao	Honshu-Japan	1831-1940	9
Towada	Honshu-Japan	1050	1
Tao-Rusyr	Kurile Islands	1952	1
Ebeko	Kurile Islands	1967-1987	2
Zavaritzki	Kurile Islands	1957	1
Gorely	Kamchatka	1984	1
Karymsky	Kamchatka	1996	1
Ukinrek	Alaska (USA)	1977	1
Mount St. Helens	USA	1980	1
Kilauea	Hawaiian Islands	1790	1
Santa Maria	Guatemala	1903	1
San Salvador	El Salvador	1917	1
Ilopango	El Salvador	1879	1
Rincon de la Vieja	Costa Rica	1983-1995	10
Poas	Costa Rica	1828-1992	37
Fernandina	Galapagos	1968	1
Planchon-Peteroa	Chile	1991	1
Copahue	Chile	1992	1
Pelee	W Indies	1902	1
Soufrière St. Vincent	W Indies	1812-1979	6
Grimsvötn	Iceland-NE	1983-1996	2
Askja	Iceland-NE	1875-1926	2

2. Submarine eruptions

Volcano name	Country or region	year(s)	number of eruptions
Campi Flegrei	Italy	1538	1
Vulcano	Italy	215 BC-126 BC	3
Campi Flegrei mar Sicilia	Italy	1632-1911	7
Pantelleria	Italy	1891	1
Santorini	Greece	1650 BC to 1939	10
Raoul Island	Kermadec	1720-1964	4
Monowai Seamt	Kermadec	1877-1928	6
Falcon Island	Tonga-SW Pacific	1877-1928	6
Metis Shoal	Tonga-SW	1851-1995	10
Home Reef	Tonga-SW	1904-1984	2
unnamed	Am. Samoa	1973	1
Ofu-Olosega	Samoa-SW Pacific	1866	1

2. Submarine Eruptions (cont'd)

Volcano name	Country or region	year(s)	number of eruptions
Tuluman	Papua New Guinea	1883-1953	2
Ritter Island	Papua New Guinea	1888-1974	3
Rabaul	Papua New Guinea	1878-1937	2
Kavachi	Solomon Islands	1939-1991	26
Kuwae	Vanuatu	1452-1980	16
Traitor's Head	Vanuatu	1881	1
Matthew Island	SW Pacific	1949	1
unnamed	SW Pacific	1963	1
Krakatau	Indonesia	1883	1
Anak Krakatau	Indonesia	1927-1945	7
Iliwerung	Lesser Sunda Is	1973-1993	3
Banda Api	Banda Sea	1988	1
Banua Wuhu	Sangihe Is-Indonesia	1835	6
Didicas	Luzon Islands-N of	1856	2
Cendres, Ile des	SE Asia	1923	1
unnamed	E of Taiwan	1853	1
unnamed	N of Taiwan	1867	1
Zengyu	N of Taiwan	1916	1
Kikai	Ryukyu Islands	1934	1
Sakurajima	Kyushu-Japan	708-1782	6
Izu-tobu	Honshu-Japan	1989	1
Nii-jima	Izu Islands-Japan	886	1
Miyake-jima	Izu Islands-Japan	1712	1
Hachijo-jima	Izu Islands-Japan	1606	1
Bayonnaise Rocks	Izu Islands-Japan	1896-1970	12
Smith Rock	Izu Islands-Japan	1672-1975	6
Nishino Shima	Japan	1973	1
Kaitoku Seamount	Japan	1543-1984	2
Kita-iwo-jima	Japan	1780-1930	3
Shin-iwo-jima	Japan	1904-1996	8
Minami-hiyoshi	Japan	1975	1
Fukujin	Japan	1951-1977	4
Farallon de Pajaros	Mariana Is-C Pacific	1934	2
Supply Reef	Mariana Is-C Pacific	1969-1989	2
Ruby	Mariana Is-C Pacific	1966	1
Alaid	Kurile Islands	1933	1
Bogoslov	Aleutian Islands	1796-1926	5
Kilauea	Hawaiian Islands	1884-1924	2
Mauna Loa	Hawaiian Islands	1877	1
Rocard	Society Islands-C Pac	1966-1972	3
Moua Pihaa	Society Islands-C Pac	1969-1970	2
MacDonald	Austral Islands-C Pac	1928	12
Barcena	Mexico	1952	1
Socorro	Mexico	1993	1
Kick-'em-Jenny	W Indies	1939-1990	10
Reykjaneshryggur	Iceland-SW	1179-1970	14
Reykjanes	Iceland-SW	1226	1
Vestmannaeyjar	Iceland-S	1896-1973	3
Kolbeinsey Ridge	Iceland-N of	1372	1
Jan Mayen	North Atlantic	1350	1
Fayal	Azores	1957	1
Pico	Azores	1963	1
San Jorge	Azores	1757-1907	3
Terceira	Azores	1867	1
Don Joao de Castro Bank	Azores	1720	1
Sete Cidades	Azores	1638-1880	5
Monaco Bank	Azores	1907-1911	2
Deception Island	Antarctica	1967-1970	2
Protector Shoal	Antarctica	1962	1

at each of them. Of the 530 historical subaqueous eruptions that have been documented, roughly 52% took place through lakes and 48% through shallow seawater (Simkin and Siebert, 1994 and later reports cited in this paper). Both eruption types are concentrated in certain geographic regions (Figs. 1 and 2): crater-lake eruptions have occurred predominantly in Japan (66), Indonesia (64), New Zealand (53) and Central America (51; Fig. 2); submarine eruptions have been most commonly reported in the Japan–Marianas region (60), in Melanesia and Australia (51), and the New Zealand–Fiji region (27). Additional submarine eruptions have no doubt occurred but not been reported.

The pattern of volcanism between submarine and crater-lake settings differs significantly. For crater-lake eruptions, the historical record (275 eruptions) is dominated by numerous events at relatively few volcanoes: 50 at Ruapehu, 47 at Aso, 37 at Poas, and 21 at Kelut, for example (Fig. 2). The number of historically active submarine vents (72) is larger than the number of crater-lake bearing volcanoes (44), but no more than 26 eruptions have been recorded at any given vent (Fig. 2). The latter fact probably reflects the incomplete observational record for submarine eruptions.

Though less numerous than active submarine vents, crater-lake bearing active volcanoes present a greater hazard because of their general proximity to population centers. Of the 13 volcanoes that have generated at least five historical crater-lake eruptions, eight have caused fatalities (Fig. 2). Fatal submarine eruptions have been mostly at volcanoes located near inhabited coastlines (e.g. Krakatau, Rabaul).

4. Maximum water depth for eruptions that breach the surface

Volcanic eruptions in lakes or oceans are not especially hazardous as long as they do not breach the water surface. Although it is intuitive that eruptions through shallow water are more likely than deep eruptions to breach the surface, the maximum water depth through which material can be ejected into the atmosphere is not. In our compilation, we find that specific water depths are rarely given and commonly change during eruptions; however, the majority of eruptions that breach the surface take place in shallow settings, through water depths of the order of meters to tens of meters. At least four volcanoes have produced subaqueous eruptions from depths of >100 m that have breached the surface (Table 3). These eruptions were all small but explosive. At Long Island they

Table 3
Eruptions that have breached the surface from water depths that can be confidently estimated at >100 m

Volcano	Year	Depth (m)	VEI	References and comments
Kick'em Jenny, West Indies	1939 1974 1988	> 230? 180 160	1 1 1	Bathymetric surveys showed a shallowing of the vent from 230 m in 1962 to 160 m in 1989. Eruptions are thought to be vulcanian, similar to those of nearby Soufriere of St. Vincent, and produce dark, ash-laden fountains tens or hundreds of meters above the sea surface (Robson and Tomblin, 1966, p. 51; Devine and Sigurdsson, 1995).
Ruapehu, New Zealand	Late 1970s, 1980s	< 180	1–2	Successive eruptions deepened the lake from 60 m in 1970 to 180 m in 1982 (Christenson and Wood, 1993).
Ritter Island, Papua New Guinea	1972 1974	~ 400 ~ 400	1 1	Depth estimated from vent location described in Cooke (1981) and bathymetry published in Johnson (1987). Explosions produced updoming of the sea surface, loud "bomb-like" noises, plumes to about 400–500 m elevation and tsunamis of about 0.2–0.5 m height (Cooke, 1981).
Long Island, Papua New Guinea	1993	300–350	1	Depth estimated at vent location using maps of lake bathymetry (Ball and Johnson, 1976). During this eruption, "The larger explosions broke the lake surface and ejected sprays of water and ash a few tens of meters above the lake surface" (Smithsonian Institution, 1993).

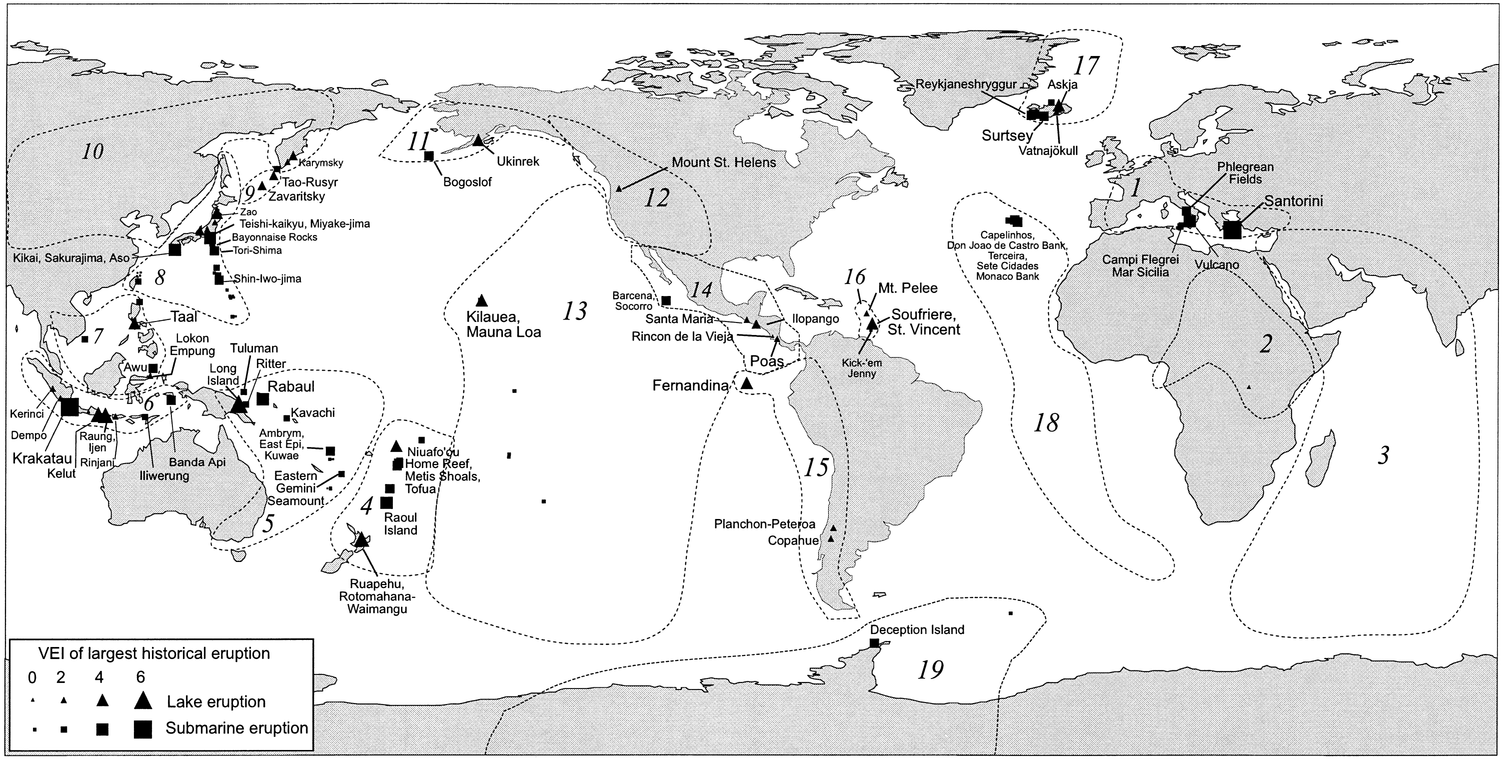

Fig. 1. Locations of volcanoes that have produce eruptions through crater lakes (triangles) or through submarine vents (squares) during recorded history. The numbered regions outlined by dashed lines are those delineated by the *Catalogue of Active Volcanoes of the World* (referred to in this paper as the CAVW region). The size of each symbol is proportional to the size of the largest eruption as measured by the Volcanic Explosivity Index (VEI) of Newhall and Self (1982).

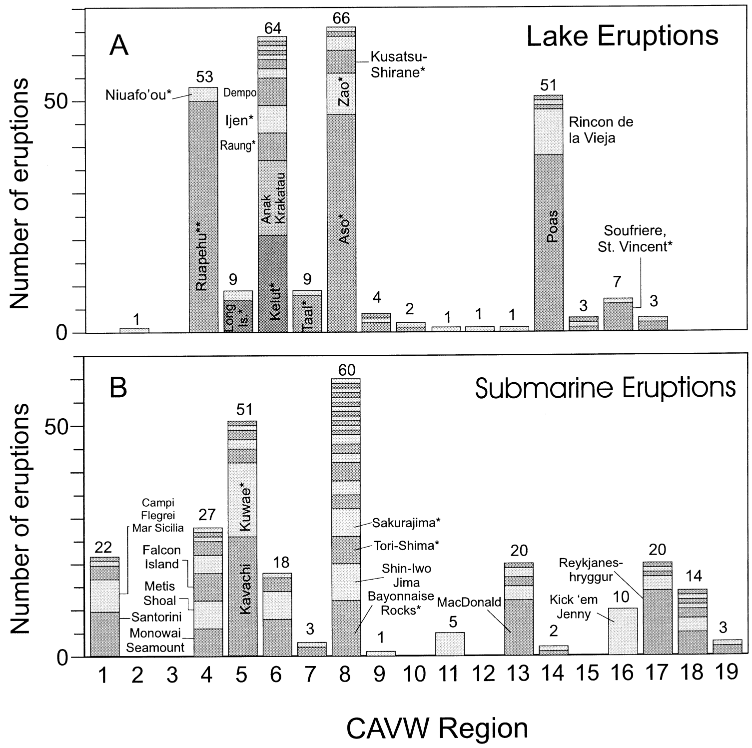

Fig. 2. Number of historical eruptions in each CAVW region through (A) crater lakes, and (B) submarine vents. Locations of regions are shown in Fig. 1. Each dark or light section of each bar represents a separate volcano. Volcanoes with the largest number of eruptions are labeled. Those with asterisks have produced fatal eruptions during historic time. Ruapehu, marked by a double asterisk, produced a fatal lahar in 1953 that was caused by a lake breakout but was not associated with an eruption (Cole and Nairn, 1975).

produced visible shock waves; at Ruapehu in 1982 they produced water jets up to 70 m in height (McClelland et al., 1989, p. 123). At Ritter Island they produced "loud bomb-like noises", plumes to 400–500 m height, and small tsunamis (Cooke, 1981). The violence of these outbursts suggest that eruptions could breach the surface from significantly greater water depth, perhaps several hundred meters or more depending on specific circumstances.

Except for Ritter Volcano (whose eruption mechanism was not interpreted), the explosivity of each of these eruptions has been attributed at least in part to magmatic gas. At Kick'em Jenny Volcano, events in 1943, 1953, 1965 and 1966 involved non-explosive dome growth and did not breach the surface whereas those in 1939, 1974 and 1988 were explosive and did breach the surface (Robson and Tomblin, 1966; Devine and Sigurdsson, 1995). Devine and Sigurdsson (1995) attribute the difference in eruptive styles to magmatic gas content. Eruptions at Ruapehu since the 1970s also involved explosions which breached the surface and non-explosive lava effusion onto the lake floor which did not (e.g. McClelland et al., 1989, pp. 123–135). Explosive lake eruptions at Ruapehu were termed "hydrothermal", implying some involvement of hydrothermal steam, though some were clearly preceded several seconds earlier by seismic signals from the magmatic system, interpreted as escape of magmatic gas (McClelland et al., 1989, p. 129). The eruption at Long Island in 1993 was described as a "magmatic gas discharge" (Smithsonian Institution, 1993). We presume that magmatic gas aids in driving material to the surface by increasing both momentum and buoyancy.

5. Deaths attributed to eruptions through surface water

The hazardous phenomena observed during eruptions through water are phreatomagmatic explosions, base surges, tephra fall (including block fall), lahars, tsunamis, lightning during convection of wet ash columns (e.g. Surtsey; Thorarinsson, 1967; Taal, 1965, J.G. Moore, pers. commun., 1997), and torrential rainstorms with associated flooding and landslides (e.g. Taal, 1965; Moore et al., 1966). In this section we investigate the cost of these hazards in human lives.

According to Blong (1984, table 3.2), volcanic eruptions have been responsible for some 240,000 deaths since the year 1600. Of these, about 49,000, or ~20%, have been associated with eruptions through surface water. Only about 8% of all recorded eruptions have taken place through lakes or seawater (Simkin and Siebert, 1994), implying that fatalities are significantly higher, on average, from eruptions through surface water than from other types of eruptions.

Table 4 lists all subaqueous eruptions for which we have obtained reports of fatalities. For many of these events it is impossible to obtain exact or even approximate death tolls, though the primary hazards that caused death (lahar, tsunami, etc.) can usually be inferred from the geologic record or from oral history. In general the fatality list is dominated by a small number of high-consequence events; particularly Krakatau in 1883 (36,140 deaths); and Kelut in 1586 (~10,000) and 1919 (~5,110). Deaths during those eruptions resulted primarily from tsunamis (Krakatau) and lahars (Kelut). Lahars have caused death in the largest number of subaqueous eruptions (20 eruptions total; Fig. 3), followed by tephra fall (including ballistics; 10 eruptions); tsunamis (7); pyroclastic flows (6); and base surges (2). By comparison, for eruptions of all kinds, tephra fall is the cause of death in the largest number of historical eruptions (106), followed by lahars (84) and pyroclastic flows (72; Simkin and Siebert, 1994; pp. 165–175). Subaqueous eruptions are distinguished from the general population of eruptions primarily by the greater frequency of lahars and water waves in causing death.

Other differences between sub-lacustrine and submarine eruption hazards are apparent when considering only eruptions that have produced hundreds of casualties or more. Among all historical eruptions (both subaerial and subaqueous), pyroclastic flows (excluding those that are obviously base surges) have been the agent of death in 32 eruptions, lahars in 25, tephra fall (including explosions and ballistics) in 11, and water waves in 9 (Fig. 3). Among subaqueous eruptions, lahars are by far the most common deadly agents (involved in 8 deadly

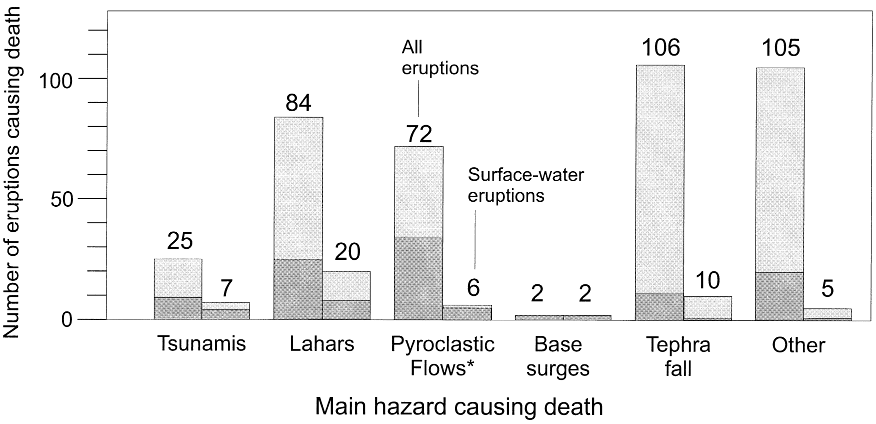

Fig. 3. Number of eruptions that have caused death from tsunamis, lahars, pyroclastic flows, base surges, tephra fall, and other causes. Data taken from Table 4. Left bars in each category give the number of eruptions of all kinds (both subaqueous eruptions and subaerial eruptions) that have caused death. Right bars give number of subaqueous eruptions causing death. Darkly shaded parts of each bar indicate the number of eruptions that have produced 100 deaths or more (or “many” deaths).

Table 4
A listing of eruptions through surface water that are known to have caused fatalities. Volcanoes in italics produced eruptions through submarine vents. Non-italicized volcanoes produced crater-lake eruptions

Volcano name	Year	VEI	Deaths	W	L	P	S	T	O	Comment, references
Santorini, Greece	A.D. 1650	4?	?	x			?	?	x	In the A.D. 1650 eruption, Fytikas et al. (1990) attribute deaths to tsunami, gas, and “a shower of black dust” during an island-forming submarine eruption. The caldera-forming eruption of 1650 B.C. was much larger than that of A.D. 1650, and man-made structures destroyed in the 1650 B.C. eruption have been extensively exhumed. To date, however, no bodies have been excavated from archaeological ruins at Akrotiri (Doumas, 1990), suggesting that most residents of that city had time to flee.
Rotomahana-Waimangu, New Zealand	1886	5	150					**X**		According to Cole and Nairn (1975), “The Rotomahana Mud ejecta [from Lake Rotomahana] fell over a wide area, burying the villages of Te Ariki, Moura and Te Wairoa and killing over 150 persons.”
Long Island, Papua New Guinea	~ 1660?	6	> 2000?	**X**		**X**	?	x	**X**	This eruption is thought to have deepened a pre-existing caldera that presently contains a large lake (Pain et al., 1981). Legends on Long Island report deaths from pyroclastic flows and tsunami. On the mainland, legends attribute widespread deaths to roof collapse and starvation (Blong, 1982). Published accounts do not discuss the degree of magma/water interaction in this eruption, though Pain et al. (1981) describe cross bedding and accretionary lapilli in the deposit that could perhaps be attributed to magma/water mixing.
Rabaul, Papua New Guinea	1937	4	507			**X**	?		x	Medical officers give 440 killed by “suffocation or burial”, with a few dying later of exposure or shock in 1937 (Johnson and Threlfall, 1985).
Aoba (Ambae), Vanuatu	~ 1870	2?	?		x					Lahars, caused either by explosive ejection of lake water or perhaps by secondary mobilization of debris on the volcano’s flank (Smithsonian Institution, 1995a).
Ambrym, Vanuatu	1913	3	21					x		“Violent phreatic eruptions”, produced when basaltic fissures propagated offshore, destroyed a mission hospital at Dip Point (McCall et al., 1970).
Kuwae, Vanuatu	~ 1452	6	many?			**X**				Pyroclastic-flow deposits containing human remains were apparently emplaced after the vent had dried out (Robin et al., 1994).
Krakatau, Indonesia	416 1883	6? 6	“many” 36,420	**X** **X**		? **X**				During the ~A.D. 416 eruption, ancient Javanese chronicles note that the surrounding land “Was inundated by the sea. The inhabitants of the northern part of the Sunda country to the mountain Raja Basa were drowned and swept away with all their property” (Judd, 1889; Reprinted in Simkin and Fiske (1983, p. 307)). The great majority of deaths in the 1883 eruption are attributed to tsunami, with a few thousand caused by pyroclastic flows that did not involve significant magma-water mixing (Self and Rampino, 1980).

Table 4 (*continued*)

Volcano name	Year	VEI	Deaths	W	L	P	S	T	O	Comment, references
Kaba, Indonesia	1833	2	126		**X**					Deaths caused by lahars when an eruption ejected water out of the crater lake at Kaba Vogelsang (Sapper, 1927, p. 326; Neuman Van Padang, 1951, p. 39).
Kelut, Indonesia	1311	3	?		x	?				Kelut has produced repeated eruptions through its crater lake that begin by expelling the water in the lake, then proceeding to Vulcanian-type explosions with the formation of pyroclastic flows (Zen and Hadikusumo, 1965). Lahars from water expulsion inundate the Plains of Blitar, destroying villages and killing inhabitants. Tunnels have repeatedly been excavated to reduce the volume of the lake (Zen and Hadikusumo, 1965). These dates and indications of deaths come from Zen and Hadikusumo (1965), Hadikusumo (1967); and Smithsonian Institution (1990).
	1334	3	?		x	?				
	1376	3	?		x	?				
	1586	5?	~10,000		**X**	?				
	1716	2	?		x	?				
	1826	4?	?		x	?				
	1848	3	21		x	?				
	1864	2	54		x	?				
	1901	3	"many"		**X**					
	1919	4	5110		**X**					
	1951	3	7					x		
	1966	4	215		**X**					
	1990	4	36		x	x		x		
Raung, Indonesia	1593	5?	?							Brouwer (1913); Neuman Van Padang (1951, p. 154); Simkin and Siebert (1994).
	1597	3	?							
	1638	4?	> 1000		**X**					
	1730	3?	"many"		**X**			?	?	
	1817	4?	?							
Ijen, Indonesia	1817	2	"many"		**X**					Explosive eruptions through the crater lake have ejected water to produce lahars (Neuman Van Padang, 1951; 1960).
Rinjani, Indonesia	1994	1–2	30		x					Deaths caused by a cold lahar following the end of the eruption (Smithsonian Institution, 1994b)
Iliwerung, Indonesia	1973	2	2	x						Simkin and Siebert (1994) mention possible disappearance of people during a tsunami caused by the submarine eruption in 1983, McClelland et al. (1989, p. 222) mention no casualties.
	1983	1	?	?						
Taal, Philippines	1911	4	1335			?	**X**	x		The 1911 eruption took place from a water-filled crater on Volcano Island (within Lake Taal). Most who died in 1911 were on Volcano Island. Pratt (1911) and Worcester (1912) provide descriptions and photos that can be now interpreted as base surges. The 1965 eruption took place through a sublacustrine vent on the margin of Volcano Island. Most deaths resulted from boats being capsized during seiches (Moore et al. (1966). Other deaths may have resulted from lightning strikes and torrential rain (J.G. Moore, written commun., 1997).
	1965	4	190	**X**					x	
Sakura-jima, Japan	1779	4	153	x		?	?	x	x	Deaths attributed to tsunami, lava, and burial of villages by tephra (Simkin and Siebert, 1994, p. 171)

Table 4 (*continued*)

Volcano name	Year	VEI	Deaths	W	L	P	S	T	O	Comment, references
Aso, Japan	1485	2	1					x		Deaths in 1872 were sulfur miners in the crater; those in 1979 were tourists. All were killed by explosions (Kuno, 1962; McClelland et al., 1989; Simkin and Siebert, 1994).
	1872	3	4					x		
	1979	4	3					x		
Kusatsu-Shirane, Japan	1932	3	2		x					Two killed during phreatic eruption when water from Yu-gama crater mixed with ash and sulfur, producing a lahar (Kuno, 1962, p. 128).
Zao, Japan	1867	2	3		x					Overflow of crater lake killed hot spring bathers during this eruption (Simkin and Siebert, 1994; Kuno, 1961).
Tori-Shima, Japan	1902	3	125							No mention of cause of death. All islanders killed during this submarine eruption near Komochi-yama (Kuno, 1961; p. 255.)
Kilauea, Hawaii	1790	4	80–300				**X**			Hawaiian warriors were killed by base surges during this eruption (Ellis, 1827; Hitchcock, 1909; Swanson and Christiansen, 1973). The explosiveness of this eruption had been attributed to influx of groundwater into the conduit by Decker and Christiansen (1984) and McPhie et al. (1990). However more recent evidence (Mastin, 1997) suggests that the eruption took place through a caldera lake.
Soufriere, St. Vincent	1902	4	1680			**X**				Explosive eruption through a crater lake. Most deaths resulted from pyroclastic flows during dry phases of the eruption (Anderson and Flett, 1903).
										Totals
				7	20	6	2	10	5	all hazards that produced fatalities
				4	8	5	2	1	1	hazards producing >100 fatalities (or "many")
										Comparison with all eruptions, through water or on dry land
				25	84	72	2[a]	106	105	All eruptions producing fatalities (from Simkin and Siebert, 1994)
				9	25	32	2	11	20	Hazards resulting in >100 fatalities (or "many") (from Simkin and Siebert, 1994)

[a] Base surges are included with pyroclastic flows in Simkin and Siebert's compilation. The two given here, listed as pyroclastic flows in Simkin and Siebert, are Taal, 1911, and Kilauea, 1790.

W = tsunami or seiche; L = lahar; P = pyroclastic flows; S = base surges; T = tephra fall, including ballistic ejection during explosions; O = other hazards (gas, famine, lightning, flooding, etc.). "x" that is *underlined* denotes pyroclastic flows that were apparently produced during dry phases of the eruption. Bold, capitalized **X** indicates a phenomenon that probably killed hundreds of people.

eruptions), followed by pyroclastic flows (5), tsunamis (4), and base surges (2). The pyroclastic flows cannot be definitively attributed to magma–water mixing (many in this table actually took place during dry phases of eruptions, as judged by deposit characteristics). But tsunamis, lahars, and base surges resulted directly from water interaction. In the next sections we investigate the types of subaqueous eruptions that have produced these phenomena.

6. Lahars

Lahars, or slurries of debris, rock, and water, are generated by mixing and mobilization of water and loose debris during eruptions, mass movements, or flooding events. In a review of lahar hazards, Neall (1976) points out that lahars produced by eruptions through crater lakes or by failure of debris damming crater lakes are potentially the most destructive type of lahar because of the high volume of water suddenly released. Volcanic lahars may be produced either during eruptions by incorporation of ejecta with water (primary lahars), or following eruptions by mobilization of erupted debris during storms or natural dam failures (secondary lahars). We consider only primary lahars in this paper.

Volcanoes that have produced primary lahars during historical eruptions through surface water (Table 5, Fig. 4) are almost exclusively stratocones >1000 m high, containing lakes <1 km in diameter. Typical eruptions from these volcanoes are explosive and eject water from the lake *en masse* onto the flanks of the volcano. The flanks of these volcanoes are steep and contain loose debris, providing favorable conditions for lahar generation.

Crater lakes of the size generally involved in lahar-generating eruptions (hundreds of meters in diameter and depth) tend to have water volumes on the order of 10^6–10^7 m^3. At Kelut Volcano, the lake volume was 1.8 million cubic meters following the artificial lowering of the lake in 1923 but increased to $\sim$22.5 million after an eruption in 1951 deepened the lake (Zen and Hadikusumo, 1965). Zen and Hadikusumo (1965) note that typical eruptions at Kelut empty the lake in a matter of seconds, after which the activity proceeds with vulcanian explosions. Even if the time period required to empty the lake were minutes, the discharge into the largest drainages would be 10^4–10^5 m^3/s-comparable to the highest discharge produced by dam failure in historical time (6.5×10^4 m^3/s at Teton Dam, Wyoming; Costa, 1988).

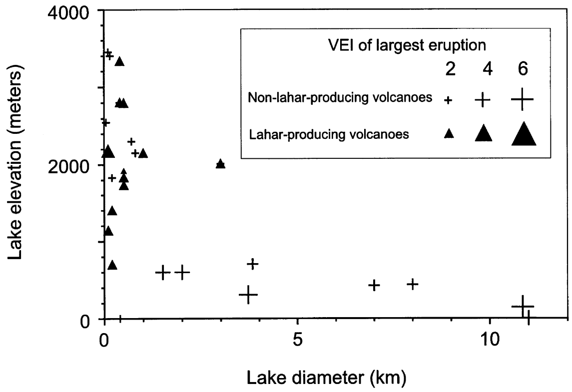

Fig. 4. Elevation and approximate diameter of volcanic lakes through which eruptions have occurred in historic time. Triangles represent volcanoes that have produced primary lahars by water ejection; crosses represent volcanoes that have not produced such lahars. The size of the symbol indicates the size of the largest eruption (for non-lahar producing volcanoes) or the size of the largest lahar-producing eruption (for lahar-producing volcanoes). Data on elevation and lake diameter taken from published maps.

Lahars from crater-lake eruptions are frequently still hazardous some tens of kilometers downstream from the summit craters. Lahar deposits from the deadly 1919 eruption of Kelut extend nearly 40 km west of the summit (Neuman Van Padang, 1951, p. 135); those from a relatively small (VEI = 1) eruption at Rincon de la Vieja in 1991 were two meters thick at 15 km distance (Smithsonian Institution, 1991a). Lahars on September 28, 1995 at Ruapehu eroded stream banks 35 km downstream from the crater (Smithsonian Institution, 1995b), near the same bridge crossing at Tangiwai that was destroyed in a 1953 crater-lake dam failure, derailing a train and killing 151 passengers (Simkin and Siebert, 1994, p. 166). The size of lahars and the distance they travel are only weakly related to eruption size, as other factors (lake volume, height and capacity of outlet, gradient of outflow channel) are at least as important in determining these characteristics.

Table 5
Subaqueous eruptions that have produced lahars by water ejection

Volcano	Year	VEI	References, comments
Santorini	1650 BC	6	Heiken et al. (1983)
Ruapehu, New Zealand	Many	2–3	Cole and Nairn (1975); McClelland et al. (1989); Nairn et al. (1979); Christenson and Wood (1993); Smithsonian Institution (1995b).
Aoba, Vanuatu	~ 1870	2	Warden (1970); Smithsonian Institution (1995a). It is not known whether this lahar was produced by water ejection or later rainfall.
Kaba, Indonesia	1833	2	Sapper (1927, p. 326); Neuman Van Padang (1951, p. 39); Simkin and Siebert (1994, p. 167)
Kelut, Indonesia	Many	3–5	Neuman Van Padang (1951, pp. 132–138); Zen and Hadikusumo (1965); Simkin and Siebert (1994, p. 71)
Ijen, Indonesia	1796 1817 1936	2 2 2	Neuman Van Padang (1951, pp. 156–159; 1960); Simkin and Siebert (1994)
Raung, Indonesia	Several	2–4	Brouwer (1913); Neuman Van Padang (1951); Simkin and Siebert (1994). The lake existed until 1838.
Lokon-Empung, Indonesia	1986	2	Smithsonian Institution (1986)
Kirishima, Japan	1822	2–3	Kuno (1962, p. 36)
Aso, Japan	1377 1434 1533	1–3	Simkin and Siebert (1994, p. 88), Kuno (1962).
Kusatsu-Shirane, Japan	1932	3	Kuno (1962)
Zao, Japan	1694 1809 1821 1867 1895 1939	2 2 2 2 2 1	Kuno (1962, p. 158); Simkin and Siebert (1994, pp. 93–94)
Rincon de la Vieja, Costa Rica	1983 1984 1991 1995	1 1 1 1	Smithsonian Institution (1987; 1991a,b; 1995c); McClelland et al. (1989, p. 504)
Copahue, Chile	1992	2	Smithsonian Institution (1992)
Mt. Pelee, Martinique	1902	2?	Lahars were produced from a crater lake in early May, 1902, prior to the cataclysmic eruption of May 8 (Lacroix, 1904). Some were likely caused by water ejection during phreatic eruptions. The largest, which killed 23 people on May 5, may have been cause by failure of a debris dam (Chrétien and Brousse, 1989).
Soufriere, St. Vincent	1902	4	Anderson and Flett (1903)

7. Tsunamis

Tsunamis are surface-water waves that are generated by impulsive displacement of water. Seiches, another type of surface-water wave, differ from tsunamis in that the former are standing waves produced by “sloshing” in lakes and closed bays whereas the latter are moving waves that generally travel in the open ocean or in large lakes.

Latter (1981) has compiled some 92 cases of tsunamis of volcanic origin and grouped them according to several causal mechanisms. Eruptions through surface water generate only a fraction of all volcanic tsunamis. Others are caused, for example, by landslides or faulting on the flanks of subaerial volcanoes, by pyroclastic flows from subaerial volcanoes that travel over water, and by shock waves generated by subaerial volcanic explosions. The mechanisms mentioned by Latter (1981) which have produced tsunamis during eruptions through surface water are: (1) subaqueous explosions; (2) fallback of debris from submarine or sublacustrine vents onto the water surface; and (3) momentum imparted to water by atmospheric shock waves and base surges. As described below, these mechanisms are all very similar.

Latter (1981) also noted caldera collapse as a causal mechanism for tsunamis. The large tsunami generated during the disappearance of Ritter Island, Papua New Guinea in 1888, followed by smaller ones in 1972 and 1974 at the same volcano were cited as the sole examples, under the interpretation that the 1888 event was a caldera collapse and the smaller events in 1972 and 1974 further subsidence events (Cooke, 1981; Latter, 1981). The disappearance of Ritter Island in 1888 has since been interpreted as a sector collapse (Johnson, 1987). In the early hours of August 27, 1883, caldera subsidence at Krakatau produced withdrawal of water from shorelines and significant currents toward the volcano in the open ocean (Verbeek, 1885), but tsunamis that took place at that time were hypothesized by Latter (1981) to have been caused by rockfall along the caldera-bounding faults rather than by subsidence itself. We have found no other documentation of tsunamis (that is, water waves that inundate shorelines) by caldera collapse during eruptions through surface water.

Table 6 shows all subaqueous eruptions known to us that have been noted to produce tsunamis or seiches in historical time. All are submarine with the exceptions of those at Lakes Taal, Karymsky, and Ruapehu. Lake Taal (11 km diameter) is the only volcano to have produced damaging or deadly tsunamis within a lake. It is also one of only two crater-lake bearing volcanoes (with Lake Ilopango, El Salvador) with an inhabited shoreline that has produced explosive eruptions in historical time.

Collapse of pyroclastic flows into water has produced the largest and deadliest of these tsunamis, as exemplified by the eruption at Krakatau in 1883. Shortly before 10 AM on August 26, 1883, a phase of this eruption ejected massive volumes of ignimbrite some 10 km laterally from the eruptive vent and built two new, short-lived islands at a location where water depths were formerly 35–40 m (Verbeek, 1885). The emplacement of the ignimbrite body generated waves up to ~40 m high near the source (Yokoyama, 1981) and about 15 m high when they reached the shores of Sunda Strait, some 30–60 km away (Judd, 1888, 1889; Yokoyama, 1981; Latter, 1981). Similarly, in 1902, eruptions from the crater at Soufriere Volcano in St. Vincent produced pyroclastic flows that traveled over the ocean to produce tsunamis (Anderson and Flett, 1903)

Aside from Krakatau, the largest and deadliest tsunamis associated with subaqueous eruptions took place at Lake Taal in the Philippines in 1749, 1911, and 1965. The eruption of 1965 occurred in an inlet to Volcano Island in the center of the lake whereas earlier eruptions emanated from a water-filled crater on Volcano Island (Worcester, 1912). Based on contemporary accounts, Latter (1981) inferred that the tsunamis were generated by base surges and shock waves that overrode the lake. Eruptions at Myojin Reef (Bayonnaise Rocks), Japan, were observed to generate tsunamis both by this mechanism and by collapse of explosion-generated water columns (Niino, 1953).

Latter (1981) gives underwater explosions as the cause of small tsunamis at Anak Krakatau (Stehn, 1929), Myojin Reef (Niino, 1953), and Tuluman (Reynolds and Best, 1976). At Anak Krakatau and Myojin Reef, investigators noted that waves arose by the collapse of a cone of water uplifted during the explosion (Stehn 1929; Niino, 1953; Morimoto, 1960). Stehn (1929) added that smaller waves were also produced by the collapse of debris ejected during each explosion. He noted that the fall of a water cone 45 m high produced a wave 4 m above normal sea-level.

Based on these descriptions, the only distinction that can be drawn between tsunamis generated by submarine explosions and those produced by collapsing eruption columns is in the volume of material falling into the water. Moreover, these two mechanisms differ from the shock wave/base surge mechanism only in that the latter imparts more lateral

Table 6
Subaqueous eruptions known to have produced tsunamis. Volcanoes that produced tsunamis in the ocean are listed in italics; those that produced tsunamis or seiches in lakes are in plain text

Volcano name	Year	VEI	Wave height (m)	Inferred cause[a]	References, comments
Santorini, Greece	1650 BC 1650 AD	6 4?	60? ?	? ?	Yokoyama (1978), McCoy (1997). Fytikas et al. (1990).
Ruapehu, New Zealand	1980s	1–2	< 2	exp	McClelland et al. (1989, p. 129)
Tuluman, Papua New Guinea	1953	2	Small	exp	Reynolds and Best (1976); Latter (1981)
Ritter Island, Papua New Guinea	1972 1974	1 1	< 0.2–0.5	exp	Cooke et al. (1976); Cooke (1981). Wave height in 1974 was estimated at Sakar Island (Cooke et al., 1976), which is at least 7 km from Ritter Island.
Rabaul, Papua New Guinea	1878 1937	3 4?	4 > 4	pf? pf?	Johnson et al. (1981); Latter (1981); Johnson and Threlfall (1985). Descriptions of the 1937 waves suggest that some were seiches. Wave heights of >4 m in 1937 were estimated at the Rabaul waterfront, ~5 km from the vent.
Kavachi, Solomon Islands	1951	2	?	?	Simkin and Siebert (1994)
Anak Krakatau, Indonesia	1929	2	4	exp	Stehn (1929). Wave height was noted at the source.
Krakatau, Indonesia	1883	6	30–40	pf	Simkin and Fiske (1983, p. 307); Yokoyama (1981) estimated 30–40 m as the maximum height at the source for the largest tsunami in 1883. Maximum tsunami heights on nearby coastlines where most fatalities occurred were about 15 m.
Banua Wuhu, Indonesia	1889 1913	2 3	? ?	? ?	Simkin and Siebert (1994)
Taal, Philippines	1715 1913 1749 1911 1965	4 3 3 4 4	 > 4.7	 shk exp, shk	Pratt (1911); Worcester (1912); Moore et al. (1966). Tsunami height in 1965 was estimated ~4 km west of the vent, on the west lakeshore (Moore et al., 1966).
Sakurajima, Japan	1779	4	6	exp	Omori (1914); Latter (1981); Kobayashi and Ishihara (1988)
Bayonnaise Rocks (Myojin Reef), Japan	1915 1952	0 2	? 2	exp exp, shk	Niino (1953); Miyoshi and Akiba (1954); Morimoto (1960); Latter (1981). Height of the tsunami in 1952 was at a location near the source.
Karymsky, Kamchatka	1996	3	~ 10	exp?	Smithsonian Institution (1996)
Soufriere, St. Vincent	1902	4	?	Pf	Anderson and Flett (1903). The eruption took place through a crater lake, but the tsunami was caused by propagation of a pyroclastic flow over the ocean.

[a] pf = produced by pyroclastic flows; exp = explosions, shk = tsunamis produced by atmospheric shock waves or base surges.

momentum to the water body and displaces water to a lesser degree by the weight and downward momentum of the ash cloud.

In general, tsunamis generated by volcanic activity are smaller than those produced by faulting or landslides because the volume of water displaced during volcanic eruptions tends to be smaller. Seismic events and major sector-collapse landslides can rapidly displace cubic kilometers of water. Only the very largest eruptions, such as the ignimbrite-forming phase at Krakatau, can displace water volumes of this magnitude.

8. Base surges

Base surges are ring-shaped clouds that propagate from the base of an eruption column at high velocity along the ground or water surface. In this study we attempt to distinguish base surges from other types of surges because the former are generally associated with hydrovolcanism (e.g. Moore, 1967; Waters and Fisher, 1971; Fisher and Schmincke, 1984, p. 247) whereas the latter are not. In the volcanologic literature, base surges have been suggested to form by column collapse, much like pyroclastic flows (Fisher and Waters, 1970; Fisher and Schmincke, 1984, p. 247; Francis, 1993). However studies of bomb tests in shallow-water (Young, 1965), cited in the first paper on volcanic base surges (Moore, 1967) concluded that the main base surge did not result from column collapse. Rather, it formed by outward expansion of gases that tore water or debris from the inner side and upper lip of the explosion cavity, forming jets that coalesced into a toroidal-shaped cloud. As noted by Moore (1967), "This main base surge appeared before the outside of the main column had started to fall, and hence could not have been formed by bulk subsidence (Young, 1965, p. 98). Only later did a second, smaller base surge develop inside the first by subsidence of the main column." Photos of volcanic base surges (e.g. Moore, 1967; Kienle et al., 1980) do not always show the clear ring-shaped form produced in man-made explosions, and it seems likely that column collapse is more important in volcanic base surges than explosion-caused surges.

Explosion tests in alluvium (Knox and Rohrer, 1963; Rohrer, 1965) have found that the maximum radial distance (r) attained by a base surge varies as the 0.3 power of the yield (Y) of the explosion. For a given yield, there is also an optimal depth (equal to 10–15 m for a 1-kiloton burst) that will produce the greatest value of r. At the optimal depth, a 1-kiloton burst will produce a base surge 2.4 km in radius (Rohrer, 1965). The optimal depth increases with the yield to the 0.33 power (Rohrer, 1965). These results suggest that the following factors are required to produce large base surges during volcanic eruptions: (1) large, discrete explosions, and (2) a very shallow explosion depth.

Table 7 shows historical eruptions through surface water where base surges have been especially noteworthy, either for the destruction they caused (e.g. Taal, 1965), or because they were well observed or photographed (e.g. Anak Krakatau or Capelinhos, reinterpreted by Moore, 1967). The incompleteness of the published accounts prevents us from making many conclusive statements about the types of eruptions that produce base surges. All are explosive. Few have taken place in settings where water depth could be easily measured, but several (e.g. Surtsey, Capelinhos, Rabaul, Anak Krakatau) erupted in emergent settings where water depth was presumably tens of meters or less. Eruptions at Ruapehu in 1975, which originated from a water depth of at least several tens of meters (Nairn et al., 1979) are the deepest known in this table. During that eruption, base surges were not directly observed but were inferred to have caused the massive ejection of water at the summit that fed lahars. The average eruption in this table is larger than the average eruption through surface water (the mean VEI of all subaqueous eruptions compiled is 1.7, that of eruptions where surges have been noted is 3.2).

Based on the extent of destruction, the greatest distance traversed by base surges that we have encountered is 6 km at Taal in 1965 (Moore et al., 1966). Surge deposits have been noted from prehistoric subaqueous eruptions at considerably greater distances (up to ~30 km at Campi Flegrei, ~12 ka; Orsi et al., 1992), but such deposits are described in association with pyroclastic flows and were probably ash-cloud surges or ground surges.

Assuming that base surges form primarily by the explosion mechanism described above (rather than column collapse), the distance that they can extend from the eruptive vent is severely constrained by the

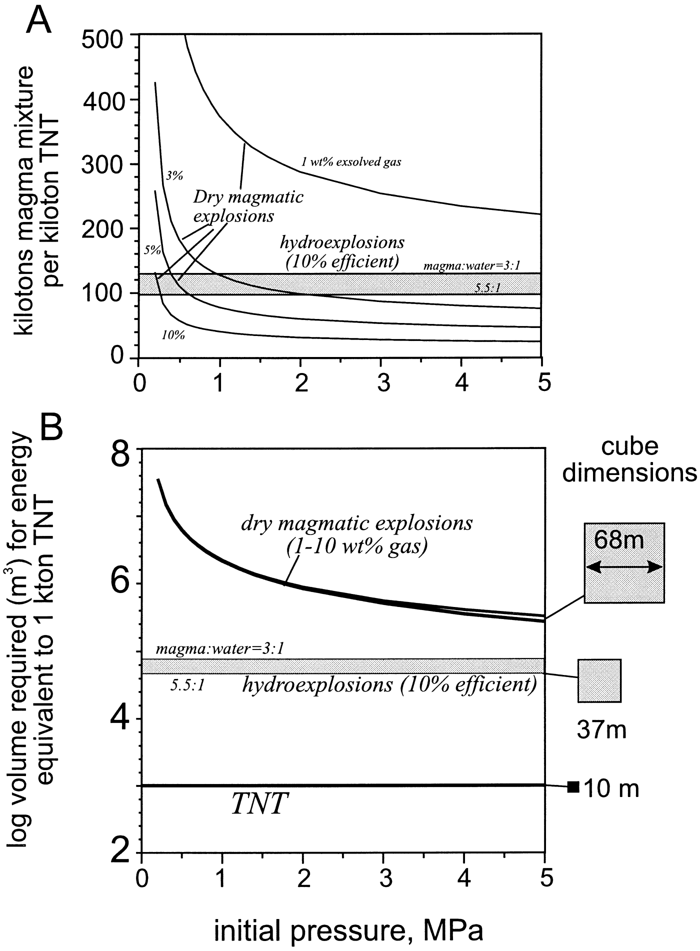

Fig. 5. (A) Kilotons of magma–fluid mixture (either magma plus liquid water, or magma plus magmatic gas) which would contain the explosive energy equivalent to 1 ktons of TNT, as a function of initial pressure of the mixture. Solid curved lines represent the mechanical energy released by decompressing a mixture of magma and magmatic gas (at an initial temperature of 900°C) from the pressure given on the abscissa to 1 atm pressure under isentropic, adiabatic conditions. Separate lines represent different amounts of exsolved gas in the mixture, in wt%. The shaded region represents the mechanical energy released in hydroexplosions (explosions caused by heating of water by magma), assuming liquid water (at $T = 25°C$) mixes and thermally equilibrates with liquid magma ($T = 1150°C$) at constant volume, then decompresses adiabatically and isentropically to 1 atm pressure. Boundaries of the shaded region encompass magma:water ratios of 3:1 to 5.5:1, assuming 10% efficiency in converting thermal energy to mechanical energy. The method of these calculations is provided in Mastin (1995). The energy released per kiloton of these mixtures is normalized to that released by TNT (4.6×10^{12} J/kton). (B) Log volume of a magma–fluid mixture that contains the explosive energy equivalent to 1 kton of TNT, as a function of pressure prior to decompression. Heavy, solid curves represent magma–gas mixtures at $T = 900°C$ and exsolved gas contents of 1–10 wt%. The shaded area represents mixtures of magma ($T = 1150°C$) and liquid water ($T = 25°C$), assuming 10% efficiency in converting thermal energy to mechanical energy, and using magma:water ratios of 3:1–5.5:1. Magma–water ratios of 5.5:1 provide the most explosive energy per unit weight or volume of the mixture (Wohletz, 1986; Mastin, 1995).

maximum size of an explosion that can be produced by volcanic processes. Using relations of Rohrer (1965), a 6-km base surge would require an explosive yield of about 16 ktons TNT detonated at an optimal depth of several tens of meters (Moore, 1967). Using calculations of volcanic energy release described in Mastin (1995), an explosion of this size, if caused by heating of water by magma, would require some 1500–2000 ktons of magma–water mixture at a near-optimal magma:water ratio (3–5.5:1), assuming

Table 7
Historical subaqueous eruptions where base surges have been especially large, destructive, or well observed

Volcano name	Year	VEI	How detected[a]	References, comments
Rotomahana-Waimangu, New Zealand	1886	5	d	Cole and Nairn (1975); Nairn (1979).
Ruapehu, New Zealand	1975	2	d,o	Destruction of summit area in 1975, inferred to be caused by base surges, extended to ~1 km from the vent (Nairn et al., 1979). Base surges were directly observed in several smaller eruptions as well (McClelland et al., 1989).
Rabaul, Papua New Guinea	1937	4	d	Surges apparent in 1937 photographs (Johnson and Threlfall, 1985). In 1994 (a subaerial eruption), directly-observed surges traveled 2–5 km from the vent (Smithsonian Institution, 1994a).
Anak Krakatau, Indonesia	1927–1940	1–3	p	Base surges are shown in photos by Stehn (1929), republished in Moore (1967). Maximum radial distance of base surges shown in photos is ~500 m.
Taal, Philippines	1911 1965	4 4	p o	Photos of the 1911 eruption (Pratt, 1911) appear to show base surges. Maximum distance traveled by base surges in 1965 (as judged by the extent of destruction) was ~6 km (Moore et al., 1966).
Bayonnaise Rocks (Myojin Reef), Japan	1952	2	p	Niino (1953) shows photos of base surges, republished in Moore (1967). Maximum radial distance of base surges in photo are ~0.7 km.
Ukinrek Maars, Alaska	1977	3	o	Kienle et al. (1980; Fig. 3) show horizontally-moving ash clouds, interpreted as surges, but, according to Self et al. (1980), not the same as the ring-shaped base surges described by Moore (1967) and Waters and Fisher (1971).
Kilauea, Hawaii	1790	4	d	Decker and Christiansen (1984); McPhie et al. (1990); Mastin (1997). See comments in Table 4.
Volcán Bárcena, Mexico	1952–1953	3	o	Richards (1959); Moore (1967).
Soufriere, St. Vincent	1979	3	d,o	Fiske and Sigurdsson (1982) mention base surges that extended to ~2.5 km.
Surtsey, Iceland	1963–1967	3	d,o	Moore (1967).
Askja, Iceland	1875	4	d	Self and Sparks (1978).
Capelinhos, Azores	1957	2	p	Moore (1967); Fisher and Waters (1971).

[a] d = deposits, o = direct observations, p = reinterpretation from photos or verbal descriptions.

an efficiency of about 10% in converting thermal energy to mechanical energy (Fig. 5A). The magma–water mixture would occupy a volume (prior to steam expansion) of about 1–2 million cubic meters (Fig. 5B)-equal to that of an eruptive conduit 50 m in diameter and 500–1000 m deep. If the explosions were caused by decompressing magma and gas with no heating of external water, an even greater volume would be required (Fig. 5B).

Volcanic surges may extend to greater distances if supplemented by gravitational column collapse. The distance to which such surges can travel is determined to a great extent by the height of the eruption column that is collapsing, which in turn depends on the temperature and density of the erupting mixture. For low to moderate magma:water ratios approximately 2:1 to 3:1; Wohletz, 1986; Mastin, 1995; Koyaguchi and Woods, 1996), their ejected mixtures are cool (~100°C), dense (with condensed water), and generate low eruptive columns with limited gravitational energy that can be transformed to kinetic energy when the column collapses. Only relatively dry hydromagmatic eruptive phases should contain sufficient thermal energy to generate high convecting columns.

9. Concluding remarks

Numerous papers in the last 30 years have emphasized that external water can significantly increase the explosiveness of some eruptions (e.g. Thorarinsson et al., 1964; Lorenz, 1973; Sheridan and Wohletz, 1983;

Wohletz, 1986; Zimanowski et al., 1991). By implication one might infer that such eruptions are more hazardous than dry magmatic ones. In some cases (e.g. Kilauea, 1790) magma–water mixing has clearly increased the explosivity of such eruptions and directly resulted in human casualties. But explosions and base surges are not the most common cause of death in eruptions through surface water. Lahars and tsunamis are more common, because they travel farther and inundate coastlines and river valleys, which are common sites of settlement.

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