Volcano-Hydrologic Hazards from Volcanic Lakes

V. Manville

Abstract

Volcanic regions typically host multiple lakes developed in explosion craters, volcano-tectonic collapse structures, and valley systems blocked as a result of eruptive activity, their boundaries and dimensions shifting in response to renewed activity and modification by background processes of erosion, sedimentation and tectonism. Such water bodies are a potent source of a wide range of complex and inter-related hydrologic hazards owing to their proximity to active volcanic vents, the consequent potential for violent mixing of magma with water, and the frequent fragility of their impoundments. These hazards arise as a result of water displacements within or from the lake basin and can be broadly sub-divided into 3 main types: (I) phenomena sourced within the lake basin as a direct or indirect consequence of subaqueous or subaerial volcanic activity; (II) floods from volcanic lakes triggered by volcanic activity, including induced breaching; and (III) floods from volcanic lakes with a non-volcanic cause. Type I hazards include subaqueous explosive volcanism and associated Surtseyan jets, base surges and tsunamis, which can impact lake shorelines and displace water over basin rims and through outlets. This results in Type II lahar and flooding hazards. Both types have been historically responsible for significant losses of life at many volcanoes worldwide. Other rapid phenomena such as pyroclastic flows, debris avalanches, and large lahars from intra- or extra-lake volcanoes are potentially tsunamigenic (Type I), and/or displacing, and can hence also lead to secondary (Type II) hazards, as can seismicity-producing volcano-tectonic movements. Slower processes including volcano-tectonic movements, subaqueous lava dome extrusion, cryptodome intrusion, and magmatic inflation can potentially produce Type II flooding through volumetric water displacement over the outlet. Erosion of the outlet can be catastrophic, magnifying the size of

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D. Rouwet et al. (eds.), *Volcanic Lakes*, Advances in Volcanology,
DOI 10.1007/978-3-642-36833-2_2,

flood events. Damming of the outlet itself can result in backflooding of the basin. Type III hazards, i.e. volcanic lake break-out floods; result from breaching of the barrier constraining a volcanic lake as a result of passive overtopping, piping, mechanical failure, or headward erosion of the natural dam. Such events range in scale from relatively minor outflows triggered by failure of crater walls or the breaching of riverine dams composed of pyroclastic, volcaniclastic, or lava flow material to catastrophic floods generated by the breaching of caldera rims. Palaeohydraulic reconstructions of some of the latter indicate that they are amongst the largest post-glacial floods on Earth, being exceeded only by late Pleistocene deluges associated with breaching of ice-dammed lakes and pluvial basins.

Keywords

Volcanic lakes · Subaqueous explosive volcanism · Base surges · Tsunami · Floods · Lahars · Natural hazards

1 Introduction

Volcanic activity is a prolific producer of lakes due to the capacity of eruptions and volcano-tectonic activity to generate both positive and negative relief. In the strictest definition, a volcanic lake is a cap of meteoric water over the vent of an active volcano: according to this criterion 16 % of the 714 identified Holocene volcanoes world-wide host one or more, frequently ephemeral, lakes in explosion craters and subsidence calderas (Delmelle and Bernard 2000). Many typical crater lakes (Fig. 1a) contain 1–10 × 10^6 m^3 of water, often at elevations several km above the surrounding landscape (Casadevall et al. 1984; Rowe et al. 1992; Christenson and Wood 1993; Kempter and Rowe 2000). Hydrothermal and hydromagmatic (maar) eruption craters (Fig. 1b) are typically <2 km in diameter and comprise a central pit ringed by a raised ejecta rim (Lorenz 1973). The transition from purely magmatic explosion craters to volcano-tectonic depressions formed by a combination of explosive ejection of material and magma withdrawal occurs at c. 2.5 km diameter (Williams 1941). The largest volcanic impoundments comprise intracaldera lakes, either developed by collapse at the summit of shield or cone volcanoes such as Crater Lake in Oregon (Fig. 1c), which impounds 1.9 × 10^{10} m^3 at an elevation of 1,882 m (Nelson et al. 1994), or superimposed on regional tectonic depressions, like Lake Taupo in New Zealand (Fig. 1d), which contains 6 × 10^{10} m^3 (Lowe and Green 1992). Lake Toba in Indonesia is the world's largest caldera lake and holds 2.4 × 10^{11} m^3 of water (Chesner and Rose 1991). A review of c. 200 Late Pleistocene or younger terrestrial calderas found that around half held one or more intracaldera lakes (Manville 2010), either with or without a surface outlet (Larson 1989).

In addition, volcanism is the third most common dam-forming mechanism, accounting for 8 % of natural-dammed lakes globally (Costa and Schuster 1988). Volcanogenic dams include lava flows (Fenton et al. 2004), pyroclastic flows (Aramaki 1981; Macías et al. 2004), debris avalanches from the collapse of stratovolcanoes (Meyer et al. 1986; Capra and Macías 2002), and rapid aggradation by lahars (Umbal and Rodolfo 1996). These blockages may impound lakes in the source crater or caldera, adjacent ones, or local valley systems (Fig. 2). All such impoundments have the potential to generate catastrophic break-out floods through sudden failure of the volcanic barrier, in some cases triggered by the resumption volcanism. The resulting floods from large volcanic lakes rank

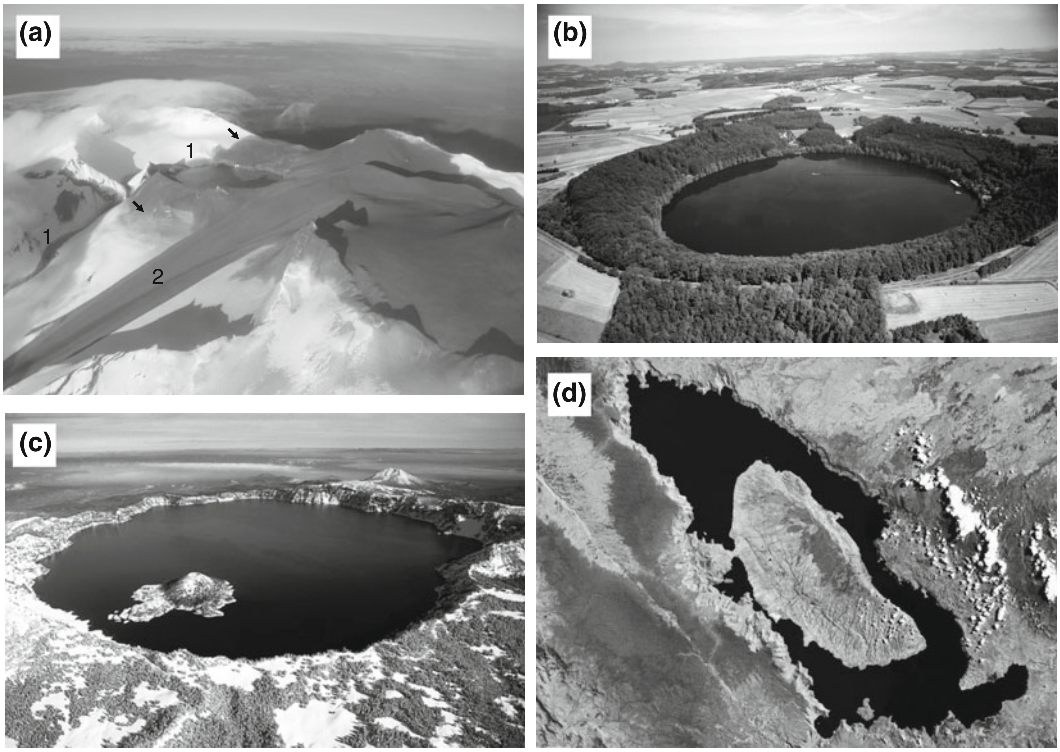

Fig. 1 A selection of volcanic lakes from around the world. **a** Crater Lake, Mt. Ruapehu, New Zealand. This c. 400 m diameter lake lies at a surface elevation of c. 2,530 mASL. Explosive volcanic activity has generated frequent hazards, including base surges (deposits arrowed) and eruption-triggered lahars by displacement waves over the outlet (1) or Surtseyan jetting over the crater rim (2). This photo was taken the day after the 25 September 2007 eruption. (Image B. Christenson, GNS Science). **b** Pulvermaar in the volcanic Eifel region of Germany. Diameter is c. 700 m. **c** Crater Lake, Oregon. Formed by caldera collapse during the 7.7 ka Mazama eruption, this 10 km diameter lake lies 1882 mASL and has no surface outlet. (Wikipedia commons). **d** Lake Toba, 87 km long, lies in a volcano-tectonic collapse structure last modified during the 74 ka Toba super-eruption. (Landsat Image)

amongst the largest post-glacial floods on Earth (O'Connor et al. 2013).

1.1 Classification of Hazards Associated with Volcanic Lakes

A wide range of hazards derive from volcanic lakes as a direct consequence of magma:water interactions at the vent, or through the interaction of volcanically generated mass-flows (pyroclastic flows, debris avalanches, lahars, and lava flows) with the water body (Fig. 3). Consequently, although only c. 3.5 % of recorded volcanic eruptions have occurred through lakes (Simkin and Siebert 1994), these have been responsible for approximately 15 % of recorded deaths (Table 1). In many cases, a primary hazardous phenomenon can trigger a series of other secondary effects in a process-chain (Fig. 3): for example, a subaqueous explosion that breaches the lake surface can generate tsunamis that overtop the lake outlet to form a lahar, which itself causes erosion of the spillway leading to further water release and downstream flooding (McGimsey et al. 1994; Waythomas et al. 1996). Under certain (poorly understood) conditions, magma:water interactions can increase the violence and explosivity of volcanic eruptions (Thorarinsson et al. 1964; Lorenz 1973; Sheridan

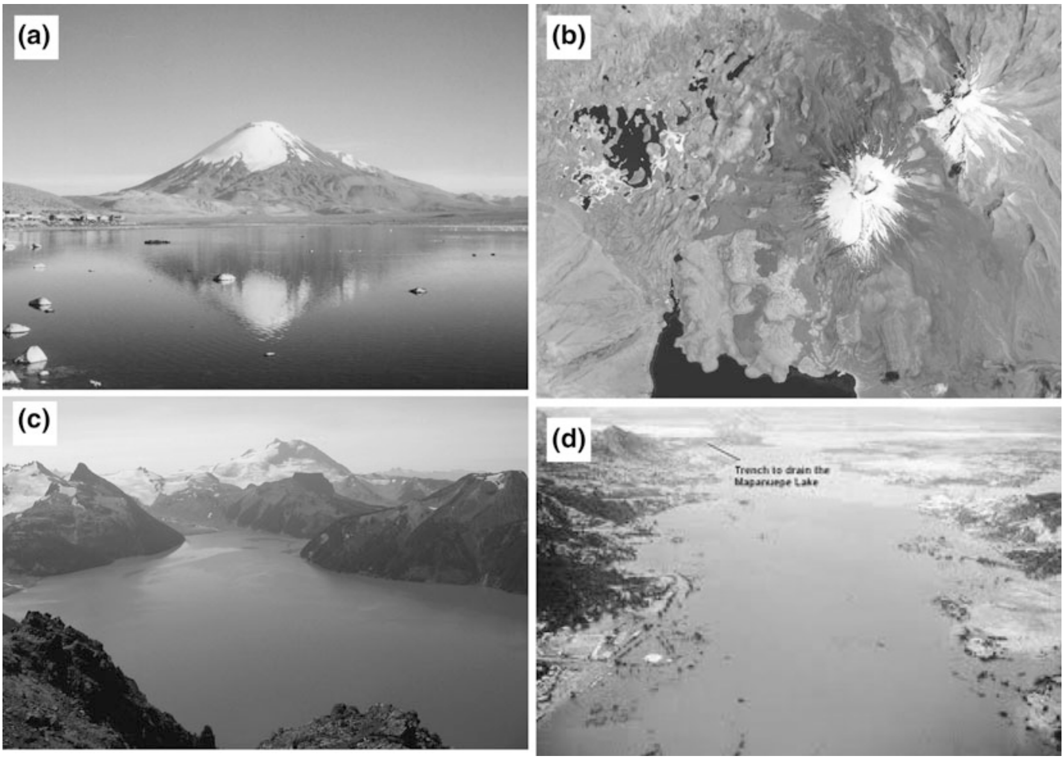

Fig. 2 Lakes impounded behind dams of volcanic material. **a** Lake Chungará, dammed at c. 6 ka by a debris avalanche from Parinacota stratovolcano, Chile. (Wikipedia commons). **b** Spaceborne view of the snow-capped cone of Parinacota: Lake Chunagará lies c. 8 km to the south. Numerous other lakes, including Cotacotani, are impounded by the irregular topography of the debris avalanche deposits to the west (NASA image ISS029-E-20003). **c** Lake Garibaldi (10 km^2, 1,500 m ASL, >250 m deep) dammed by lave flows from Mt. Price and Clinker peak, British Columbia, Canada. (Wikipedia commons). **d** Lake Mapanuepe, dammed by lahars in the Marella river, Pinatubo, Philippines 1991 (USGS image)

and Wohletz 1983; Wohletz 1986). Factors that influence the explosivity of the interaction likely include magma type, mass eruption rate, nature of magma pre-fragmentation, and water depth (Wohletz 1986; Mastin 1995; Koyaguchi and Woods 1996). The net effect can be to increase the area of the primary hazard by up an order of magnitude through the generation of base surges (Moore 1967) and even more with tsunamis (Latter 1981). A 0.01 km^3 monogenetic basaltic eruption in an arid environment would produce a localised scoria cone, the same magma volume erupted in wet environment can produce a 1 km diameter maar/tuff-ring with phreatomagmatic base surges extending to >3 km radius (Németh et al. 2012). The travel distance of tsunamis is effectively limited by the dimensions and bathymetry of the water body, in lakes this can be 10's of km. Alternatively, magma and water can mix relatively non-violently (Batiza and White 2000). A review of historical eruptions through volcanic lakes shows that c. 2 % involved relatively passive growth of subaqueous to emergent lava domes (Table 1). Other hazards reported during eruptions through water include tsunamis and seiches generated by volcano-tectonic displacements of the lake floor, Surtseyan jets, tephra and ballistic fall, lahars, lightning (associated with wet ash clouds), and torrential rainstorms (Mastin and Witter 2000). Growth in population and infrastructure, particularly in the developing world, has increased exposure to hazards from volcanic lakes and a number of major cities are vulnerable to volcano-lake

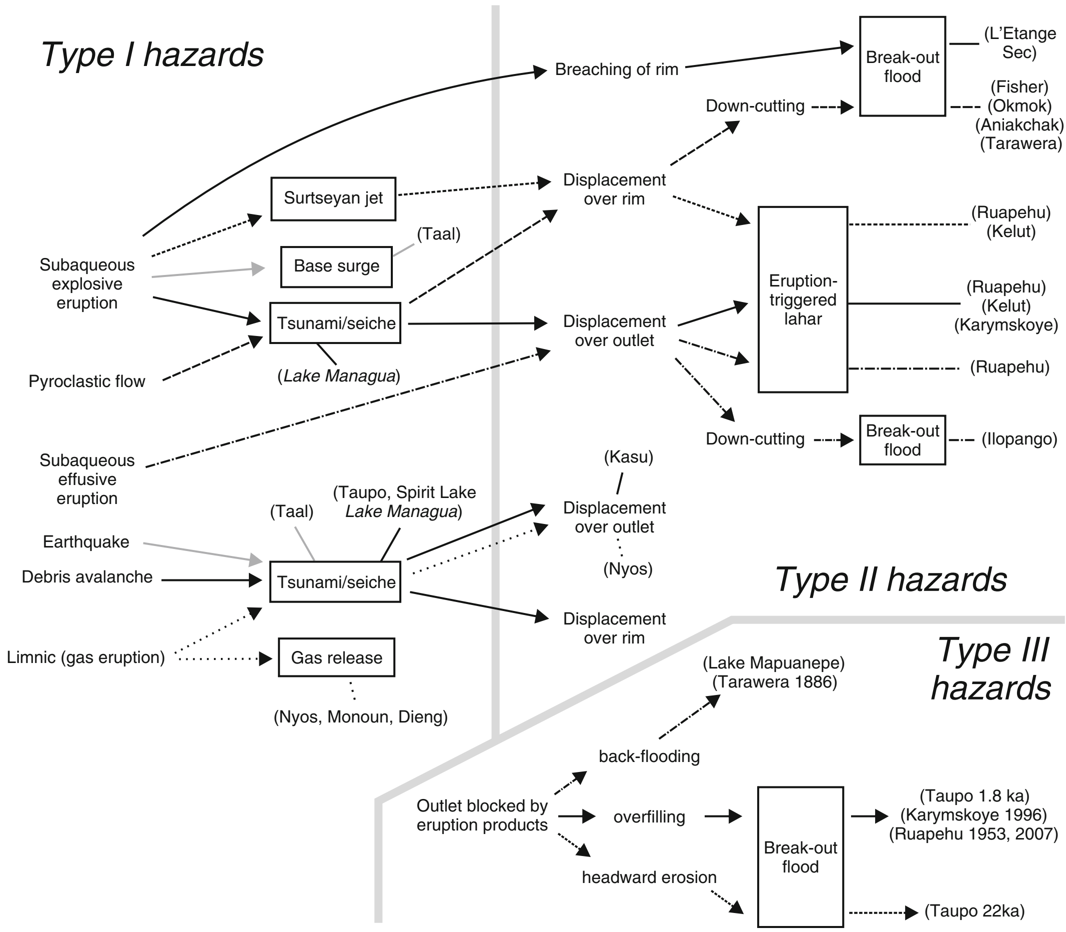

Fig. 3 Classification of the main hazards associated with volcanic lakes, including triggering mechanisms and process-chains. Examples of volcanoes where these hazards have been observed historically are shown in *brackets*; names are *italicized* where the hazard has been inferred

interactions including Managua, the capital of Nicaragua (population 2.2 million). Therefore, characterisation and understanding of the range of hazards is vital to their mitigation.

2 Subaqueous Explosive Volcanism

The rapid conversion of thermal to kinetic energy during the violent mixing of magma and water in a subaqueous eruption fuel-coolant reactions (Wohletz 1986; Frost et al. 1994; White 1996) produces an expanding and buoyantly rising bubble of water vapour, magmatic gas, and magma fragments whose interactions with the ambient water column can cause ballistic ejection of most of the volume of a crater lake from its basin (Nairn et al. 1979), as well as generating base surges (Moore 1967; Waters and Fisher 1971) and impulsive tsunami in larger water bodies (Watts and Waythomas 2003). Volcanic tsunamis (Latter 1981), including explosion generated waves, are treated separately in this discussion due to their range of potential triggering mechanisms.

Table 1 Compilation of historical Type I and II hazardous events at volcanic crater and caldera lakes, with a focus on the best characterised or most deadly

Volcano, Location	Date	Lake type	S	B	T	L	P	A	D	Other	Fatalities	Events	Notes, references
Ruapehu, New Zealand	25 Sep. 2007	Crater	X	x	x	x	–	–	–	–	–	53	More than 53 eruptions have occurred through Crater Lake in historic times, typically in the form of minor phreatic to larger phreatomagmatic explosions accompanied by Surtseyan jets, base surges, and tsunamis confined to the lake basin (Hackett and Houghton 1989; McClelland et al. 1989). Larger events have swept the summit area with base surges and ballistic fall-out in 1969 (Healy et al. 1978) and 1975 (Nairn et al. 1979). Magmatic eruption episodes occur every c. 50 years, including in 1945-46 when a lava dome was extruded (Beck 1950) and 1995-1996 (Cronin et al. 1996, 1997). Eruption-triggered lahars have entered areas now occupied by ski fields on 6 occasions, most recently in 2007 (Kilgour et al. 2010). Break-out lahars from Crater Lake happened in 1953 (O'Shea 1954) and 2007 (Massey et al. 2010)
	23 Sep. 1995		X	x	x	x	–	–	–	–	–		
	18 Sep. 1995		X	x	x	x	–	–	–	–	–		
	24 April 1975		X	X	X	X	–	x	–	–	–		
	22 June 1969		X	X	x	x	–	x	–	–	–		
	1945		X	–	–	X	–	X	X	–	–		
	1861–2012		–	–	–	–	–	–	–	–	–		
Tarawera, New Zealand	10 Jun. 1886	Valley/ crater	X	X	X	–	–	X	–	x	151	1	Basaltic fissure eruption through Lakes Rotomahana/Rotomakariri generates base surges that travelled up to 6 km, these and wet ash fall kill 151 (Nairn 1979; Simmons et al. 1993). Blockage of outlet to Lake Tarawera by primary and remobilised eruption products results in 12.8 m rise in lake level, inundating lake shore villages (White et al. 1997)
Taupo, New Zealand	1846	Caldera	–	–	x	–	–	–	–	–	–	1	Landslide from the Hipaua Cliffs geothermal area at the south end of Lake Taupo killed over 150 and generated a small tsunami when it entered the lake (Hegan et al. 2001)

(continued)

Table 1 (continued)

Volcano, Location	Date	Lake type	S	B	T	L	P	A	D	Other	Fatalities	Events	Notes, references
White Island, New Zealand	1826–2012	Crater	X	x	–	–	–	x	–	–	–	>>1	Intermittent moderate phreatomagmatic eruptions, sometimes occurring through ephemeral crater lakes have occurred through the historical period, most recently in July 2000 (BGVN 25:07) (Houghton and Nairn 1991)
Raoul Island, Kermadecs	17 Mar. 2006	Crater	x	x	–	–	–	x	–	–	1	1	Phreatomagmatic eruption through Green Lake (BGVN 31:03)
Aoba (Ambae), Vanuatu	Nov. 2005–Jan. 2006	Caldera	x	x	x	–	–	–	–	–	–	2	Growth of tuff ring in Lake Voui produced Surtseyan eruptions with hazards confined to lake basin (Németh et al. 2006; Bani et al. 2009) (BGVN 30:11). Phreatic eruptions also occurred in 1995 (BGVN 20:02)
Niuafo'ou, Tonga	1814–1985	Caldera	–	–	–	–	–	–	–	–	–	3	At least 3 eruptions have occurred through the central caldera lake during historical times (BGVN 28:04, SEAN 10:09)
Long Island, Papua New Guinea	Nov. 1993	Caldera	x	–	–	–	–	–	–	–	–	8	Phreatomagmatic eruptions and emissions discoloured 8 km diameter Lake Wisdom. Largest explosions broke lake surface in depths of 300–350 m. Similar eruptions beneath the lake or on Motmot Island have occurred in 1933, 1943, 1953, 1955 and 1968. (BGVN 18:12)
	1660	Caldera	–	x	X	X	?	x	–	X	>2,000		Explosive eruption deepened a pre-existing caldera lake (Pain et al. 1981)
Kasu, Papua New Guinea	20 Apr. 1999	Crater	–	–	X	–	–	–	–	–	1	1	A 150,000 m^3 landslide into the small crater lake generated a 15 m high wave that washed over the outlet, injuring 11 and killing one (Wagner et al. 2003)
Rabaul, Papua New Guinea	Mar. 1940	Crater	–	–	–	–	–	–	–	–	–	1	Small phreatic eruptions occurred through an ephemeral lake developed in the crater of Tavurvur (Simkin and Siebert 1994)

(continued)

Table 1 (continued)

Volcano, Location	Date	Lake type	S	B	T	L	P	A	D	Other	Fatalities	Events	Notes, references
Karkar, Papua New Guinea	1979–9180	Crater	x										Phreatomagmatic eruptions through small intermittent crater lake
Kerinci, Indonesia	Sep. 1937	Crater	–	–	–	–	–	–	–	–	–	1	Phreatic eruption through ephemeral lake developed in crater of Indonesia's highest volcano (Simkin and Siebert 1994)
Kaba, Indonesia	1833	Crater	–	–	–	X	–	–	–	–	126	1	Eruption ejected crater lake at Kan Vogelsang (van Padang 1951)
Dempo, Indonesia	1905–2006	Crater	x	x	–	x	–	–	–	–	–	8	Eruptions through the crater lake have occurred on 8 occasions, most severely in Dec. 1939, and most recently on 25 Sep. 2006 (BGVN 34:03)
Anak Krakatau, Indonesia	1931–1959	Crater	–	–	–	–	–	–	–	–	–	16	Eruptions through ephemeral crater lakes have occurred on at least 16 occasions since the growth of Anak Krakatau in the 1883 caldera, most recently in 1959 (Simkin and Siebert 1994)
Kelimutu, Indonesia	1968	Crater	–	–	–	–	–	–	–	–	–	1	Small eruption through Tiwu Nua Muri, one of 3 crater lakes at the summit of this stratovolcano.
Dieng Volcanic Complex, Indonesia	1766-2009	Crater	x	–	x	x	–	–	–	x	149	18	This region contains a caldera, two stratovolcanoes, 20 craters and geothermal areas. It has a history of producing lethal gas eruptions, phreatic explosions and other hazards. Since the 18th century 18 phreatic eruptions through 7 different crater lakes have caused lahars on 3 occasions and deaths on 8. On 20 Feb. 1979, a limnic eruption of CO_2 from Sinila killed 149 (SEAN 04:03) (Le Guern et al. 1982)

(continued)

Table 1 (continued)

Volcano, Location	Date	Lake type	S	B	T	L	P	A	D	Other	Fatalities	Events	Notes, references
Kelut, Indonesia	Nov. 2007	Crater	–	–	–	–	–	–	X	–	–	35	Passive extrusion of a lava dome displaced the crater lake (BGVN 37:03)
	10 Feb. 1990		–	x	x	x	–	–	–	–	36		Ganung Kelut is one of the most dangerous volcanoes in Indonesia. More than 30 eruptions have occurred since AD 1000, typically of VEI magnitude 2–4, on a c. 13 year cycle (8-18 year range). These have ejected the summit crater lake to form lethal lahars on 10 occasions, killing >15,000 in total (Thouret et al. 1998). Tunnels were constructed during 1923–1926 to artificially lower the lake level following the devastating 1919 eruption (Zen and Hadikusumo 1965; Smart 1981; Suryo and Clarke 1985). Following their destruction by the 1951 eruption (which produced no lahars because of the reduced crater lake volume) they were rebuilt
	26 Apr. 1966		–	–	–	X	–	–	–	–	282		
	31 Aug. 1951		–	–	–	–	–	–	–	–	7		
	19 May 1919		–	–	–	X	–	–	–	–	5,110		
	22 May 1901		–	–	–	X	–	–	–	–	Many		
	4 Jun. 1864		–	–	–	x	–	–	–	–	54		
	24 Jan. 1851		–	–	–	x	–	–	–	–	21		
	1826		–	–	–	x	–	–	–	–	–		
	1716		–	–	–	x	–	–	–	–	–		
	1586		–	–	–	X	–	–	–	–	>10,000		
	AD1000–1586		–	–	–	X	–	–	–	–	Many		13 other explosive eruptions through the crater lake of Kelut are known from this period
Tengger, Indonesia	24 Jan. 1842	Crater	–	–	–	–	–	–	–	–	–	1	Explosion through crater lake (Simkin and Siebert 1994)
Raung, Indonesia	1838	Crater	–	–	–	x	–	–	–	–	–	6	Eruptions through the summit crater lake of Raung produced eruption-triggered lahars until modification of the crater area by the 1838 eruptions prevented ponding of water (van Padang 1951)
	16 Jan. 1817		–	–	–	–	–	–	–	–	–		
	1730		–	–	–	X	–	–	–	–	Many		
	1638		–	–	–	X	–	–	–	–	>1,000		
	1597		–	–	–	–	–	–	–	–	–		
	1593		–	–	–	–	–	–	–	–	–		
Rinjani, Indonesia	1994	Crater	–	–	–	–	–	–	–	–	30	2	Phreatomgmatic eruptions from cone growing on lake shore. Fatalities resulted from cold lahar —possibly rain triggered (BGVN 20:05)
	1944		–	–	–	–	–	–	–	–	–		Eruption through crater lake.

(continued)

Table 1 (continued)

Volcano, Location	Date	Lake type	S	B	T	L	P	A	D	Other	Fatalities	Events	Notes, references
Kawah Ijen, Indonesia	28 Jun. 1999	Crater	–	–	–	–	–	–	–	–	–	8	Kawah Ijen hosts a c. 1 km diameter, hot, highly acidic crater lake at an elevation of 2,200 mASL, and is the focus of sulphur mining activity. 8 historical eruptions have occurred through the crater lake, producing lethal lahars on a number of occasions
	3 Feb. 1994		–	–	–	–	–	–	–	–	–		
	3 Jul. 1993		–	–	–	–	–	–	–	–	–		
	22 Apr. 1952		–	–	–	–	–	–	–	–	–		
	5 Nov. 1936		–	–	x	–	–	–	–	–	–		
	25 Feb. 1917		–	–	–	–	–	–	–	–	–		
	15 Jan. 1817		–	–	X	–	–	–	–	–	yes		
	1796		–	–	x	–	–	–	–	–	–		
Awu, Indonesia	1966	Crater	–	–	–	X	X	–	–	–	<39	7	Powerful explosive eruptions through the crater lake of this massive stratovolcano generated devastating lahars and pyroclastic flows. Smaller eruptions through crater lake also occurred in 1921, 1922 and 1930 (Delmelle and Bernard 2000; Simkin and Siebert 1994). 1966 eruption changed crater geometry and minimised size of lake.
	1892		–	–	–	X	X	–	–	–	1,530		
	1856		–	–	–	X	X	–	–	–	>3,000		
	1711		–	–	–	X	X	–	–	–	>3,200		
Galunggung, Indonesia	1982	Crater	–	–	–	x		–	–	–	8	2	Eruptions expelled half of c. 8.6 × 10^6 m^3 crater lake as hot lahar (SEAN 07:03). Since 1984 only a shallow wide lake has survived.
	1822		–	–	–	X	x	–	–	–	3,600		Eruptions through crater lake expelled massive lahars that destroyed 114 villages (Delmelle and Bernard 2000)
Lokon-Empung, Indonesia	22 Mar. 1986	Crater	–	–	x	–	–	–	–	–	–	2	Eruptions expelled a small (0.7 × 10^6 m^3) lake from the Tompaluan crater generating lahars (SEAN 11:03)
	27 Nov. 1969		–	–	–	–	–	–	–	–	–		
Mahawu, Indonesia	16 Nov. 1977	Crater	–	–	–	–	–	–	–	–	–	1	Phreatic explosion through intermittent small crater lake (SEAN 12:07)
Tongkoko, Indonesia	1801	Crater	–	–	–	–	–	–	–	–	–	1	Eruption through crater lake that no longer exists.

(continued)

Table 1 (continued)

Volcano, Location	Date	Lake type	S	B	T	L	P	A	D	Other	Fatalities	Events	Notes, references
Taal, Philippines	31 Jan. 1968	Caldera	–	–	–	–	–	–	–	–	–	9	Historical eruptions at Taal have been concentrated on volcano island, and involve small crater lakes and/or interactions with the larger caldera lake. Other eruptions involve lake water flooding volcanic fissures.
	5 Jul. 1966		–	–	–	–	–	–	–	–	–		
	28–30 Sep. 1965		x	X	x	–	x	x	–	–	>190		Initial magmatic eruption on volcano island evolved to phreatomagmatic when caldera lake waters gained access to vent. Base surges travelled over 6 km (Moore et al. 1966a, 1966b; Moore 1967)
	27 Jan. 1911		x	X	X	–	x	x	–	–	>1,335		Most fatalities occurred in boats capsized by tsunamis and seiches. Similar waves up to 2-5 m high and other phenomena accompanied eruptions in 1716, 1731, 1749 and 1754 (Latter 1981; Newhall and Dzurisin 1988)
Pinatubo, Philippines	Jul.–Oct. 1992	Caldera	–	–	–	–	–	–	X	–	–	1	Growth of a lava dome on the floor of the flooded 2.5 km diameter caldera created by the 1991 eruption (BGVN 17:06).
Aso, Japan	17 Feb. 2008	Crater	–	–	–	–	–	–	–	–	–	55	Historic activity at Aso caldera has been confined to the Naka-dake crater in the central resurgent dome and cone complex. Frequent VEI magnitude 0–2 eruptions have expelled an ephemeral crater lake on 55 recorded occasions, dating back to AD 769 and most recently in 2008
	1979		–	–	–	–	–	–	–	–	3		
	1872		–	–	–	–	–	–	–	–	4		
	1485		–	–	–	–	–	–	–	–	1		
Kusatsu-Shirane, Japan	6 Jan. 1989	Crater	–	–	–	x	–	–	–	–	2	5	Historic events have included at least 5 small phreatic/phreatomagmatic explosions through one or more of the three summit crater lakes and their margins. (SEAN 07:10)
Zao, Japan	1183-1940	Crater	–	–	–	x	–	–	–	–	3	17	Eruptions through the Okama crater lake of Goshiki-dake in the Zao volcanic complex have occurred 17 times since historic records began in AD1183, most recently in May 1940, with a larger event in 1895 (Miura et al. 2012)

(continued)

Table 1 (continued)

Volcano, Location	Date	Lake type	S	B	T	L	P	A	D	Other	Fatalities	Events	Notes, references
Towada, Japan	915	Caldera	–	–	–	–	–	–	X	–	–	1	Eruption of the Goshikiiwa lava dome on the flanks of an older intracaldera volcano
Haku-san, Japan	1579	Crater	–	–	–	x	–	–	–	–	–	1	Eruption through crater lake
Kirishima, Japan	1716-1959	Crater	–	–	–	–	–	–	–	–	–	3	Kirishima is a cluster of c. 20 Quaternary volcanoes. Historical eruptions have occurred through the crater lake of Shinmoe-dake, most recently in 1959, and also in 1822 and 1716
Karymskoye, Kamchtaka	2 Jan. 1996	Caldera	X	X	X	–	–	–	–	x	–	1	Surtseyan phreatomagmatic eruption constructed a tuff ring in the lake. Adjacent lake shores were swept with base surges and tsunamis up to 25 m above lake level. Outlet river was blocked by pyroclastic material causing temporary lake level rise of 2.6 m (Belousov et al. 2000; Belousov and Belousov 2001; Torsvik et al. 2010)
Tao-Rusyr, Kamchtaka	12 Nov. 1952	Caldera	–	–	–	–	–	–	X	–	–	1	Extrusion of a lava dome on the flank of Krenitzyn Peak interacted with the 7 km diameter caldera lake
Ebeko, Kamchtaka	1965–1989	Crater	–	–	–	–	–	–	–	–	–	5	5 small eruptions have occurred through minor crater lakes
Zavaritzki, Kamchtaka	1923?	Caldera	–	–	–	–	–	–	X	–	–	1	Lava dome extrusion.
Gorely, Kamchtaka	1984	Crater	–	–	–	–	–	–	–	–	–	1	Gorely caldera complex hosts 11 summit and 30 flank craters, some containing lakes. One historical eruption through a crater lake is known
Maly Semiachik, Kamchatka	1804–1952	Crater	–	–	–	–	–	–	–	–	–	5	A number of historic eruptions have occurred through Troitsky Crater
Ukinrek, Alaska	1977	Maar crater	–	–	–	–	–	–	X	–	–	1	A lava dome was extruded into one of the two maars formed by the 1977 eruption

(continued)

Table 1 (continued)

Volcano, Location	Date	Lake type	S	B	T	L	P	A	D	Other	Fatalities	Events	Notes, references
Kilauea, Hawai'i	1790	Caldera	–	X	–	–	–	–	–	–	80–300	1	Phreatomagmatic eruption through inferred caldera lake (Mastin 1997)
Lake Nyos, Cameroon	21 Aug. 1986	Maar crater	–	–	X	x	–	–	–	X	1,746	1	Catastrophic exsolution of magmatic CO_2 resulted in limnic eruption of c. 1 km^3 of gas that overspilled the lake basin to suffocate >1,700 people (Kling et al. 1987; Barberi et al. 1989; Tazieff 1989). Tsunami waves ran up to 25 m above lake level and a 6 m high surge was displaced over the outlet
Lake Monoun, Cameroon	15 Aug. 1984	Maar crater	–	–	–	–	–	–	–	X	37	1	Limnic eruption of CO_2 (Sigurdsson et al. 1987)
Nyamuragira, Zaire	1920	Crater	–	–	–	–	–	–	–	–	–	1	Reprted eruption through crater lake (Simkin and Siebert 1994)
Soufrière, St. Vincent (WI)	13 Apr. 1979	Crater	–	–	–	X	x	–	X	x	–	6	Historical explosive eruptions have ejected crater lakes and generated pyroclastic flows followed by lava domes. Most deaths resulted form pyroclastic flows. (Anderson and Flett 1903; Shepherd et al. 1979)
	6 May 1902		–	–	–	X	x	–	–	x	1,680		
	27 Apr. 1812		–	–	–	X	x	–	–	x	–		
Pelée, Martinique (WI)	23 Apr. 1902	Crater	–	–	–	X	–	–	–	–	23	1	Eruptions triggered breaching of L'Etang Sec causing a hot lahar that triggered a tsunami when it reached the coast. Shortly followed by the catastrophic pyroclastic flow that killed 29,000 (Fisher and Heiken 1982; Chrétien and Brousse 1989)
Santa Maria, Guatemala	1903	Crater	–	–	–	–	–	–	–	–	–	1	Eruption through lake developed in crater formed by VEI magnitude 6 eruption in AD 1902 (Rose 1972; Simkin and Siebert 1994)
San Salvador, El Salvador	7 Jun. 1917	Crater	–	–	–	–	–	–	–	–	–	1	Eruption permanently expelled crater lake.

(continued)

Table 1 (continued)

Volcano, Location	Date	Lake type	S	B	T	L	P	A	D	Other	Fatalities	Events	Notes, references
Santa Ana, El Salvador	1 Oct. 2005	Crater	–	–	–	x	–	–	–	x	2	1	Eruption through small crater lake coincided with heavy rain that also triggered lahars (BGVN 30:09) (Hernández et al. 2007)
Ilopango, El Salvador	1880	Caldera	X	X	X	–	–	–	X	x	–	1	Eruption of an intra-lake dacitic lava dome raised lake level by 1.2 m, triggering increased overflow and downcutting of the outlet by 9.2 m, releasing 1.2×10^9 m^3 of water at peak discharges of 3×10^3 m^3/s (Mann et al. 2004)
Rincón de la Vieja, Costa Rica	1922–1998	Crater	–	–	–	X	x	–	–	–	–	13	A small hyper-acidic crater lake 1750 m ASL has been the source of at least 13 historic eruptions at this remote volcano, most recently on 15 Feb. 2008 (BGVN 23:03)
Poás, Costa Rica	1828–2011	Crater	x	–	–	–	–	–	–	–	–	47	Poás hosts three craters and two crater lakes. The active Laguna Caliente has been the source of numerous small phreatic and phreatomagmatic eruptions since 1828, most recently in Feb. 2011 (BGVN 36:04)
Volcan Copahue, Chile/ Argentina	1 Jul. 2000	Crater	–	–	–	X	x	–	–	–	–	4	Eruptions through the Del Agrio crater lake have occurred 4 times since 1992 (BGVN 25:06)
Planchón-Peteroa, Chile	9 Feb. 1991	Crater	–	–	–	x	–	–	–	–	–	1	Phreatomagmatic eruption through small crater lake (BGVN 16:01)
Fernandina, Galapagos	14 Sep. 1988	Caldera	–	–	X	–	–	–	–	–	–	1	Approximately 1 km^3 of the caldera rim, oversteepened by collapse of the caldera floor in 1968, failed to form a debris avalanche that displaced the 2 km diameter caldera lake to the N and NW as a tsunami. (SEAN 13:10)
Askja, Iceland	Jul. 1926	Caldera	–	–	–	–	–	–	–	–	–	1	Explosive eruption created new island at S end of Öskjuvatn lake.

Data principally derived from Simkin and Siebert (1994), Mastin and Witter (2000), Neall (1996), and the Smithsonian Institution Global Volcano Programme (SEAN and BGVN reports). Hazard codes are: *S* Surtseyan jetting; *B* base surges; *T* tsunami; *L* lahars; *P* pyroclastic flows; A ash fall; *D* dome growth; and other as explained in the notes

2.1 Surtseyan Jets

Surtseyan jets, also known as "cock's (rooster) tail" or "cypressoid" jets (Fig. 4) are characteristic of subaqueous explosive volcanism (Thorarinsson et al. 1964), and have been observed in a number of lacustrine (Belousov et al. 2000; Belousov and Belousov 2001) and shallow marine settings (Morimoto 1948; Machado et al. 1962; Reynolds et al. 1980). They comprise black jets of tephra and water that are ejected on sub-ballistic trajectories to heights of up to 800 m at velocities exceeding c. 100 m/s, and are produced during discrete explosions in relatively shallow water (<200 m). As the jets cool, they become fringed with white clouds of condensing steam (Fig. 4).

By analogy with conventional (Cole 1948; Kedrinksii 2005) and nuclear (Glasstone and Dolan 1977) explosive tests, detailed observations and analysis of selected eruptions (Belousov et al. 2000; Kilgour et al. 2010), and numerical simulations (Morrissey et al. 2010) a subaqueous volcanic explosion forms a sub-spherical bubble filled with super-heated explosion products including water vapour, magmatic gases and pyroclastic material (Fig. 5). This rises buoyantly towards the surface, expanding as its internal pressure equilibrates with the confining hydrostatic pressure. Ahead of this, the explosion shock wave impinges on the water surface, typically forming a symmetrical spray dome by spallation and cavitation that may rise several hundred metres into the air but which contains a volumetrically insignificant volume of water. The ascending explosion bubble then deforms the water surface above it, forming a rapidly rising dome of water. When this breaches, the explosion bubble vents to the atmosphere. The sudden drop in internal pressure causes the water:gas interface at the bubble's base to rebound, rapidly collapsing the transient cavity and generating vertically- and radially-directed jets as it 'turns inside out' (Fig. 5).

2.2 Base Surges

Base surges are ring-shaped basal clouds (Figs. 4 and 5) that sweep outwards as a dilute density current from the base of a vertical explosion column (Moore 1967). They are produced during subaqueous explosive eruptions principally through disruption of the rim of the transient cavity (Fig. 5), and secondarily by collapse of Surtseyan jets, and move radially outwards as mixtures of pyroclasts, water droplets and steam at typical velocities of 20–65 m/s (Moore 1967;

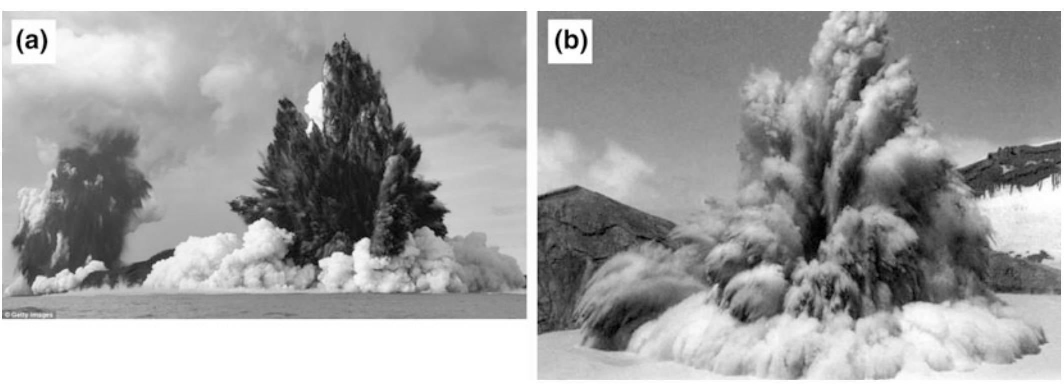

Fig. 4 **a** Surtseyan jets generated during the eruption of a submarine volcano north of Tongatapu in the Tonga Islands rising to >800 m. Darker 'cypressoid' or 'rooster-tail' jets are composed of mixtures of water droplets, gas and pyroclastic fragments, lighter clouds are steam and condensate. A toroidal base surge is propagating out from the base of one of the eruption columns (*Getty images*). **b** Small Surtseyan jet and base surge generated during a minor phreatic eruption, typical of activity during the late 1970s and early 1980s at Ruapehu volcano, New Zealand (Image GNS archive)

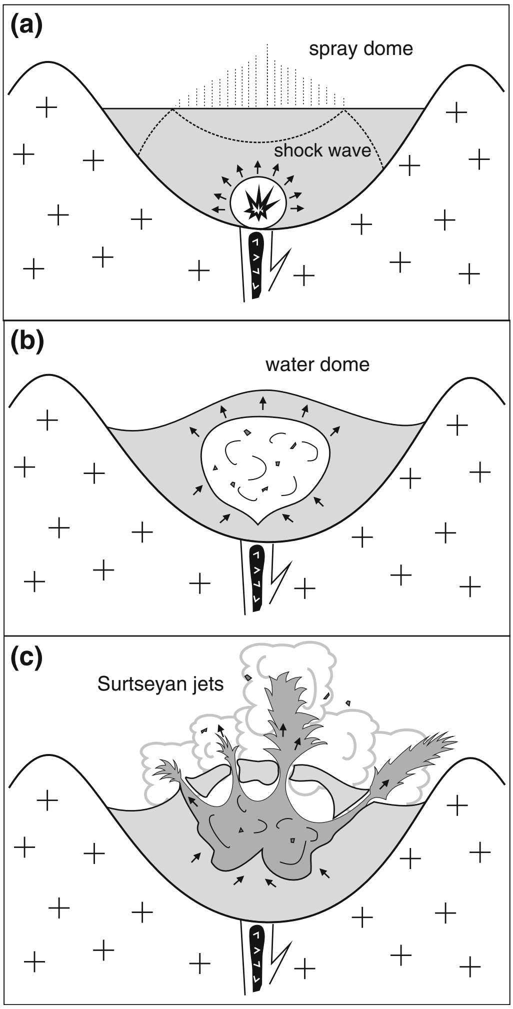

Fig. 5 Inferred sequence of events during a subaqueous explosive eruption. **a** Initial explosion during magma-water mixing: this fuel:coolant reaction generates a shock-wave whose energy is largely reflected off the air:water interface at the lake surface, but still manages to raise a dome of spray. **b** As the explosion bubble of eruption products and water vapour equilibrates with the ambient hydrostatic pressure it expands and rises buoyantly, lifting a semi-spherical dome of water above it. **c** The water dome breaches as it thins and stretches and as the explosion bubble breaches the surface, the sudden drop in internal pressure as the transient cavity vents to the atmosphere causes its base and sides to rebound, generating vertical and radial water jets that entrain the bubble contents and remnants of the water dome

Belousov et al. 2000). Base surges generated at Taal volcano in the Philippines are likely to have been responsible for most of the deaths on Volcano Island during the 1911 eruption, while in 1965 they reached up to 8 km from the vent, depositing surge-bedded dunes proximally and wet-mud aggregates and coatings distally (Moore et al. 1966a, b; Moore 1967). Base surges generated by explosive eruptions through a postulated caldera lake have been suggested as playing a role in the 1790 AD Kilauea eruption that killed 80–300 people (Mastin 1997).

2.3 Seiches

Seiches are standing waves produced in semi- or fully enclosed bodies of water due to resonant amplification of waves initiated by another mechanism (i.e. fluctuations in atmospheric pressure, earthquakes, or tsunami). Under certain circumstances they may be higher and more persistent than the original tsunami: studies at intermontane Lake Tahoe indicate potential seiche run-ups of up to 10 m in response to seismogenic fault offsets of the lake bed (Ichinose et al. 2000). Seiches are also a demonstrated hazard at volcanic lakes: a tectonic earthquake at Taal caldera lake in 1749 destroyed villages and caused fatalities (Newhall and Dzurisin 1988), while seiches of up to 0.5 m were reported at Lake Taupo in response to seismic faulting during earthquake swarms in 1922 and 1983 (Ward 1922; Otway 1986; Webb et al. 1986). Seiches set up by volcanic explosions during the 1965 Taal eruption capsized a number of boats, resulting in a number of fatalities (Moore et al. 1966b).

2.4 Atmospheric Effects—Rain and Lightning

Phreatomagmatic eruptions through volcanic lakes can result in torrential local rain due to steam condensation, potentially aided by nucleation on ash particles, sometimes in association with intense lightning activity (Mastin and Witter 2000). This can contribute to local flood hazards and syn-eruptive reworking of pyroclastic deposits. Examples have been observed at Taal volcano (Moore et al. 1966a, b), and inferred at: (i) Lake Taupo during the Hatepe and Rotongaio phases of the 1800a Taupo eruption (Walker 1981; Smith and Houghton 1995); and (ii) deposition of the Rotomohana Ash during the 1886 eruption at Tarawera (Nairn 1979; Walker et al. 1984).

3 Volcanic Tsunamis

Tsunami triggered by volcanic processes account for 25 % of all volcano-related fatalities since 1783 (Witham 2005), mostly associated with the marine 1883 Krakatau eruption (Carey et al. 2001). A range of triggers have been implicated (Latter 1981), with wave generation typically accomplished by volumetric water displacement (Fig. 6), for example by: a gas-filled explosion bubble (Egorov 2007; Morrissey et al. 2010); pyroclastic flows (Waythomas and Neal 1998; McCoy and Heiken 2000; de Lange et al. 2001; Watts and Waythomas 2003); basin floor displacement; and subaerial and/or subaqueous mass flows including debris avalanches (Johnson 1987; Tinti et al. 2006a; Begét et al. 2008) and landslides (Ward 2001), and lahars (Chrétien and Brousse 1989; Walder et al. 2003). While the greater travel distance of such events is largely irrelevant in the context of confined lake basins, the generating mechanisms remain pertinent.

3.1 Explosion-Generated Tsunamis

During subaqueous volcanic explosions, tsunamis are principally generated during the phase of updoming of the water surface, including the period when the bubble breaches the surface and the uplifted rim of the transient cavity is pushed outwards by its expanding contents (Figs. 5 and 6). Smaller tsunamis are also generated by fallback of Surtseyan tephra jets and coupling of the water surface with atmospheric shock waves and base surges (Latter 1981; Mastin and Witter 2000;

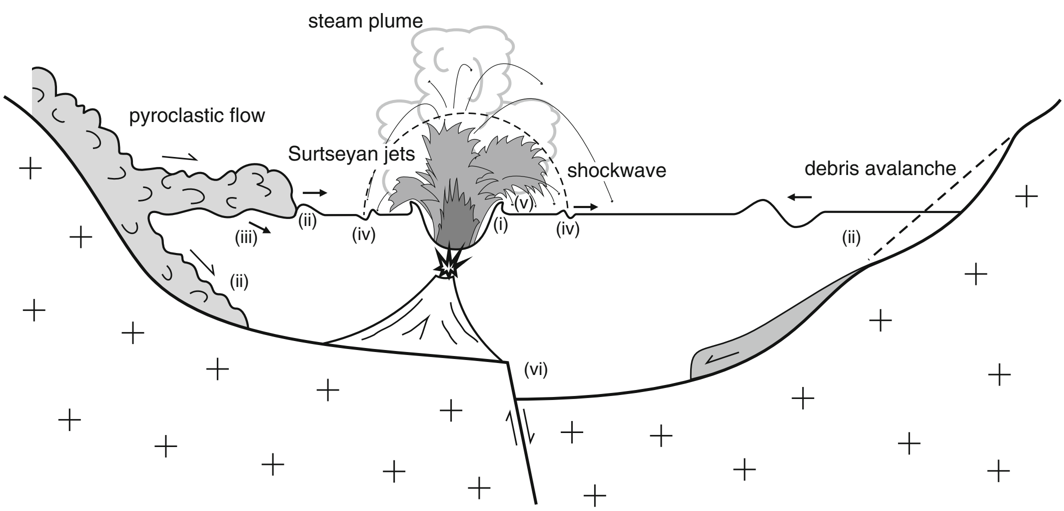

Fig. 6 Tsunami-generating mechanisms associated with volcanic lakes, including subaqueous explosive eruptions. Surface waves may be triggered by upward and lateral displacement of water due to: (*i*) an expanding explosion bubble; and (*ii*) entry, and continued subaqueous movement of an initially subaerial (or wholly subaqueous) gravitational mass flow (pyroclastic flow, landslide, debris avalanche, or major lahar). Other causes include downward and lateral displacement of water caused by: (*iii*) the sinking of material from a segregating pyroclastic flow travelling over the water surface; (*iv*) coupling with a base surge or atmospheric pressure wave; and (*v*) collapse of jetted material. Also, (*vi*) upward or downward displacements due to seismogenic (i.e. rapid) volcano-tectonic movements. Of these only (*i*), (*ii*) and (*vi*) are capable of generating large waves in the far field (Watts and Waythomas 2003)

Watts and Waythomas 2003). Observations of tsunami waves at volcanic lakes are limited to the 1996 Karymskoye Lake eruption (Belousov et al. 2000), minor phreatic events at Ruapehu during the 1970s and 1980s (McClelland et al. 1989), Taal volcano in 1911 and 1965 (Moore et al. 1966a, b), and a number of other crater lakes (Table 1) mainly known for their eruption-triggered lahar record (Mastin and Witter 2000). During the 1996 eruption at Karymskoye Lake "a light gray 'collar' [which] appeared around the focus (epicentre) of the explosion, representing a nearly axially-symmetric elevation of the water surface 130 m high that propagated radially at about 40–20 m/s to form the tsunami" (Belousov et al. 2000). Run-up from these surface gravity waves reached 30 m on adjacent shorelines 1.3 km away from the eruption centre (Belousov et al. 2000; Torsvik et al. 2010). Tsunami run-up deposits have been identified c. 20 m above the contemporaneous lake level at Lake Managua in Nicaragua in association with the 6.3 ka Mateare Tephra eruption (Freundt et al. 2006, 2007), and at Fisher caldera in Alaska (Stelling et al. 2005).

3.2 Pyroclastic Flow-Generated

Pyroclastic flows, comprising hot, gas-rich, debris-laden, ground-hugging free-surface gravity currents that travel laterally away from their sources (Sparks 1976; Druitt 1998), are a common phenomenon associated with explosive volcanic activity and are demonstrably tsunamigenic (Latter 1981; Carey et al. 1996, 2000; Hart et al. 2004).

Most studies of volcanic tsunamis are based on submarine and coastal volcanoes, including the 1883 AD Krakatau eruption in Indonesia (Self and Rampino 1981) which produced proximal tsunami waves up to 35 m high that caused c. 36,000 deaths in coastal areas of Java and Sumatra up to 100 km from the volcano, and were still lethal in Sri Lanka 2,500 km away (Latter 1981; Carey et al. 2000, 2001). Pre-historic tsunami generated by pyroclastic flows entering the sea are known from a number of other regions, including Alaska (Waythomas and Neal 1998) and the Mediterranean, where they are associated with the Minoan eruption of Santorini (McCoy and Heiken 2000).

Pyroclastic flow-triggered lacustrine tsunamis have not been observed in historical times. However, they have been inferred at Lake Managua in Nicaragua where the c. 24 ka Apoyo ignimbrite erupted from a caldera 20 km away is estimated to have entered the lake at volume fluxes of 3×10^6 m^3/s and velocities of 65 m/s (Freundt et al. 2006), and at Lake Tarawera in New Zealand during the c. 1315 AD Kaharoa eruption (Hodgson and Nairn 2005). They will certainly have occurred at many caldera lakes where voluminous explosive activity has produced pyroclastic flows from mid-lake vents, for example during several Holocene eruptions at Lake Taupo (Wilson 1993). Tsunamis with this source mechanism are also implicated in the triggering of break-out floods at a number of Alaskan calderas (Table 2). At Fisher, an eruption at c. 1.5 ka from an mid-lake vent apparently triggered breaching of the southern caldera wall by overtopping waves with run-ups exceeding 20 m (Stelling et al. 2005).

3.3 Debris Avalanches/Landslide-Triggered

Debris avalanches generated by the gravitational collapse of a volcanic edifice are a common phenomenon at stratovolcanoes around the world, occurring on average 4 times per century (Siebert 1984, 1996) due to a range of causes (McGuire 1996). Such failures are highly tsunamigenic (Keating and McGuire 2000), as has been demonstrated at a number of coastal (Siebert et al. 1995; Begét et al. 2008) and island volcanoes (Johnson 1987; Tinti et al. 2006b; Chiocci et al. 2008). For example, the tsunami generated by the 1792 AD collapse of the Mayuyama dome at Shimabara killed an estimated 15,000 people around the shores of the Sea of Japan (Neall 1996; Tanguy et al. 1998).

Table 2 Compilation of known break-out floods from volcanic lakes, including Type II and III events

Volcano	Location	Date	Lake type	Dam type	Hazard type	Dam height (lake depth) m	Lake volume m^3	Breach depth m	Volume released m^3	Peak discharge m^3/s	Notes, references
Ruapehu, New Zealand	Whangaehu River	18 Mar. 2007	Crater	Tephra	III	6.4	1.0×10^7	6.4	1×10^6	530	Followed 1995–1996 eruptions (Manville and Cronin 2007; Manville et al. 2007; Massey et al. 2010)
		24 Dec. 1953	Crater	Ice/tephra	III	20	1.0×10^7	8	1.8×10^6	350	Followed refilling of lake after 1945-46 eruptions. Lahar destroyed Tangiwai railway bridge with loss of 151 lives. (Healy 1954; O'Shea 1954; Manville 2004). Breakouts also inferred in 1925 and 1861 (Manville et al. 2007; Graettinger et al. 2010)
		January 1925	Crater	Ice?	III						Unexplained flood surge on Whangaehu River, the natural outlet to Crater Lake, no eruption observed (Manville et al. 2007)
		13 Feb. 1861	Crater	Ice/tephra	III				6×10^6		Largest lahar in historic sequence, possible break-out. No eruption observed (Manville et al. 2007). All prehistoric lahars post-dating 1800a have been much bigger (Hodgson et al. 2007)
Taupo, New Zealand	Waikato River	c. 1.78 ka	Caldera	Pyroclastic flow	III	34	8×10^{10}	32	2×10^{10}	3×10^4	Followed damming of the outlet gorge by ignimbrite erupted during the 1.8 ka Taupo eruption (Manville et al. 1999)
		c. 24 ka	Caldera	Pyroclastic flow	III	(330)	1.1×10^{11}	80	6×10^{10}	1×10^5	Triggered by headward erosion through ignimbrite shield. Permanently changed course of lower Waikato River. (Manville and Wilson 2004)

(continued)

Table 2 (continued)

Volcano	Location	Date	Lake type	Dam type	Hazard type	Dam height (lake depth) m	Lake volume m^3	Breach depth m	Volume released m^3	Peak discharge m^3/s	Notes, references
Tarawera, New Zealand	Tarawera River	1904	valley	lahar	III	12.8	2.3×10^9	3.3	1.3×10^8	780	Triggered by 3 days of heavy rain 18 years after 1886 eruption. (White et al. 1997; Hodgson and Nairn 2005)
		c. 1315	Valley	Pyroclastic flow/lahar	II	(118)	4×10^9	40	1.7×10^9	5×10^4	Syn-eruptive event breaching composite pyroclastic flow/lahar dam, possibly triggered by pyroclastic flow-generated tsunamis (Hodgson and Nairn 2005). Earlier break-outs are hypothesized on geological grounds (Manville et al. 2007)
Aoba (Ambae), Vanuatu		1916	Caldera	Rim	III						Report of a large flood on SE coast that killed c. 100 linked to possible break-out from Lake Manaro Lakua (Bani et al. 2009)
Kelut, Indonesia		1875	Crater	Rim					3.8×10^7		Cold lahar triggered by failure of crater rim (Schuster 2000)
Raung, Indonesia		1638	Crater	Rim							
Pinatubo, Philippines	Bucao River	10 Jul. 2002	Caldera	Rim	III	(175)	1.6×10^8	23	6.5×10^7	3×10^3	Caldera lake break-out following 1991 eruption generated largest single lahar of post-eruption sequence (Lagmay et al. 2007)

(continued)

Table 2 (continued)

Volcano	Location	Date	Lake type	Dam type	Hazard type	Dam height (lake depth) m	Lake volume m^3	Breach depth m	Volume released m^3	Peak discharge m^3/s	Notes, references
	Pasig-Potrero river	22 Sep. 1994	Valley	Lahar	III						Voluminous pyroclastic flows generated during the 1991 Pinatubo eruption dammed tributaries along multiple radial drainages surrounding the volcano. Break-outs from these ephemeral lakes, which were often re-dammed by secondary pyroclastic flows or lahars were a recurrent hazard in the years after the eruption. Peak discharges reached 1000–5000 m^3/s. In the Pasig-Portero River (east side of Pinatubo), break-outs in 1991 and 1994 killed 7 and 25 respectively and buried several villages including Bacalor. (Arboleda and Martinez 1996; Scott et al. 1996b)
		29 Aug. 1992	Valley	Secondary pyroclastic flow	III						
		7 Sep. 1991	Valley	Pyroclastic flow	III						
	Santo Tomas River	12 Oct. 1991	Valley	Lahar	III					400	The Marella-Mapanuepe junction of the Santa Tomas river system on the west side of Pinatubo was dammed on multiple occasions by lahars flowing down the Marella River. The resulting Lake Mapanuepe grew to a maximum size of 6.7 km^2, 7.5×10^7 m^3 volume, and 25 m depth, breaking out on multiple occasions, until its level was stabilised by construction of an artificial spillway in Nov. 1992 (Rodolfo et al. 1996; Umbal and Rodolfo 1996)
		21 Sep. 1991	Valley	Lahar	III					500	
		25 Aug. 1991	Valley	Lahar	III					650	

(continued)

Table 2 (continued)

Volcano	Location	Date	Lake type	Dam type	Hazard type	Dam height (lake depth) m	Lake volume m^3	Breach depth m	Volume released m^3	Peak discharge m^3/s	Notes, references
	Sacobia River	25 Jul. 1991	Valley	Pyroclastic flow	III						Break-out lahars in the Sacobia River were triggered by failure of primary and secondary pyroclastic flow dams (Scott et al. 1996b)
Parker, Philippines		2002		Landslide	III				2.7×10^7		Breach of the rim in 1995 caused a large flood that undercut and destabilised the outlet walls. An earthquake in 2002 caused further landsliding, blocking the gorge and resulting in another flood (Catane et al. 2005)
		1995		Rim	III				3×10^7		
Bandai, Japan		Apr. 1889	Valley	Debris avalanche	III						The 1888 collapse of Bandai volcano generated a debris avalanche that impounded 5 lakes: Lake Onagawa breached a year later (Schuster 2000)
Asama, Japan	Agatsuma River	5 Aug. 1783	Valley	Pyroclastic flow	III						Pyroclastic flow temporarily blocked river, breaching generated hot lahar that killed 919 people (Aramaki 1956, 1981; Simkin and Siebert 1994; Yasui and Koyaguchi 2004)
Numuzawa, Japan	Tadami River	5 ka	Valley	Pyroclastic flow	III	100	1.7×10^9	70	1.6×10^9	2.7×10^4	Pyroclastic flow from caldera-forming eruption dammed adjacent river valley (Kataoka et al. 2008)
Towada, Japan	Oirase River	12–15 ka	Caldera	Pyroclastic flow	III		1.3×10^{10}	76	6×10^9	2–30 × 10^5	First identified intracaldera lake break-out flood in Japan (Kataoka 2011; Gomez et al. 2012)

(continued)

Table 2 (continued)

Volcano	Location	Date	Lake type	Dam type	Hazard type	Dam height (lake depth) m	Lake volume m^3	Breach depth m	Volume released m^3	Peak discharge m^3/s	Notes, references
Karymskoye, Kamchatka	Karymskaya River	15 May 1996	caldera	tuff ring	III	2.6			3.25×10^7		Tuff cone produced by subaqueous eruption near outlet to Akademiya Nauk intracaldera lake temporarily blocked outlet to the 4 km diameter lake (Belousov and Belousov 2001)
Crater Peak, Alaska	Chakatchatna River	1992	Valley	Lahar	III	10	3.2×10^7	10		$1–8 \times 10^3$	Eruptions from Spurr volcanic complex, including Crater Peak have dammed Chakachatna River at least 5 times in last 10 ka with a combination of lahar and debris avalanche deposits (Waythomas 2001)
		1953	Valley	Lahar	III	20	1.2×10^8	20		$8–15 \times 10^3$	
Spurr Volcano, Alaska		Late Holocene	Valley	Lahar	III	60	4.5×10^8	61		1×10^4	
		Holocene	Valley	Debris avalanche	III	150	1.23×10^9	150		3×10^4	
Iliamna, Alaska	Johnson River	Late Holocene	Valley	Lahar	III						Waythomas (2001)
Novarupta, Alaska		1912	Valley	Pyroclastic flow	III						Tributary valleys blocked by Valley of Ten Thousand Smokes pyroclastic flow and secondary phreatic explosion crater rims. Breaching of a dam formed a pumiceous debris flow deposit with a volume of 3-6 × 10^6 m^3 (Hildreth 1983)
Wrangell Volcano, Alaska	Copper River	Pleistocene	Valley	Debris avalanche	III						Waythomas (2001)
Aniakchak, Alaska	Aniakchak River	c. 3.4 ka	Caldera	Pyroclastic flow		183	3.7×10^9	183	3.7×10^9	1×10^6	Caldera lake break-out flood (McGimsey et al. 1994; Waythomas et al. 1996)
Okmok, Alaska	Crater Creek	1817	Caldera	Scoria cone	III	8	8×10^6	–	–	2×10^3	Minor eruption dammed intracaldera lake. Break-out flood destroyed Aleut village (Wolfe and Begét 2002)

(continued)

Table 2 (continued)

Volcano	Location	Date	Lake type	Dam type	Hazard type	Dam height (lake depth) m	Lake volume m^3	Breach depth m	Volume released m^3	Peak discharge m^3/s	Notes, references
Okmok, Alaska		c. 1.5 ka	Caldera	Pyroclastic flow	II	150	5.8×10^9	150	5.8×10^9	1.9×10^6	Caldera lake break-out (Wolfe and Begét 2002; Begét et al. 2005)
Chiginagak, Alaska	Volcano Creek	May 2005	Crater	Glacier	II		5.4×10^6	45	3.8×10^6		Break-out from acidic crater lake following geothermal melting of ice-cap, sulphuric acid vapour damaged vegetation along flood path (Schaefer et al. 2008)
Fisher, Alaska		1.5 ka	Caldera	Pyroclastic flow	II	100			1×10^{10}		Triggered by overtopping waves generated by explosive eruption through intracaldera lake (Stelling et al. 2005)
Mount Meager, Canada	Lillooet River	2.35 ka	Valley	Pyroclastic flow	III	100	0.25–1×10^9				Block and ash flows and welded pyroclastic flow deposits dammed river valley resulting in staged break-out flood (Hickson et al. 1999)
Uinkaret Volcanic Field	Colorado River	104 ± 12 ka	Valley	Lava flow	III	180	–	–	2.7×10^9	1.7×10^5	Pleistocene eruptions have dammed Grand Canyon with basaltic lava flows on at least 5 occasions (Fenton et al. 2004; Fenton et al. 2006)
		165 ± 18 ka	Valley	Lava flow	III	280			9×10^9	3.8×10^5	
		Pleistocene	Valley	Lava flow	III	302	1.1×10^{10}	302	$1.1 x10^{10}$	5.3×10^5	
Crater Lake, USA	Williamson River	7.7 ka	Valley	Pyroclastic flow	III	21	6.5×10^9	17	5.5×10^9	1.3×10^4	Valley dammed by pyroclastic flow from Mount Mazama eruption (Conaway 2000)
Mount St. Helens	North Fork Toutle River	18 May 1980	Valley	Debris avalanche	III	9.1	0.3×10^6			450	Break-out from Elk Rock Lake tributary dammed by Mount St. Helens debris avalanche (Jennings et al. 1981)

(continued)

Table 2 (continued)

Volcano	Location	Date	Lake type	Dam type	Hazard type	Dam height (lake depth) m	Lake volume m^3	Breach depth m	Volume released m^3	Peak discharge m^3/s	Notes, references
	North Fork Toutle River	19 Mar. 1982	Crater	Snow/ tephra	II		4×10^6			2.6–4.4×10^3	Melting of snow and ice by lateral blast resulted in accumulation of an ephemeral lake that broke out to form a large lahar (Pierson 1997)
	North Fork Toutle River	2.5 ka	Valley	Debris avalanche	III						Break-out from ancestral Spirit Lake (Scott 1988)
Newberry Volcano	Paulina Creek	1860-1730	Caldera	?	III	78	3.2×10^8	2	1.24×10^7	200	Chitwood and Jensen (2000), O'Connor and Beebee (2009)
Medicine Lake Volcano		Late Pleistocene	Caldera	?	II						Possible eruption-triggered break-out from ice-covered caldera lake (Donnelly-Nolan and Nolan 1986)
El Chichón, Mexico	Rio Magdalena	27 May 1982	Valley	Pyroclastic flow	III	75	4.8×10^7	25	1.7×10^7	1.1×10^4	Breaching of pyroclastic flow dam triggered hot lahar 55 days after its emplacement. Flow temperatures reached: 82 °C 10 km downstream and 52 °C at 35 km where 1 person died (Macías et al. 2004). Lake developed in new eruption crater
Volcan de Colima, Mexico	Rio Armeria	3.6 ka	Valley	Debris avalanche	III		0.4×10^9				Córtes et al. (2010)
Colima, Mexico	Naranjo River	Pleistocene	Valley	Debris avalanche	III	150	1×10^9	150	1×10^9	5.7×10^5	Break-out bulked with material eroded from dam to form massive lahar with peak discharge of 3.5×10^6 m^3/s. (Capra and Macías 2002)
Santaguito (Santa Maria), Guatemala	Nimá I	Nov. 1983	Valley	Lahar	III						Lahars in Nimá II blocked Nimá I River, before a spillway could be completed the lake broke-out destroying several dozen houses (McClelland et al. 1989).

(continued)

Table 2 (continued)

Volcano	Location	Date	Lake type	Dam type	Hazard type	Dam height (lake depth) m	Lake volume m^3	Breach depth m	Volume released m^3	Peak discharge m^3/s	Notes, references
	Nimá I, Nimá II and Tambo Rivers	24 Jul. 1978	Valley	Pyroclastic flow	III						Block and ash flows erupted on 23 Jul dammed 3 rivers, break-outs the next day destroyed farms and damaged bridges. (McClelland et al. 1989)
Nevado del Huila, Colombia	Paèz River	Late Pleistocene	Valley	Debris avalanche	III	150	0.5×10^9				Breaching of dam generated a 100 m deep lahar that bulked by a factor of 3.2 and travelled more than 67 km downstream (Pulgarin et al. 2004)
Antuca, Chile	Rio Laja	9.7 ka	Valley	Debris avalanche	III						Thiele et al. (1998)
Mt Pelee, Martinique	Rivière Blanche	5 May 1902	Crater	Rim	II	–	–	–	5×10^6	–	Rim of l'Etang Sec crater failed due to eruption (or explosively ejected water). 23 fatalities (Chrétien and Brousse 1989)
Eyjafjallajökull, Iceland	Markarfljót River	15 April 2010	Englacial	Ice	II	–	–	–	$4\text{-}8 \times 10^6$	$5\text{-}15 \times 10^3$	Largest of a complex series of lake drainages Magnússon et al. (2012). Similar floods in 1612, 1821-23 Björnsson (2002)
Grimsvötn, Iceland	Gígjukvísl River, Skeidárasandur	4-5 Nov. 1996	Englacial	Ice	II	(175)			3.2×10^9	5.3×10^4	Triggered by subglacial Gjálp eruption (Gudmundsson et al. 1997; Tweed and Russell 1999)
	Skeidárasandur	1938	Englacial	Ice	II				4×10^9		Triggered by subglacial fissure eruption (Björnsson 2002).
Oraefajökull, Iceland		1727	Subglacial	Ice	III	–	X	–	–	–	
		1362	Subglacial	ice	II		X			1×10^5	Flood lasted < 1 day and destroyed several farmsteads.

(continued)

Table 2 (continued)

Volcano	Location	Date	Lake type	Dam type	Hazard type	Dam height (lake depth) m	Lake volume m^3	Breach depth m	Volume released m^3	Peak discharge m^3/s	Notes, references
Katla, Iceland	Mýrdalssandur	12 Oct. 1918	Subglacial	ice	II				5×10^9	2.8×10^5	Tómasson (1996). Similar events have occurred in 1179, 1311, 1660 and 1721.
Kverkfjöll/ Bárdarbunga, Iceland	Jökulsá á Fjöllum	Holocene	Subglacial	Ice	II					9×10^5	Alho et al. (2005), Howard et al. (2012)
Laacher See, Germany	Rhine River	12.9 ka	Valley	Pyroclastic flow	III	15			9×10^8	1×10^4	Neuwied Basin backflooded, break-out flood deposits can be traced 50 km downstream to Bonn (Park and Schmincke 1997; Schmincke et al. 1999; Baales et al. 2002)

Data principally derived from Simkin and Siebert (1994), Newhall and Dzurisin (1988), and Manville (2010)

Lacustrine tsunamis generated by landslides, rockfalls and icefalls are well known, and are often implicated in the failure of natural landslide and moraine dams (Lliboutry et al. 1977; Hermanns et al. 2004; Kershaw et al. 2005). Volcanogenic examples are less frequent (Table 1), but the most notable historic case is the 18 May 1980 debris avalanche at Mount St. Helens, which entered Spirit Lake (itself the product of valley-damming by a prehistoric flank collapse) to generate a wave with a run-up of 260 m (Voight et al. 1981). In 1999, a relatively small (150,000 m^3) landslide from the crater walls of the Quaternary Kasu tephra cone in the highlands of Papua New Guinea displaced 5–10 % of the lake's volume, triggering a 15 m high wave that overtopped a low point on the crater rim killing one person (Wagner et al. 2003). At Fernandina volcano in the Galapagos, c. 1 km^3 of the caldera rim collapsed forming a debris avalanche that displaced the existing 2 km wide shallow intracaldera lake to the N and NW as a tsunami in 1988 (SEAN 13:10). Collapse of a geothermally-weakened fault scarp at the southern end of Lake Taupo in 1846 AD generated a lethal debris avalanche that triggered a small tsunami when it entered the lake (Hegan et al. 2001).

Prehistoric tsunamis induced in volcanic lakes by mass movements are inferred at Lake Managua, Nicaragua, where two recent debris avalanche deposits from Volcán Mombacho penetrate up to 7 km into the lake to form small islands (Freundt et al. 2007).

3.4 Lahar-Triggered

Lahars entering volcanic lakes are also tsunamigenic if they are sufficiently rapid and voluminous (Walder et al. 2006): the 18 May 1980 Pine Creek lahar at Mount. St. Helens generated a 0.4 m high wave on Swift Reservoir 22.5 km away from its entry point (Pierson 1985). During the May 1902 eruption of Soufrière St. Vincent, a lahar triggered by collapse of the crater rim of L'Etang Sec generated a 3–4 m high tsunami when it reached the sea (Chrétien and Brousse 1989). Similarly, very large and fast jökulhlaups have produced waves in coastal waters around Iceland (Björnsson 2002).

3.5 Earthquake-Triggered

Tectonic movements on faults crossing volcanic lakes can cause displacements sufficient to generate tsunami or excite seiches, whether related to volcanic activity or not. Recorded examples include at Taal in 1749 AD, where villages were destroyed and lives lost (Newhall and Dzurisin 1988), and at Lake Taupo in association with historic earthquake swarms (Ward 1922; Otway 1986; Webb et al. 1986).

4 Limnic Gas Eruptions

A special hazard at volcanic lakes, and some other major volcanically-influenced water bodies such as Lake Kivu (Nayar 2009), is the explosive exsolution of dissolved magmatic gases, principally CO_2 and methane, which accumulate in the water column (Tazieff 1989). Eruptions can be driven by over-saturation, climatic conditions, landslides into the lake, or volcanic activity. In 1984 a gas burst from Lake Monoun killed 37 people (Sigurdsson et al. 1987), and was followed 2 years later by the Lake Nyos disaster in the same country (Kling et al. 1987; Barberi et al. 1989; Tazieff 1989). Lake Nyos is a small (1,925 × 1,180 m) water body hosted in a maar-diatreme crater. On 21 August 1986, a small landslide into the 208 m deep lake triggered overturn and the catastrophic release of 0.3–1 km^3 of CO_2 which overflowed the crater outlet and travelled over 10 km downstream as a dense, suffocating flow. Water surges triggered by the gas release caused waves that washed up to 25 m above the lake shoreline and 6 m deep over the outlet (Kling et al. 1987).

5 Volcanogenic Floods from Volcanic Lakes

Volcanic lakes are prone to sudden and catastrophic releases of water, either directly as a result of explosive volcanic activity (Table 1), or due to failure of their impoundments following active (i.e. eruption-triggered) or passive (i.e. overfilling) overtopping and runaway erosion (Table 2). In either case, the combination of large volumes of water, significant topographic elevation, and abundant pyroclastic material available for remobilisation makes such events particularly hazardous as they tend to travel down existing river valleys, which are frequently the locus of extensive populations.

Crater lakes, developed in pits excavated by explosions above volcanic vents, are prone to explosive (ballistic) ejection or displacement (including by waves) during eruptive activity. Consequently, primary eruption-triggered lahars from such water bodies have been one of the most lethal historic volcanic hazards (Table 1).

5.1 Eruption-Triggered Lahars

The summit of the stratovolcano of Mt. Kelut (1,731 m) on the Indonesian Island of Java is occupied by a crater lake that has been the source of multiple eruption-triggered lahars that have claimed tens of thousands of lives over the past millennium. Initial explosive phases of VEI-4 eruptions, occurring at mean intervals of 13 years (range 8–18) have ejected up to 40×10^6 m^3 of water in a matter of seconds, before progressing to Vulcanian eruptions, sometimes accompanied by pyroclastic flows. The resulting lahars have devastated the densely populated Plains of Blitar, destroying villages and killing tens of thousands since records began in c. AD 1000 (van Padang 1951; Zen and Hadikusumo 1965). In May 1848 an eruption caused partial breaching of the crater rim, releasing 48.7×10^6 m^3 of water (Neall 1996). Similar events (Table 1) are reported at Galunggung, Kaba, Raung, and Ijen (Mastin and Witter 2000).

The summit crater of Mt. Ruapehu, New Zealand's largest and most active onshore andesitic stratovolcano, hosts a hot acidic lake at an elevation of c. 2,530 m. Primary lahars have accompanied all large historic eruptions through the explosive ejection of Crater Lake water over the rim (Fig. 1a), and volumetric displacement (Healy et al. 1978; Nairn et al. 1979; Cronin et al. 1997), sometime forming unusual snow slurry lahars (Kilgour et al. 2010). Secondary lahars have been triggered by heavy rain on ash deposits (Cronin et al. 1997; Hodgson and Manville 1999), while break-out lahars have followed magmatic eruptions by a decade (Manville et al. 2007) (see below).

5.2 Floods Triggered by Tsunami

During the 1996 eruption of Karymskoye in Kamchatka, tsunamis triggered by subaqueous explosive eruptions caused water to surge over the outlet from the lake as a series of waves, triggering flooding along the Karymskaya River with a maximum discharge of 500 m^3/s (Belousov and Belousov 2001). Similar lahars have been observed at Ruapehu where explosions have also displaced water over the outlet area when the lake has been full during eruptions (Cronin et al. 1997; Kilgour et al. 2010).

5.3 Floods Triggered by Lake Floor Displacement

Volcano-tectonic uplift of basin floors has been implicated as a factor in the generation of a number of volcanic floods. This may occur through emplacement of a subaqueous lava dome or shallow intrusion, or through inflation of a shallow magma chamber, although it has been argued that even a significant magma intrusion event would produce negligible surface deformation at a caldera lake like Taupo (Ellis et al. 2007). Rates of water displacement by subaqueous intrusion of lava domes are limited by the effusion rate, which is typically 1–10 m^3/s.

Higher rates may be associated with inflation of a shallow magma chamber, either due to injection of a hot slug of basaltic magma or runaway vesiculation at its top, or thermal expansion of groundwater.

A historical flood of this type from an intracaldera lake occurred at Ilopango Caldera, El Salvador (Goodyear 1880; Newhall and Dzurisin 1988; Richer et al. 2004). The present lake occupies a nested rectangular caldera most recently modified by eruption of the Tierra Blanca Joven ignimbrite in AD 479 (Rose et al. 1999). In January 1880, subaqueous eruption of a dacitic lava dome raised the level of the 108 km^2 lake by 1.2 m (Goodyear 1880) over a period of 5 days. Increased overflow through the narrow outlet channel of the Río Desagüe caused rapid downcutting, with the lake level falling by 9.2 m between 12 and 20 January. Peak discharges are estimated at c. 3×10^3 m^3/s based on drawdown rates of c. 0.1 m/h, resulting in destruction of the downstream town of Atusulca (Newhall and Dzurisin 1988; Richer et al. 2004). By 8 February the lake had fallen by an additional 2.6 m, corresponding to a total water loss of 1.2×10^9 m^3.

Displacement of the floor of Crater Lake, Ruapehu, during the 1995 eruption sequence is recorded by a stage hydrograph on the single outlet channel 58 km downstream at Karioi. The data shows a complex series of transient, spiky, primary explosion-triggered lahars superimposed on a broad trend lasting c. 14 days with a peak discharge of c. 30 m^3/s that is inferred to represent steady uplift of the lake floor by rising magma (Cronin et al. 1997). Total displacement by this uplift is estimated at c. 6×10^6 m^3, representing half the volume of the pre-eruption lake, and a volume equivalent to that expelled by explosive ejection over the rim and outlet. An alternative explanation is that this represents superposition of the exponential waning limbs of individual eruption-triggered flows. Water displacements are also associated with the October 2006 (Kilgour et al. 2007) and September 2007 (Kilgour et al. 2010) phreatic events at Ruapehu, where increased lake level has also been associated with injection of water from the sub-lake hydrothermal system (Christenson and Wood 1993; Christenson et al. 2010).

5.4 Jökulhlaups

A special class of potentially hazardous volcanic lake comprises sub-glacial water bodies, breakouts from which, termed jökulhlaups, have been identified as the most frequently occurring volcanic hazard in Iceland where a number of large basaltic calderas filled with subglacial lakes lie beneath the Vatnajökull and Mýrdalsjökull icecaps (Björnsson 1975, 1992; Tómasson 1996; Björnsson 2002). Most such floods are relatively small, and result from semi-periodic accumulation and drainage of geothermally sustained subglacial lakes. However, larger, less frequent events with peak discharges in the range 10^3–10^5 m^3/s are associated with major subglacial volcanic eruptions that create transient lakes or overfill existing ones (Tómasson 1996; Gudmundsson et al. 1997; Tómasson 2002; Carrivick et al. 2004). Despite being functionally a class of glacier-lake breakout because the outflow hydrograph is controlled by the glacier not the volcano (Walder and Costa 1996; Clarke 2003), they are included here since the lake is the result of volcanic activity. Volcanogenic floods generated by the melting of snow and ice (Pierson et al. 1990) are however excluded unless a transient lake is developed (Waitt et al. 1983; Pierson 1997). In the latter case, a directed blast from the Mount St. Helens lava dome on 19 March 1982 dynamically mixed hot pyroclastic debris with snow and ice in the crater basin. A meltwater lake developed within tens of minutes to cover an area of 0.3 km^2 to a depth of 8–15 m, as indicated by rafted pumice blocks and mudlines, before simultaneously breaching through outlet channels on either side of the lava dome. The lake held c. 4×10^6 m^3 of water at its highstand, but the total outflow was considerably more as contributions from snowmelt continued during lake drainage. Combined peak discharge for the two spillways is estimated at 2.6–4.4 × 10^3 m^3/s: bulking and transformation to debris flow increased this to 9 × 10^3 m^3/s by 6 km downstream.

6 Non-volcanogenic Floods from Volcanic Lakes

In addition to the volcanogenic triggering of break-out floods from volcanic lakes, these water bodies are also vulnerable to non-volcanic breaching of their impoundments, resulting in partial or total drainage of the whole basin. Newly created volcanic lakes are particularly vulnerable to breaching as they fill with meteoric water due to the inherent instability of their dams, which are typically constructed of unconsolidated, often low density material, and without the benefit of engineered spillways. Failure of the volcanic dam or basin rim can occur due to either overtopping or piping from within (Waythomas et al. 1996; Massey et al. 2010) or headward erosion of an external drainage (Karátson et al. 1999). A review of the geological literature reveals that such floods are a relatively common phenomena worldwide (Table 2).

6.1 Crater Lakes

The best characterised example of a passive break-out from a Crater Lake is at Mt. Ruapehu, New Zealand. Following the 1995–1996 sequence that emptied the Crater Lake during a series of initially phreatic, phreatomagmatic and then purely magmatic eruptions (Nakagawa et al. 1999), the lake basin refilled with precipitation run-off and fumarolic condensate over the following 11 years. On 18 March 2007, the rising Crater Lake breached the tephra dam following destabilisation of its downstream face by piping flow (Massey et al. 2010); releasing c. 1.3 million m^3 of water in less than 2 h (Manville and Cronin 2007). The flood bulked up through entrainment of snow, ice, colluvium, and older lahar deposits in the Whangaehu Gorge to form one of the largest lahars of the historical sequence (Carrivick et al. 2009; Graettinger et al. 2010; Procter et al. 2010; Lube et al. 2012). No lives were lost during this event owing to improvements in knowledge and monitoring, in contrast with the 1953 Tangiwai lahar that claimed 151 lives (Healy 1954; O'Shea 1954). This break-out was triggered by collapse of an unstable barrier composed of volcanic material deposited during the 1945 eruption and buttressed by the Crater Basin Glacier (O'Shea 1954; Manville 2004). Approximately 1.8 × 10^6 m^3 of 26 °C water was released into the headwaters of the Whangaehu River over a period of 1–2 h following piping failure of the tephra dam (Fig. 7a). The flow rapidly entrained snow, ice, and volcanic debris and alluvium to transform into a debris- to hyperconcentrated flow that critically damaged a railway bridge 39 km downstream at Tangiwai (Fig. 7b), resulting in the loss of 151 lives (O'Shea 1954; Stilwell et al. 1954). Palaeohydraulic analysis indicates that the peak discharge from Crater Lake was c. 350 m^3/s, bulking to 2,000 m^3/s by 10 km downstream (Manville 2004) and attenuating to c. 590–650 m^3/s at Tangiwai.

Other historic non-volcanic floods from crater lakes include the 1875 non-volcanic failure of 60 m of the western rim of Mt. Kelut (Table 2), which collapsed during heavy rain releasing a lethal cold lahar and changing the principle lahar path to the southwest (Suryo and Clarke 1985). Elsewhere in Indonesia, break-out of a crater lake has been correlated with a devastating flood in AD 1638 at Raung (van Padang 1951).

A mudflow and flood in 1541 AD that destroyed part of the former capital of Guatemala, Ciudad Vieja, claiming >1,300 lives has been attributed to collapse of the crater rim of Agua following a period of torrential rain (Mooser et al. 1958; Neall 1996). No lake was reported in the crater prior to this event, although it is possible that an ephemeral water body formed and failed due to the intense precipitation.

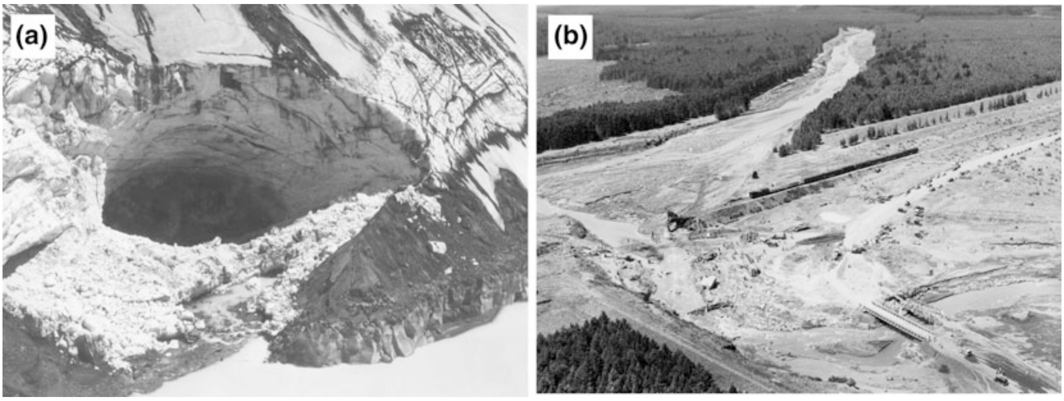

Fig. 7 **a** Breach in tephra dam/glacier ice resulting from the 24 December 1953 break-out of Ruapehu's Crater Lake. Mouth of ice tunnel is c. 50 m wide and 30 m high. Remnants of tephra dam visible to *left* of breach. (GNS archive). **b** Oblique aerial view of Tangiwai, 38 km downstream from Crater Lake. The lahar came from the *top* of the picture and partially destroyed the railway bridge just before the Wellington-Auckland express train arrived [Archives New Zealand, R5, W2279/13, 300/1607]

An unusual mechanism for generating a crater lake break-out has been inferred for the c. 2.5 km diameter Albano composite maar in Italy (Funiciello et al. 2003; De Benedetti et al. 2008). In Roman times, the lake stood some 70 m higher than its current surface elevation of 293 m, coincident with the low point of the topographic rim, which also forms the apex of a 60 km^2 outwash fan of laharic deposits. This fan indicates at least two catastrophic water releases from the lake during the Holocene (Funiciello et al. 2003), while Roman archives record an overspill event in 398 BC (De Benedetti et al. 2008). Both authors speculate that during climatic highstand periods, seismically-triggered injections of CO_2-rich hydrothermal fluid into the groundwater and lake bed triggered dramatic rises in lake level accompanied by overspill and partial failure of the crater rim.

6.2 Caldera Lakes

Historical examples of break-out floods from caldera lakes include Pinatubo, in the Philippines, in 2002. The 5–7 km^3 DRE eruption of Pinatubo in June 1991 formed a 2.5 km wide summit caldera that accumulated a lake over the following decade (Stimac et al. 2004). As the lake approached the low point on the rim (960 mASL) a crisis developed due to recognition of the potential for catastrophic breaching and the release of a huge lahar into the heavily populated Balin-Baquero catchment. During August-September 2001 a trench was dug by hand through the unconsolidated 1991 pyroclastic deposits forming the upper part of the rim in an attempt to trigger a controlled break-out, or at least prevent a further rise in lake level (Lagmay et al. 2007). However, outflow through the trench was too slow to produce a controlled breach. Failure of the caldera rim was delayed until 10 July 2002 when Typhoon Gloria delivered 740 mm of rain to the Pinatubo area (Bornas et al. 2003). Approximately 65 × 10^6 m^3 of water was released at up to 3,000 m^3/s, lowering the lake level by 23 m and eroding a V-shaped notch in the caldera rim. Downstream bulking of the flow with abundant pyroclastic debris from the 1991 eruption generated the largest lahar of the entire post-Pinatubo sequence, aggrading the Bucao River valley by 3–5 m and threatening the town of Botolan (population 40,000).

Subaqueous eruption of a tuff ring in Karymskoye lake, Kamchatka, on 3 January 1996 generated not only primary lahars through the explosive displacement of lake water, but also temporarily blocked the outlet to the 4 km diameter Akademiya Nauk caldera (Belousov and Belousov 2001). After rising by 2.6 m, the 12.5 km^2 lake breached the pyroclastic barrier on 15 May 1996, triggering a flood that deposited a small fan downstream of the outlet gorge.

The c. 10 km diameter Aniakchak caldera was formed by a major ignimbrite emplacing eruption at c. 3.4 ka on the Alaskan peninsula (Miller and Smith 1977). Post-eruption, the closed topographic depression (Fig. 8) was partially filled by an intracaldera lake that rapidly drained following failure of the caldera rim, releasing c. 3.7×10^9 m^3 of water at a peak rate of 7.7×10^4 to 1.1×10^6 m^3/s and cutting a 183 m deep notch (McGimsey et al. 1994; Waythomas et al. 1996). Highstand terraces indicate that the lake was close to its maximum capacity before the breakout, suggesting failure was initiated by overtopping, possibly triggered by tsunamis or water displacement during an intracaldera eruption. Similar scenarios have been reconstructed at the Fisher (Stelling et al. 2005) and Okmok (Almberg et al. 2003) calderas in Alaska, and at Towada volcano in Japan (Kataoka 2011) on the basis of geological and geomorphic evidence (Table 2).

Lake Taupo, the largest lake in the central North Island of New Zealand partially occupies a volcano-tectonic collapse structure whose present configuration largely reflects caldera collapse during the 26.5 ka Oruanui eruption and faulting and downwarping on regional structures (Davy and Caldwell 1998; Wilson 2001). The 530 km^3 DRE Oruanui eruption destroyed a long-lived Pleistocene lake system and deposited hundreds of metres of unwelded pyroclastic deposits around the collapse caldera to produce a closed topographic depression (Wilson 2001; Manville and Wilson 2004). Following the eruption, water in Lake Taupo accumulated to reach a highstand elevation of c. 500 m, as marked by an irregularly preserved shoreline terrace (Grange 1937; Manville and Wilson 2003, 2004). Overtopping caused an initial overspill and 10–20 m drop to a level controlled by a resistant sill of welded ignimbrite, allowing development of another palaeoshorelines terrace. Some time before 22 ka, headward erosion through non-welded pyroclastic flow deposits 20 km to the east breached the caldera rim, releasing an estimated 60 km^3 of water in a break-out flood peaking at 3.5×10^5 m^3/s (Manville and Wilson 2004). During the 1800 a Taupo eruption, the outlet gorge from the lake was blocked by voluminous pyroclastic flow deposits (Wilson and Walker 1985) while much of the pre-eruption lake was expelled, evaporated, or drained into a sub-rectangular caldera collapse structure (Davy and Caldwell 1998). Over a period of several decades (Wilson and Walker 1985; Smith 1991a), the

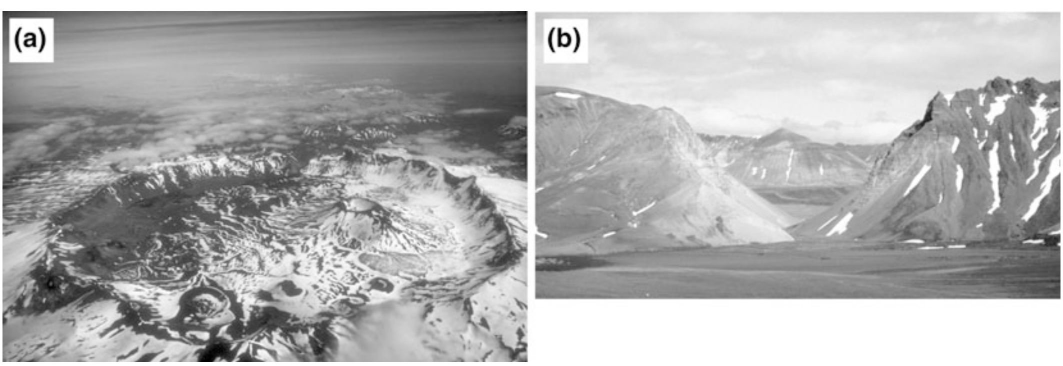

Fig. 8 Aniakchak caldera in Alaska formed at c. 3.4 ka: the intracaldera lake later breached to produce the largest known Holocene terrestrial flood, releasing 3.7×10^9 $m^3$of water at a peak discharge of up to 1×10^6 m^3/s (Waythomas et al. 1996). **a** Aniakchak caldera looking east, diameter c. 10 km (Image M. Williams, National Park Service 1977). **b** 'The Gates' the c. 200 m deep breach cut in the rim of the Aniakchak caldera by the break-out flood (*Image* C.A. Neal, USGS)

lake refilled to a mean highstand level of +34 m above the modern elevation of 357 m, as marked by a semi-continuous, tectonically warped and offset wave-cut bench and highstand shoreline deposit (Wilson et al. 1997; Riggs et al. 2001; Manville and Wilson 2003). Failure of the 12 km long unconsolidated pumiceous pyroclastic dam was initiated by overtopping, and is inferred to have been catastrophic based on the absence of intermediate shoreline terraces between the highstand and a wave-cut bench at +2–5 m (Manville et al. 1999), releasing c. 20 km^3 of water in a single phase. Flood deposits can be traced for over 220 km downstream from Lake Taupo (Manville et al. 1999; Manville 2002), and include: a 12-km-long vertical-walled spillway immediately downstream of the outlet floored with lithic gravel and boulder lags; streamlined landforms sculpted from older deposits and exhumed river terraces; bouldery fan deposits and expansion bars downstream of valley constrictions; fine-grained slackwater deposits in off-channel embayments and hydraulically ponded depressions; valley-wide erosional unconformities; and buried forests in distal areas.

6.3 Pyroclastic Dams

As well as impounding water bodies within the depressions of erupting volcanic centres, pyroclastic material emplaced laterally by pyroclastic flows and surges, or by vertical fallout from Plinian or ballistic eruptions can dam existing valley systems at varying distances from the active volcano.

The 1991 Pinatubo eruption in the Philippines generated proximal pyroclastic flow deposits up to 200 m thick that locally dammed numerous catchments (Scott et al. 1996a). Most lakes were shallow and short-lived, failing by overtopping during the 1991 wet season, but others filled and failed repeatedly as secondary pyroclastic flows and/or lahars rebuilt barriers at late as 1994 (Table 2).

Pyroclastic flows emplaced by the March-April 1982 eruption of El Chichón in southern Mexico partially filled the drainage network on and around the volcano, blocking the adjacent Río Magdalena with deposits up to 30 m thick and 300–400 m wide that extended for c. 1 km along the valley (Silva et al. 1982; Macías et al. 2004). By the time the dam failed by overtopping on 26 May it impounded a 5 km-long lake with a volume of 48 × 10^6 m^3 that reached boiling temperatures due to its contact with 650 °C pyroclastic material. Drainage is estimated to have taken c. 2 h, generating a scalding flood that cooled from 82 °C at 10 km downstream to 52 °C at a hydroelectric plant 35 km downstream where a worker was killed. Peak discharge was estimated at 1.1 × 10^4 m^3/s (Macías et al. 2004), while the break-out deposits covered 5 km^2 and thinned from 8.5 to 2 m distally. Deposit sedimentology indicates that the flow evolved from clear-water, through hyperconcentrated flow to debris flow (Costa 1988). This event resembles an oral legend of a hot flood in the same area centuries before (Duffield 2001).

In 1912, the largest pyroclastic eruption of the 20th Century occurred in the Valley of Ten Thousand Smokes in Katmai National Park in Alaska (Hildreth 1983). A chain of secondary phreatic explosion craters impounded a 1.5 km long supra-ignimbrite lake that failed in the summer of 1912 or 1913. The resulting flood scoured the surface of the pyroclastic flow deposit to a depth of 1–2 m, transported 0.5 m diameter blocks of welded tuff over 20 km, and aggraded the lower parts of the valley by 1–8 m (Hildreth 1983). The eruption at Katmai also created a small caldera, now occupied by a lake. As the rate of filling has slowed markedly since the 1950s a break-out is considered unlikely (Motyka 1977).

The eruption of Asama, Japan, in 1783 AD dammed the Agatuma-gawa River with a block-and-ash flow. Breaching of the dam resulted in a catastrophic flood that destroyed over 1,200 houses and killed an estimated 1,300 people (Aramaki 1981; Yasui and Koyaguchi 2004).

Emplacement of the 30 km^3 Taupo ignimbrite over an area of 20,000 km^2 radially disposed around the vent also blocked numerous other catchments, leading to the development of multiple supra-ignimbrite lakes (Smith 1991b; Manville et al. 2005), the largest of which impounded c. 1.5 × 10^9 m^3 of water over an area of 190 km^2 in the Reporoa Basin (Manville 2001). Further lakes formed in areas where river valleys were dammed by distal pyroclastic flow lobes (Segschneider et al. 2002). Overtopping failure of these lakes likely generated break-out floods and is believed to have contributed to the re-establishment of drainage systems (Meyer and Martinson 1989; Manville 2002). In more distal areas, aggradation by lahars also dammed tributaries to form numerous shallow, ephemeral lakes.

The eruption of the Laacher See volcano at 12.9 ka, the largest late Quaternary eruption in central and western Europe, blocked the Rhine River to a depth of at least 15 m by a combination of primary pyroclastic flows that travelled down tributary valleys and reworked pyroclastic fall material from the lower Neuwied Basin (Park and Schmincke 1997; Baales et al. 2002). Six km upstream of the gorge blockage site an ephemeral lake developed in the Neuwied Basin proper, covering 80–140 km^2 at its maximum as marked by highstand rafts of floated pumice c. 15 m above the pre-eruption land surface. The lake is inferred to have failed catastrophically by earthquake shaking during late stage explosions from Laacher See (Park and Schmincke 1997), releasing an estimated 9 × 10^8 m^3 of impounded water in a flood that scoured channels floored by dense lag deposits in the Neuwied Basin as it drained and deposited fluvially-reworked pyroclasts for over 50 km downstream as far as Bonn.

6.4 Lava Flow Dams

Lava flows are eminently capable of blocking river valleys owing to their downslope flow and physical properties and dimensions. Lava flows emplaced during the 1846–1847 eruptions of Volcán Quizapu in Chile blocked a number of tributaries of the Rio Blanquillo (Hildreth and Drake 1992). In 1932 a pumiceous lahar accompanying an eruption triggered break-out and permanent drainage of the Lagunas del Blanquillo, causing much damage downstream on the Río Maule: concerns had been expressed about the dam-break hazard from these lakes as early as 1916.

Eruption of a rhyolitic lava flow at 23 ka dammed the 25 × 15 km Laguna del Maule intracaldera lake basin in Chile, raising the lake level by 160 m. A single sharp strandline suggests rapid break-out of the lake, while its catastrophic nature is indicated by a narrow gorge cut through the lava and boulder bars and scablands below the gorge outlet (Hildreth, pers. comm. 2004).

Basaltic lava flows have dammed a number of rivers in the western United States (Ely et al. 2012). As well as rivers in Arizona, Idaho, Oregon, and Washington, the Colorado River in the western Grand Canyon in Arizona has been dammed at least 13 times in the last 1.2 Ma (Hamblin 1994; Fenton et al. 2002). Evidence for catastrophic failure of some of these dams has been presented by Fenton et al. (2002, 2003), who argued that emplacement of basaltic lava erupted from the Uinkaret Volcanic Field adjacent to the canyon on unstable talus slopes and alluvium deposits, in addition to the hyaloclastic foundations of the flows formed through interaction of the lava with river water, made the blockages inherently unstable. At least 5 lava dams failed catastrophically between 100 and 525 ka, depositing flood gravels 20–110 m thick between 53 and 200 m above current river level and up to 53 km downstream from the inferred dam site (Fenton et al. 2003). Sedimentary evidence of large scale floods from these break-outs includes downward fining boulder deposits with maximum clast dimensions of up to 35 m, giant cross-beds (up to 45 m high foresets), slackwater deposits, and high-water markers that decline exponentially in elevation downstream of the dam site. The Qfd4 unit flood at 165 ± 18 ka resulted from failure of a 280 m high dam impounding an estimated 9 km^3 of water: peak outlet discharge is estimated as 2.8–4.8 × 10^5 m^3, declining to 1.6 × 10^5 m^3/s by 59 km downstream (Fenton et al. 2003). The youngest flood event, Qfd5 at 104 ± 12 ka, resulted from failure of a 180 m high dam with a reservoir volume of 2.7 km^3 to give an estimate peak discharge of 1.4–2 x 10^5 m^3/s. Non-catastrophic breaching of many valley lava flow dams occurred over thousands of years following filling of the impoundment with sediment (Crow et al. 2008; Ely et al. 2012).

Late Pleistocene basaltic lava flows erupted from the Fort Selkirk area in Canada dammed the Yukon River to a depth of c. 30 m, representing the most recent volcanic blockage of this drainage: distinctive pillow lavas are interpreted as representing lava emplacement into standing water (Huscroft et al. 2004). A coarse unit composed of basalt boulders >1 m in diameter outcropping 6 km downstream of the inferred dam site are interpreted as the product of a catastrophic breaching of the barrier.

6.5 Debris Avalanche Dams

The growth of a volcanic edifice is typically limited by the gravitational stability of its cone, with periods of instability experienced as a consequence of both endogenous and exogenous factors (Siebert 1984; McGuire 1996). Structural failure can then be triggered by other factors such as tectonic or volcanic earthquakes (Vidal and Merle 2000) or pore fluid pressure changes induced by magma intrusion (Iverson 1995). Such failures typically generate massive landslides, or debris avalanches (Glicken 1998; Siebert 1996), with the largest terrestrial examples having volumes of c. 30 km^3 (Stoopes and Sheridan 1992).

The May 1980 eruption of Mount St. Helens in the western USA was accompanied by emplacement of a 2.3 km^3 debris avalanche deposit following gravitational collapse of the volcanic edifice (Lipman and Mullineaux 1981; Glicken 1998). The debris avalanche deposits impounded or modified three large lakes (Coldwater Creek, South Fork Castle Creek, and Spirit Lake) and several smaller ones (Jennings et al. 1981; Meier et al. 1981; Youd et al. 1981; Meyer et al. 1986; Glicken et al. 1989). Failure of the blockage to Maratta Creek on 19 August 1980 transferred water to the Elk Rock impoundment, which itself overtopped and breached on 27 August, releasing 0.3 × 10^6 m^3 of water into the North Fork Toutle River with a peak discharge of 450 m^3/s (Jennings et al. 1981; Costa 1985). Modelling of the potential peak discharges from failure of the three largest lakes (Jennings et al. 1981; Dunne and Fairchild 1983; Swift and Kresch 1983) suggested clear-water peaks > 7.5 × 10^4 m^3/s were possible, prompting intervention by the U.S. Army Corps of Engineers to artificially stabilise their levels (Costa 1985). A pre-historic break-out from an ancestral Spirit Lake similarly dammed by a debris avalanche occurred at c. 2.5 ka, generating a peak discharge estimated at 2.6 × 10^5 m^3/s (Scott 1989).

A number of prehistoric break-out floods from debris avalanche dammed lakes have been identified globally. In Alaska the upper Chakachatna valley was dammed to a depth of 150 m by a Holocene debris avalanche from the Spurr volcanic complex, impounding a lake estimated to have held 1.2 × 10^9 m^3 of water (Waythomas 2001). Other examples include a major debris avalanche from the Antuco volcano at c. 9.7 ka that dammed the outlet to the Río Laja in Chile, impounding a large lake that subsequently failed to generate an outwash fan covering an area of 50 × 60 km (Thiele et al. 1998), and collapse of the eastern flank of the Nevado de Colima Volcano in Mexico at 18.5 ka which produced a voluminous debris avalanche that dammed the Naranjo River 20 km away to a depth of 150 m. Obstruction of the drainage produced a temporary impoundment of c. 1 km^3 of water, which eventually breached the dam through overtopping, generating a peak discharge estimated at 5.7 × 10^5 m^3/s (Capra and Macías 2002). Bulking of the flow through entrainment of material from the dam and along the flood path increased the peak discharge by a factor of 6 and deposited c. 10 km^3 of debris.

6.6 Lahar Dams

Rapid sedimentation by lahars is capable of damming rivers at confluences where one stream aggrades its bed more rapidly than the other (Rodolfo et al. 1996). The dominant stream builds a steep-fronted delta, fed by sediment-laden underflows, which progrades into the subordinate channel as the stagnation zone at the flow confluence migrates. Damming occurs when the rate of aggradation is faster than the rate of water level rise in the impounded channel.

Remobilisation of voluminous pyroclastic flow deposits at Pinatubo in the Philippines following the June 1991 eruption led to multiple instances of lahar-dammed lakes and subsequent breakouts in a number of catchments (Pierson et al. 1992; Newhall and Punongbayan 1996). The largest such impoundment, Lake Mapanuepe (Fig. 2d), covered an area of 6.7 km^2 and held 75×10^6 m^3 of water at its maximum extent in 1991 (Umbal and Rodolfo 1996). Eighteen breakouts, peaking at 400–650 m^3/s, were recorded in 1991 alone as the lake repeatedly overtopped and partially breached the impounding lahar deposit, which was rapidly rebuilt by aggradation of 7–20 m/year (Rodolfo et al. 1996). In total, the dam reached a height of c. 25 m before engineering intervention stabilised the lake elevation at 111 m. Numerous other lakes filled and spilled between 1991 and 1994, generating large lahars and entrenching drainage routes that became conduits for subsequent damaging flows (Newhall and Punongbayan 1996; Rodolfo 2000). Similarly, the 1902 eruption of Santa Maria in Guatemala resulted in the creation of at least 16 lahar-dammed lakes large enough to be mapped in the decades after the eruption (Kuenzi et al. 1979). However, it is not recorded whether any of these failed catastrophically.

A number of small, short-lived lakes were impounded by lahar dams in the upper Chakachatna River valley, following historic eruptions in 1953 and 1992 of the Spurr volcanic complex in Alaska (Waythomas 2001). The 1953 lahar dam was c. 20 m high, 600 m long and 200 m wide; the 1992 lahar dam was approximately 10 m high, 200 m long and 50 m wide: lake volumes are estimated at 10^7–10^8 m^3 from modern topography. Lahar dams up to 60 m high have also formed at least twice in the late Holocene, impounding up to 4.5×10^8 m^3 of water.

In the aftermath of 1886 AD basaltic plinian eruption of Tarawera, New Zealand (Walker et al. 1984), the level of Lake Tarawera rose by 12.8 m, before a rain-triggered break-out in November 1904 reduced it by 3.3 m, producing a flood estimated to have peaked at c. 780 m^3/s 24 km downstream (White et al. 1997). The post-eruptive rise has been attributed to construction of a small alluvial fan across the outlet channel by flash-flood induced remobilisation of 1886 pyroclastic and older debris in the Tapahoro gully (Hodgson and Nairn 2000).

As well as multiple pyroclastic-flow dammed lakes, numerous temporary impoundments were created in the aftermath of the 1.8 ka Taupo eruption through volcaniclastic resedimentation and laharic aggradation of up to 10s of metres in distal areas (Kear and Schofield 1978; Manville 2002; Segschneider et al. 2002).

6.7 Composite Dams

Composite dams are those formed by a combination of mechanisms, most commonly primary and secondary pyroclastic flows and lahars (Table 2). One such example occurred at Lake Tarawera following the c. 1315 AD Kaharoa eruption (Nairn et al. 2001). Lake Tarawera lies within the 64 ka Haroharo caldera in the Okataina Volcanic Centre in New Zealand (Nairn 2002), and is bounded by the western rim of the caldera and the resurgent lava dome complexes of Haroharo and Tarawera to the east. The 5-7 km^3 DRE Kaharoa eruption formed much of the Tarawera dome complex and deposited widespread plinian falls (Nairn et al. 2001). Primary block-and-ash flows and pyroclastic debris remobilised by flash floods off the Tapahoro dome blocked the narrow lake outlet, infilling a narrow channel cut through a c. 5 ka pyroclastic/volcaniclastic fan implicated in a previous highstand. Lake Tarawera rose by c. 30 m above its pre-eruption level before tsunami generated by late-stage pyroclastic flows overtopped the dam and triggered its catastrophic failure (Hodgson and Nairn 2005). Approximately 1.7×10^9 m^3 of water was released into the head of the Tarawera valley as the lake level fell by >40 m, excavating a 300 m wide and 3 km long spillway before overtopping the 70 m high Tarawera Falls. Flood deposits including boulders up to 13 m in diameter and giant bars extend c. 40 km from the lake; approximately 700 km^2 of the Rangitaiki Plains was resurfaced and the shoreline advanced by c. 2 km (Pullar and Selby 1971). Peak discharge at the outlet was estimated at 1.5×10^5 m^3/s assuming instantaneous breach formation, while boulder flow-competence relations further downstream indicate flows in the 10^4–10^5 m^3/s range (Hodgson and Nairn 2005).

7 Discussion

A review of hazards from volcanic lakes due to eruptive activity or other causes reveals a great deal of complexity in triggering mechanisms and hazardous phenomena. Well-studied historic examples such as the 1996 eruptions at Karymskoye (Belousov and Belousov 2001) and Taal (Moore et al. 1966a), the 1991 Pinatubo eruption and its aftermath (Newhall and Punongbayan 1996), and lahar events at Ruapehu (Cronin et al. 1997; Kilgour et al. 2010) and Kelut (Suryo and Clarke 1985) demonstrate this variety and complexity: in many cases individual hazards contribute to subsequent effects in a process-chain. Examination of the geological record reveals a fuller range of both hazards and event magnitudes.

Moderate-sized (10^7–10^8 m^3) crater lakes developed at the summits of andesitic-dacitic stratovolcanoes in relatively humid arc environments are potentially the most dangerous volcanic lakes due to their capacity for almost instantaneous expulsion of large water volumes during subaqueous explosive eruptions, which can occur with little or no effective warning (e.g. Mt. Kelut, Ruapehu). Smaller water bodies are either evaporated or the expelled water is too widely dispersed during eruptions to generate significant lahars. In larger diameter lakes the Surtseyan jets that are the main displacers of water cannot reach their rims, and water depths >100 m suppress the ability of subaqueous explosions to breach the surface (Mastin and Witter 2000; Morrissey et al. 2010).

At crater and caldera lakes more than 2 km in diameter, base surges and tsunamis generated by volcanic activity, or collapse of the caldera walls (Ramos 1986), are the most significant hazard. Examples with populated shorelines that fall into this category include Taal in the Philippines, where historic eruptions have resulted in major loss of life, Taupo and Rotorua in New Zealand, Ilopango in El Salvador, and Toya and Towada in Japan. Volcano-tectonic lakes facing similar hazards include Lakes Managua and Nicaragua in Nicaragua. Tianchi (Baitoushan) at the summit of Mount Paektu/Changnai on the North Korea/China border is vulnerable to both renewal of volcanic activity and collapse of the steep walls of this very young (c. 1 ka) 5 km diameter lake (Wei et al. 2003, 2004). Lakes Quilotoa and Cuicocha in Ecuador are also potentially hazardous (Gunkel et al. 2008).

Volcanic lakes have lifespans measured in minutes to thousands of years. Intervals between creation and failure are a function of the geometry and stability of the lake-forming blockage, and the rate of lake level rise, which is itself a function of the catchment area, the proportion occupied by the lake, climatic effects, and seepage losses (Capra 2007). Examination of Tables 1 and 2 shows that a number of hazardous volcanic lakes have been destroyed in the past few hundred years while new ones have been created. Natural dams composed of unconsolidated pyroclastic deposits are extremely vulnerable to break-outs triggered by non-volcanic processes, such as erosion following overtopping (El Chichón), internal piping (Ruapehu), or headward erosion. Where barriers are composed of indurated material such as lava flows or welded ignimbrites, lakes can persist for many thousands of years: some, such as Crater Lake, Oregon, never reach overtopping level because seepage losses match water inflows as the lake level rises and hydrostatic pressures increase. Others, such as Aniakchak (McGimsey et al. 1994; Waythomas et al. 1996) and Fisher volcano (Stelling et al. 2005) in Alaska appear to have reached a stable highstand level controlled by a hard rock sill. Failure required active breaching of the rim by tsunamis generated during intra-lake eruptions, in the case of Fisher volcano this was 7.9 ka after caldera formation (Stelling et al. 2005).

The largest volcanic flood hazards derive from break-outs from intracaldera lakes (Taupo, Okmok, Aniakchak, Towada), and from valleys dammed by debris avalanches (Colima, Mount St. Helens) because of the potential volumes of water involved. Avalanche-dammed lakes are particularly hazardous not only because they can be voluminous but also because flood discharge can be amplified by the erosion and entrainment of unconsolidated material from the blockage (Capra and Macías 2002).

Other hazards can arise at crater lakes due to acid brine seepage, which can weaken the edifice (Reid et al. 2001), potentially leading to sector collapse debris avalanches and break-out lahars, e.g. at Rincon de la Vieja, Costa Rica (Kempter and Rowe 2000), and Copahue, Argentina (Varekamp et al. 2001). Acid brines can also contaminate drinking and irrigation water, while acid gas aerosols released from hyper-acidic crater lake waters are an unusual potential hazard along flow paths (Schaefer et al. 2008).

7.1 Mitigation

A variety of engineering interventions have been applied to prevent break-outs of unstable lakes and to mitigate lake break-out floods (Schuster 2000). Successfully applied techniques include: (i) reinforced spillways and check dams on weak blockages; (ii) drainage and diversion channels or tunnels across or through stable (bedrock) abutments; and (iii) pumps or siphons to lower lake level. These methods vary in expense and difficulty, and some are reliant on suitable topography or an adequate timeframe and success is not guaranteed. Diversion tunnels are probably the most long-term (and expensive solution), but despite their success at some volcanoes (e.g. Kelut and Mount St. Helens), they require maintenance and are vulnerable to destruction by renewed volcanic activity. There are also considerable eruption and other risks to workers during construction phases. Downstream mitigation measures against lahars and floods include construction of check dams, bunds and dykes, and raising and strengthening of bridges.

7.1.1 Engineering Interventions

Engineering interventions to reduce the hazard from volcanic lakes pre-date the Romans: at Albano maar, a tunnel dug by the Etruscans to drain the lake below its overspill level was rebuilt by the Romans in c. 396 BCE (Funiciello et al. 2003; De Benedetti et al. 2008). This 1.5 km long tunnel lowered the lake by 70 m and still functions today.

Mt. Kelut in Indonesia is probably the best example of a successful, although protracted, expensive, and technologically challenging intervention (Zen and Hadikusumo 1965; Suryo and Clarke 1985). The first attempt to control eruption-triggered lahars from the summit crater lake was construction of a diversion dam on the Badak ravine in 1905 following the 1901 eruption. This was overwhelmed by the 1919 lahars when all water was explosively expelled from the lake, triggering flows up to 58 m deep that travelled up to 38 km from source, inundating 131 km^2, destroying more than 100 villages and killing over 5,000 people. Following this disaster, an earlier plan to drain the lake was implemented in September 1919. This involved excavating a 955 m long tunnel with a 3 % gradient designed to intercept the bottom of the lake. Tunnelling was begun at both ends as the lake was dry following the eruption earlier in the year, but was stopped at the upstream end by lava ascent a year later. After tunnelling upwards for 735 m, volcanic debris in the inner crater wall was encountered and the tunnel needed to be lined with concrete. Meanwhile, the crater lake had been refilling until by early April 1923 it held 22 × 10^6 m^3 of water: at this point leakage into the tunnel killed 5 workers. This led to modification of the plan to include a series of tunnels through which water would be siphoned at progressively lower levels (Fig. 9). The first tunnel was driven just above the then lake level of 1,185 m, preventing any further rise, and the lake was progressively lowered to 1,129 m. The volcano erupted again on 31 August 1951, but the small (<2 × 10^6 m^3) volume of lake water was largely evaporated rather than explosively expelled, leading to minimal lahars. Unfortunately the tunnels were blocked by the eruption and the crater deepened by c. 70 m (Zen and Hadikusumo 1965). In 1954, work was begun to reactivate the tunnels, with 3 being cleared by 1955 when the lake volume was limited to 23.5 × 10^6 m^3. A new tunnel was then driven 20 m below the lowest old tunnel, and two galleries and further adits were then driven from it towards the lake in the hope that seepage would drain the water. Unfortunately the desired drainage rate was never achieved and the project was abandoned in March 1963. On 26 April 1966 an eruption expelled the c. 20 × 10^6 m^3 of water in the lake, generating lahars that destroyed the rebuilt Badak diversion dam, killing 208, and again damaging the tunnel system. In June 1966 a new tunnel was dug linking the then empty crater to an older unfinished drive. Completion of this by the end of December 1967 limited the lake to a maximum volume of 4.3 × 10^6 m^3 with the result that the 1990 eruptions produced only minor primary lahars that killed only 32 (Thouret et al. 1998).

At Mount St. Helens, the levels of the three largest lakes impounded by the 1980 debris avalanche were stabilised by the U.S. Army Corps of Engineers by the construction of permanent spillways and bedrock drainage tunnels (Costa 1985). The greatest assessed risk was from Spirit Lake: numerical studies suggested that failure of the debris avalanche dam could generate a flood with a peak discharge of 7.5 × 10^4 m^3/s (Swift and Kresch 1983). To gain time, a 20-pump facility was installed to remove up to 5 m^3/s of water through a 1.5 m diameter pipe buried in the dam crest while a 2.59 km long, 3.4 m diameter tunnel was bored through the ridge to the west of the lake, ultimately stabilising the lake at 1,048 m (Schuster and Evans 2011). Meanwhile, Coldwater Lake was stabilised by construction of a permanent spillway across a resistant bedrock abutment, and Castle Lake was stabilised by construction of an armoured spillway.

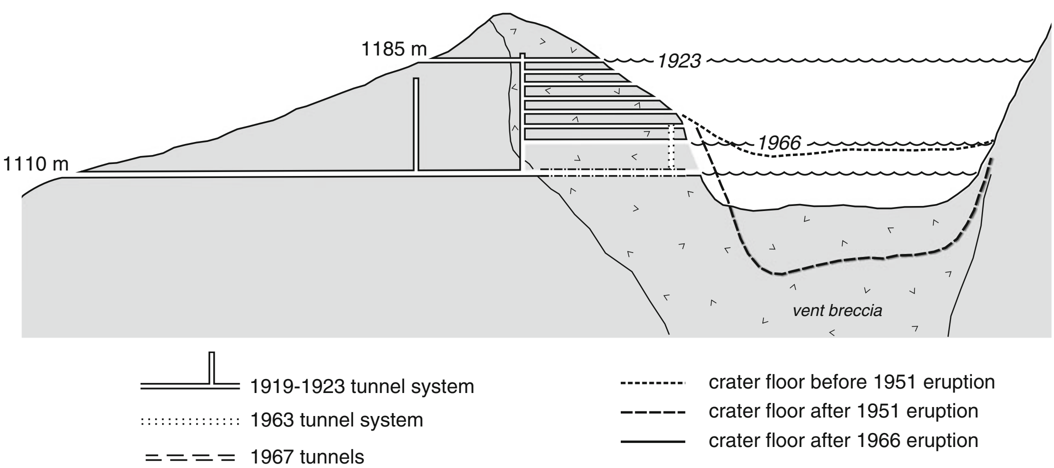

Fig. 9 Cross-section of the crater lake of Mt. Kelut in Indonesia showing the tunnel system used to lower the lake level and reduce the hazard from eruption-triggered lahars (after Zen and Hadikusumo 1965)

Repeated break-out floods from the lahar-dammed Mapanuepe Lake were a feature of the early years at Pinatubo in the Philippines following the 1991 eruption (Rodolfo et al. 1996; Umbal and Rodolfo 1996). Its level was stabilised in November 1992 by excavation of a bedrock spillway through an adjacent rock spur. Geological and anthropological data indicate that a similar lake occupied this site on two previous occasions (Rodolfo and Umbal 2008).

Emptying of the summit Crater lake of Mt. Ruapehu during the 1995–1996 eruptions (Johnston et al. 2000), coupled with deposition of a c. 8 m thick blanket of tephra over the former outlet area, raised the possibility of a future break-out lahar in a repeat of the 1953 Tangiwai lahar scenario, which resulted in New Zealand's worst volcanic disaster (Healy 1954; O'Shea 1954). Given the decade-long delay between formation of the tephra barrier and the subsequent breakout in March 2007 (Manville and Cronin 2007; Massey et al. 2010; Lube et al. 2012) there was adequate time to quantify the relative risks of intervention at the crater rim versus downstream mitigation efforts. The situation was complicated by the status of the summit of Ruapehu as a World Heritage Site, its location in a National Park, and not least Crater Lake's special spiritual significance to the local Māori population. Numerical modelling of the potential magnitude of any lahar event (Hancox et al. 2001) and a residual analysis of the risks of intervention versus non-intervention (Taig 2002) resulted in the decision to install a real-time telemetered warning system on the tephra dam and downstream channel, a bund at the apex of the Whangaehu Fan to prevent overspill into vulnerable northern drainages, raising and strengthening of the State Highway 49 road bridge at Tangiwai, a system of automatic lights and gates to close roads close to or crossing the predicted lahar path, and a public education campaign (Keys 2007; Becker et al. 2008; Keys and Green 2008). In the event, the lahar occurred as predicted with no loss of life or injuries and minimal infrastructural damage.

7.1.2 Limnic Gas Eruptions

Following the gas eruptions from Lakes Monoun and Nyos, warning systems comprising CO_2 monitors, sirens and public education were implemented, as well as a pipe system designed to safely degas the lake water (Kusakabe et al. 2008). Reinforcement of the outlet to Lake Nyos to stabilise the natural dam is also currently underway (Aka and Yokoyama 2013), in response to the potential for breaching to catastrophically release the upper 40 m of lake water. This would not only cause flooding into Nigeria over 200 km downstream, but also release another burst of CO_2 due to depressurisation of the gas-saturated deep water (Lockwood et al. 1988).

8 Conclusions

Although hydrologic hazards from volcanic lakes are over-represented in terms of fatalities per eruption, improvements in volcano monitoring and increased awareness are mitigating the risk at many volcanoes around the world. Timely and appropriate engineering interventions have been effective in minimising deaths at a number of volcanoes (Kelut) and preventing disasters at others (Mount St. Helens, Lake Nyos). Although currently very few volcanic lakes are monitored on a regular basis, changes in a lake's appearance, thermal, and/or chemical characteristics could be diagnostic of impending volcanic activity (Oppenheimer 1993; Hurst and Vandemeulebrouck 1996; Christenson 2000; Christenson et al. 2010). Break-outs associated with collapse of blockages are less predictable, unless the lake level is approaching the overflow point, or seepage on the downstream face of the dam is obvious and sediment-laden (Turner et al. 2007; Massey et al. 2010).

Most fatalities due to volcanic activity occur between 10–30 km away from the vent (Auker et al. 2013). This reflects the combination of (i): this distance being within the range of the heaviest tephra falls; (ii) the typical travel distance of pyroclastic flows, lahars and intra-lake tsunamis; and (iii) the tendency for populations to be concentrated on the gentler slopes and flat alluvial (often lahar) terraces and plains flanking and downstream of volcanoes, (volcanic) lakeshores, and along coastlines vulnerable to volcanogenic tsunamis. However, this is also far enough away for a combination of effective monitoring and warning systems, public education, land-use planning, and engineering interventions to mitigate many of the hazards presented by volcanic lakes. In the future, a combination of clearer understanding and better practice are likely to be most effective in alleviating the associated dangers.

Acknowledgments Research for this study began under the Catastrophic Flooding and Lahars programme founded by B.F. Houghton and funded by the Foundation for Research Science and Technology, New Zealand under contracts C05516 and C0005X6 to Manville. The manuscript benefited from reviews by TC Pierson and JE O'Connor.

References

Aka FT, Yokoyama T (2013) Current status of the debate about the age of Lake Nyos dam (Cameroon) and its bearing on potential flood hazards. Nat Hazards 65:875–885

Almberg LD, Beget JE, Larsen JF (2003) Magmatic production rate determined by volcaniclastic lithofacies variations in a rapidly fluctuating caldera lake, Okmok Volcano, Alaska. In: Proceedings and abstract volume of IUGG 2003 Congress, Sapporo, Japan: A. p 519

Anderson TR, Flett JS (1903) Report on the eruptions of the Soufriere, in St. Vincent in 1902, and on a visit to Montagne Pelee, Martinique—part 1. Philos Trans Roy Soc Ser A 200:353–553

Aramaki S (1956) The 1783 activity of Asama volcano, part 1. Jpn J Geol Geogr XXVII(2–4):189–229

Aramaki S (1981) The sequence and nature of 1783 eruption of Asama volcano. In: Abstracts of the symposium on Arc Volcanism, Tokyo and Hakone-Machi, Japan, pp 11–12

Arboleda RA, Martinez MML (1996) 1992 lahars in the Pasig-Potrero river system. In: Newhall CG, Punongbayan RS (eds) Fire and Mud, eruptions and lahars of Mount Pinatubo. University of Washington Press, Seattle, Philippines, pp 1045–1052

Auker MR, Sparks RSJ, Siebert L, Crossweller HS, Ewert J (2013) A statistical analysis of the global historical volcanic fatalities record. J Appl Volcanol 2. doi:10.1186/2191-5040-2-2

Baales M, Jöris O, Street M, Bittman F, Wninger B, Wiethold J (2002) Impact of the late glacial eruption of the Laacher See volcano, central Rhineland, Germany. Quatern Res 58:273–288

Bani P, Join J-L, Cronin SJ, Lardy M, Rouet I, Garaebiti E (2009) Characteristics of the summit lakes of Ambae volcano and their potential for generating lahars. Nat Hazards Earth Syst Sci 9:1471–1478

Barberi F, Chelini W, Marinelli G, Martini M (1989) The gas cloud of Lake Nyos (Cameroon, 1986): results of the Italian technical mission. J Volcanol Geoth Res 39:125–134

Batiza R, White JDL (2000) Submarine lavas and hyaloclastite. In: Sigurdsson H, Houghton B, McNutt S, Rymer H, Stix J (eds) Encyclopedia of volcanoes. Academic Press, New York, pp 361–381

Beck AC (1950) Volcanic activity at Mt. Ruapehu from August to December, 1945. NZ J Sci Technol B31:1–13

Becker J, Manville V, Leonard G, Saunders W (2008) Managing lahars the New Zealand way: a case study from Mount Ruapehu volcano. Natural Hazards Observer XXXII(5):4–6

Begét JE, Larsen JF, Neal CA, Nye CJ, Schaefer JR (2005) Preliminary volcano-hazard assessment of Okmok volcano, Umnak Island, Alaska. Alaska department of natural resources, division of geological and geophysical surveys, report of investigations 2004-3, 32 p

Begét JE, Gardner C, Davis K (2008) Volcanic tsunamis and prehistoric cultural transitions in Cook Inlet, Alaska. J Volcanol Geoth Res 176:377–386

Belousov A, Belousov M (2001) Eruptive process, effects and deposits of the 1996 and the ancient basaltic phreatomagmatic eruptions in Karymskoye lake, Kamchatka, Russia. In: White JDL, Riggs NR (eds) Volcanogenic sedimentation in lacustrine settings. International Association of Sedimentologists, Special Publication, vol 30, pp 35–60

Belousov A, Voight B, Belousova M, Muravyev Y (2000) Tsunamis generated by subaquatic volcanic explosions: unique data from 1996 eruption in Karymskoye Lake, Kamchatka, Russia. Pure Appl Geophys 157:1135–1143

Björnsson H (1975) Subglacial water reservoirs, jökulhlaups and volcanic eruptions. Jökull 25:1–14

Björnsson H (1992) Jökulhlaups in Iceland: prediction, characteristics and simulation. Ann Glaciol 16:95–106

Björnsson H (2002) Subglacial lakes and jökulhlaups in Iceland. Glob Planet Change 35:255–271

Bornas MA, Tungol N, Maximo RPR, Paladio-Melosantos ML, Mirabueno HT, Javier DV, Corpuz EG, Dela Cruz EG, Ramos AF, Marilla JD, Villacorte EU (2003) Caldera-rim breach and lahar from Mt. Pinatubo, Philippines: natural breaching and resulting lahar. In: Proceedings and abstract volume of IUGG 2003 Congress, Sapporo, Japan A, p 558

Capra L (2007) Volcanic natural dams: identification, stability, and secondary effects. Nat Hazards 43:45–61

Capra L, Macías JL (2002) The cohesive Naranjo debris-flow deposit (10 km^3): a dam breakout flow derived from the Pleistocene debris-avalanche deposit of Nevado de Colima Volcano (México). J Volcanol Geoth Res 117:213–235
Carey S, Sigurdsson H, Mandeville C, Bronto S (1996) Pyroclastic flows and surges over water: an example from the 1883 Krakatau eruption. Bull Volc 57:493–511
Carey S, Sigurdsson H, Mandeville C, Bronto S (2000) Volcanic hazards from pyroclastic flow discharge into the sea: examples from the 1883 eruption of Krakatau, Indonesia. In: McCoy FW, Heiken G (eds) Volcanic hazards and disasters in human antiquity. Geological Society of America, Special Publication, vol 345, pp 1–14
Carey S, Morelli D, Sigurdsson H, Bronto S (2001) Tsunami deposits from major explosive eruptions: an example from the 1883 eruption of Krakatau. Geology 29:347–350
Carrivick JL, Russell AJ, Tweed FS, Twigg D (2004) Palaeohydrology and sedimentary impacts of jökulhlaups from Kverkfjöll, Iceland. Sed Geol 172:19–40
Carrivick JL, Manville V, Cronin SJ (2009) A fluid dynamics approach to modelling the 18th March 2007 lahar at Mt. Ruapehu. NZ Bull Volcanol 71:153–169
Casadevall TJ, de la Cruz-Reyna S, Rose WI, Bagley S, Finngean DL, Zollwer WH (1984) Crater lake and post-eruption hydrothermal activity, El Chichón volcano, Mexico. J Volcanol Geoth Res 23:169–191
Catane SG, Taniguchi H, Goto A, Givero AP, Mandanas AA (2005) Explosive volcanism in the Philippines. CNEAS monograph series. Centre for Northeast Asian studies, Tohuku University, Tohuku, 146 p
Chesner CA, Rose WI (1991) Stratigraphy of the Toba tuffs and the evolution of the Toba caldera Complex, Sumatra, Indonesia. Bull Volcanol 53:343–356
Chiocci FL, Romagnoli C, Tomassi P, Bosman A (2008) The Stromboli 2002 tsunamigenic submarine slide: characteristics and possible failure mechanisms. J Geophys Res 113:B10102
Chitwood L, Jensen R (2000) Large prehistoric flood along Paulina Creek. In: Jensen R, Chitwood L (eds) What's new at Newberry volcano, Oregon. USDA Forest Services, Bend, Oregon, pp 31–40
Chrétien S, Brousse R (1989) Events preceding the great eruption of 8 May, 1902 at Mount Pelée, Martinique. J Volcanol Geoth Res 38:67–75
Christenson BW (2000) Geochemistry of fluids associated with the 1995–1996 eruption of Mt. Ruapehu, New Zealand: signatures and processes in the magmatic-hydrothermal system. J Volcanol Geoth Res 97:1–30
Christenson BW, Wood CP (1993) Evolution of a vent-hosted hydrothermal system beneath Ruapehu Crater Lake, New Zealand. Bull Volc 55:547–565
Christenson BW, Reyes AG, Young R, Moebis A, Sherburn S, Cole-Baker JC, Britten K (2010) Cyclic processes and factors leading to phreatic eruption events: insights from the 25 September 2007 eruption through Ruapehu Crater Lake, New Zealand. J Volcanol Geoth Res 191:15–32
Clarke GKC (2003) Hydraulics of subglacial outburst floods: new insights from the Spring-Hutter formulation. J Glaciol 49:299–313
Cole RH (1948) Underwater explosions. Princeton University Press, Princeton 437 p
Conaway J (2000) Hydrogeology and paleohydrology in the Williamson River Basin, Klamath County, Oregon. Unpublished M.Sc. thesis, department of geology. Portland State University, Portland, 117 p
Córtes A, Macías JL, Capra L, Garduño-Monroy VH (2010) Sector collapse of the SW flank of Volcán de Colima, México: the 3600 yr BP La Lumbre-Los Ganchos debris avalanche and associated debris flows. J Volcanol Geoth Res 197:52–66
Costa, J. E. 1985. Floods from dam failures. USGS Open-file report 85-560, 54 p
Costa JE (1988) Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows and debris flows. In: Baker VR, Kochel RC, Patton PC (eds) Flood geomorphology. Wiley, New York, pp 113–122
Costa JE, Schuster RL (1988) The formation and failure of natural dams. Geol Soc Am Bull 100:1054–1068
Cronin SJ, Neall VE, Lecointre JA, Palmer AS (1996) Unusual "snow slurry" lahars from Ruapehu volcano, New Zealand, September 1995. Geology 24:1107–1110
Cronin SJ, Neall VE, Lecointre JA, Palmer AS (1997) Changes in Whangaehu River lahar characteristics during the 1995 eruption sequence, Ruapehu volcano, New Zealand. J Volcanol Geoth Res 76:47–61
Crow R, Karlstrom KE, McIntosh WC, Peters L, Dunbar NW (2008) History of Quaternary volcanism and lava dams in western Grand Canyon based on lidar analysis, $^{40}Ar/^{39}Ar$ dating, and field studies: implications for flow stratigraphy, timing of volcanic events, and lava dams. Geosphere 4:181–206
Davy BW, Caldwell TG (1998) Gravity, magnetic and seismic surveys of the caldera complex, Lake Taupo, North Island, New Zealand. J Volcanol Geoth Res 81:69–89
De Benedetti AA, Funiciello R, Giordano G, Diano G, Caprilli E, Paterne M (2008) Volcanology, history and myths of the Lake Albano maar (Colli Albani volcano, Italy). J Volcanol Geoth Res 176:387–406
de Lange WP, Prasetya GS, Healy TR (2001) Modelling of tsunamis generated by pyroclastic flows (ignimbrites). Nat Hazards 24:251–266
Delmelle P, Bernard A (2000) Volcanic lakes. In: Sigurdsson H, Houghton B, McNutt S, Rymer H, Stix J (eds) Encyclopedia of volcanoes. Academic Press, New York, pp 877–895
Donnelly-Nolan JM, Nolan KM (1986) Catastrophic flooding and eruption of ash-flow tuff at Medicine Lake volcano, California. Geology 14:875–878
Druitt TH (1998) The eruption, transport and sedimentation of pyroclastic flows. In: Gilbert J, Sparks RSJ (eds) The physics of explosive volcanic eruptions. Geological Society of London, Special Publication, vol 145, pp 145–182

Duffield WA (2001) At least Noah had some warning. EOS Trans AGU 82(28):305–309

Dunne T, Fairchild LH (1983) Estimation of flood and sedimentation hazards around Mt. St. Helens. Shin Sabo 36:12–22

Egorov Y (2007) Tsunami wave generation by the eruption of underwater volcano. Nat Hazards Earth Syst Sci 7:65–69

Ellis SM, Wilson CJN, Bannister S, Bibby H, Heise W, Wallace L, Patterson N (2007) A future magma inflation event under the rhyolitic Taupo volcano, New Zealand: numerical models based on constraints from geochemical, geological, and geophysical data. J Volcanol Geoth Res 168:1–27

Ely LL, Brossy CC, House PK, Safran EB, O'Connor JE, Champion DE, Fenton CR, Bondre NR, Orem CA, Grant GE, Henry CD, Turrin BD (2012) Owyhee Rover intracanyon lava flows: does the river give a dam? Geol Soc Am Bull 124:1667–1687

Fenton CR, Cerling TE, Nash BP, Webb RH, Poreda RJ (2002) Cosmogenic ^{3}He ages and geochemical discrimination of lava-dam outburst-flood deposits in western Grand Canyon, Arizona. In: House PK, Webb RH, Baker VR, Levish DR (eds) Ancient floods, modern hazards: principles and applications of paleoflood hydrology. Am Geophys Union, Washington, D. C., pp 191–215

Fenton CR, Webb RH, Cerling TE (2003) Peak discharge estimates of two Pleistocene lava-dam outburst floods, western Grand Canyon, Arizona, USA. In: Ely LL, O'Connor JE, House PK (eds) Abstract volume, Paleoflood III conference. Hood River, Oregon, p 18

Fenton CR, Poreda RJ, Nash BP, Webb RH, Cerling TE (2004) Geochemical discrimination of five Pleistocene lava-dam outburst flood deposits, western Grand Canyon, Arizona. J Geol 112:91–110

Fenton CR, Webb RH, Cerling TE (2006) Peak discharge of a Pleistocene lava-dam outburst flood in Grand Canyon, Arizona, USA. Quatern Res 65:324–335

Fisher RV, Heiken G (1982) Mt. Pelée, Martinique: May 8 and 20, 1902, pyroclastic flows and surges. J Volcanol Geoth Res 13:339–371

Freundt A, Kutterolf S, Wehrmann H, Schmincke H-U, Strauch W (2006) Eruption of the dacite to andesite zoned Mateare Tephra, and associated tsunamis in Lake Managua, Nicaragua. J Volcanol Geoth Res 149:103–123

Freundt A, Strauch W, Kutterolf S, Schmincke H-U (2007) Volcanogenic tsunamis in lakes: examples from Nicaragua and general implications. Pure appl Geophys 164:527–545

Frost DL, Lee JHS, Thibault P (1994) Numerical computation of underwater explosions due to fuel-coolant interactions. Nucl Eng Des 146:165–179

Funiciello R, Giordano G, De Rita D (2003) The Albano maar lake (Colli Albani Volcano, Italy): recent volcanic activity and evidence of pre-Roman Age catastrophic lahar events. J Volcanol Geoth Res 123:43–61

Glasstone S, Dolan PJ (1977) The effects of nuclear weapons. United States department of defence and the energy research and development administration, Washington D.C., 644 p

Glicken, H, Meyer, W, Sabol, M (1989) Geology and ground-water hydrology of Spirit Lake blockage, Mount St. Helens, Washington, with implications for lake retention. US Geol Surv Bulletin 1789:30

Glicken H (1998) Rockslide-debris avalanche of May 18, 1980, Mount St. Helens Volcano, Washington. Bull Geol Surv Jpn 49:55–106

Gomez C, Kataoka KS, Tanaka K (2012) Large-scale internal structure of the Sanbongi Fan—Towada volcano, Japan: putting the theory to the test, using GPR on volcaniclastic deposits. J Volcanol Geoth Res 229–230:44–49

Goodyear WA (1880) Earthquake and volcanic phenomena, December 1879 and January 1880, in the Republic of Salvador, Central America. Panama Star and Herald, p 56

Graettinger AH, Manville V, Briggs RM (2010) Depositional record of historic lahars in the Whangaehu valley, Ruapehu, New Zealand: implications for trigger mechanisms, flow dynamics, and lahar hazards. Bull Volc 72:279–296

Grange LI (1937) The geology of the Rotorua-Taupo subdivision. N Z Geol Surv Bull 37:138

Gudmundsson MT, Sigmundsson F, Björnsson H (1997) Ice-volcano interaction of the 1996 Gjálp subglacial eruption, Vatnajökull, Iceland. Nature 389:954–957

Gunkel G, Beulker C, Grupe B, Viteri F (2008) Hazards of volcanic lakes: analysis of Lakes Quilotoa and Cuicocha, Ecuador. Advances in Geosciences 14:29–33

Hackett WR, Houghton BF (1989) A facies model for a quaternary andesitic composite volcano: Ruapehu, New Zealand. Bull Volc 51:51–68

Hamblin WK (1994) Late Cenozoic lava dams in the western Grand Canyon. Geological Society of America, Memoir 183

Hancox GT, Keys H, Webby MG (2001) Assessment and mitigation of dam-break lahar hazards from Mt. Ruapehu Crater Lake following the 1995–1996 eruptions. In: McManus KJ (ed) Engineering and development in hazardous terrains. In: Proceedings of New Zealand Geotechnical Society/NZ Institute of Professional Engineers Conference, Christchurch, New Zealand, pp 385–409

Hart K, Carey S, Sigurdsson H, Sparks RSJ, Robertson REA (2004) Discharge of pyroclastic flows into the sea during the 1996–1998 eruptions of the Soufrière Hills volcano, Montserrat. Bull Volcanol 66:599–614

Healy J (1954) The Whangaehu lahar of 24th December 1953. New Zealand geological survey, T20/501 Ruapehu immediate reports, vol 1, no 587

Healy J, Lloyd EF, Rushworth DEH, Wood CP, Glover RB, Dibble RR (1978) The eruption of Ruapehu, New Zealand on 22 June 1969. NZ Depart Sci Ind Res Bull 224:1–80

Hegan BD, Johnson JD, Severne C (2001) Landslide risk from the Hipaua geothermal area near Waihi village at the southern end of Lake Taupo. In: McManus KJ (ed) Engineering and development in hazardous terrains. In: Proceedings of New Zealand Geotechnical Society/NZ Institute of Professional Engineers Conference, Christchurch, New Zealand, pp 439–448

Hermanns R, Nierdermann S, Ivy-Ochs S, Kubik PW (2004) Rock avalanching into a landslide-dammed lake causing multiple dam failure in Las Conchas valley (NW Argentina)—evidence from surface dating and stratigraphic analyses. Landslides 2:113–122

Hernández PA, Pérez NM, Varekamp JC, Hernriquez B, Hernández A, Barrancos J, Padrón E, Calvo D, Melián G (2007) Crater lake temperature changes of the 2005 eruption of Santa Ana volcano, El Salvador, Central America. Pure appl Geophys 164:2507–2522

Hickson CJ, Russell JK, Stasiuk MV (1999) Volcanology of the 2350 B.P. eruption of Mount Meager volcanic complex, British Columbia, Canada: implications for hazards from eruptions in topographically complex terrain. Bull Volcanol 60:489–507

Hildreth W (1983) The compositionally zoned eruption of 1912 in the valley of ten thousand Smokes, Katmai National Park, Alaska. J Volcanol Geoth Res 18:1–56

Hildreth W, Drake RE (1992) Volcán Quizapu, Chilean Andes. Bull Volcanol 54:93–125

Hodgson KA, Manville V (1999) Sedimentology and flow behaviour of a rain-triggered lahar, Mangatoetoenui stream, Ruapehu volcano, New Zealand. Geol Soc Am Bull 111:743–754

Hodgson KA, Nairn IA (2000) The catastrophic—1350 AD post-eruption flood from Lake Tarawera, New Zealand. Bay of plenty regional council, resource planning report. 61 p

Hodgson KA, Nairn IA (2005) The—AD 1315 syn-eruption and AD 1904 post-eruption breakout floods from Lake Tarawera, Haroharo caldera, North Island, New Zealand. NZ J Geol Geophys 48:491–506

Hodgson KA, Lecointre J, Neall VE (2007) Onetapu formation: the last 2000 yr of laharic activity at Ruapehu volcano, New Zealand. NZ J Geol Geophys 50:81–99

Houghton BF, Nairn IA (1991) The 1976–1982 Strombolian and phreatomagmatic eruptions of White Island, New Zealand: eruptive and depositional mechanisms at a wet volcano. Bull Volcanol 54:25–49

Hurst AW, Vandemeulebrouck J (1996) Acoustic noise and temperature monitoring of the crater lake of Mount Ruapehu volcano. J Volcanol Geoth Res 71:45–51

Huscroft CA, Ward BC, Barendregt RW, Jackson LE Jr, Opdyke ND (2004) Pleistocene volcanic damming of Yukon river and the maximum age of the Reid glaciation, west-central Yukon. Can J Earth Sci 41:151–164

Ichinose G, Anderson JG, Satake K, Schwieckert RA, Lahren MM (2000) The potential hazard from tsunami and seiche waves generated by large earthquakes within Lake Tahoe, California-Nevada. Geophys Res Lett 27:1203–1206

Iverson RM (1995) Can magma-injection and groundwater forces cause massive landslides on Hawaiian volcanoes? J Volcanol Geoth Res 66:295–308

Jennings ME, Schneider VR, Smith PE (1981) Computer assessments of potential hazards from breaching of two debris dams, Toutle river and Cowlitz river systems. In: Lipman PW, Mullineaux DR (eds) The 1980 eruptions of Mount St. Helens, Washington. United States geological survey professional paper, vol 1250, pp 829–836

Johnson RW (1987) Large-scale volcanic cone collapse: the 1888 slope failure of Ritter volcano, and other examples from Papua New Guinea. Bull Volcanol 49:669–679

Johnston DM, Houghton BF, Neall VE, Ronan KR, Paton D (2000) Impacts of the 1945 and 1995–1996 Ruapehu eruptions, New Zealand: an example of increasing societal vulnerability. Geol Soc Am Bull 112:720–726

Karátson D, Thouret J-C, Moriya I, Lomoschitz A (1999) Erosion calderas: origins, processes, structural and climatic control. Bull Volcanol 61:174–193

Kataoka KS (2011) Geomorphic and sedimentary evidence of a gigantic outburst flood from Towada caldera after the 15 ka Towada-Hachinohe ignimbrite eruption, northeast Japan. Geomorphology 125:11–26

Kataoka KS, Urabe A, Manville V, Kajiyama A (2008) Large-scale breakout flood from an ignimbrite-dammed river: aftermath of the Numazawako eruption (BC 3400), northeast Japan. Geol Soc Am Bull 120:1233–1247

Kear D, Schofield JC (1978) Geology of the Ngaruawahia subdivision. NZ Geol Surv Bull 88:168

Keating BH, McGuire WJ (2000) Island edifice failures and associated tsunami hazards. Pure Appl Geophys 157:899–955

Kedrinksii VK (2005) Hydrodynamics of explosions: experiments and models. Springer, Berlin, 362 p

Kempter KA, Rowe GL (2000) Leakage of active crater lake brine through the north flank at Rincón de la Veja volcano, northwest Costa Rica, and implications for crater collapse. J Volcanol Geoth Res 97:143–159

Kershaw JA, Clague JJ, Evans SG (2005) Geomorphic and sedimentological signature of a two-phase outburst flood from moraine-dammed Queen Bess Lake, British Columbia. Earth Surf Proc Land 30:1–25

Keys HJR (2007) Lahars of Ruapehu volcano, New Zealand: risk mitigation. Ann Glaciol 45:155–162

Keys HJR, Green PM (2008) Ruapehu lahar New Zealand 18 March 2007: lessons for hazard assessment and risk mitigation 1995–2007. J Disaster Res 3:284–296

Kilgour G, Jolly AD, Sherburn S, Scott B, Miller C, Rae AJ (2007) The October 2006 eruption of Ruapehu Crater Lake. In: Mortimer N, Wallace L (eds) Proceedings, Joint GSNZ/NZGS annual conference, Tauranga

Kilgour G, Manville V, Della Pasqua F, Reyes AG, Graettinger AH, Hodgson KA, Jolly AD (2010) The 25 September 2007 eruption of Mt. Ruapehu, New Zealand: Directed ballistics, Surtseyan jets, and ice-slurry lahars. J Volcanol Geoth Res 191:1–14

Kling GW, Clark MA, Compton HR, Devine JD, Evans WC, Humphrey AM, Koenigsberg EJ, Lockwood JP, Tuttle ML, Wagner GN (1987) The 1986 Lake Nyos gas disaster in Cameroon, West Africa. Science 236:169–175

Koyaguchi T, Woods AW (1996) On the formation of eruption columns following explosive mixing of magma and surface water. J Geophys Res 101:5561–5574

Kuenzi WD, Horst OH, McGehee RV (1979) Effect of volcanic activity on fluvial-deltaic sedimentation in a modern arc-trench gap, southwestern Guatemala. Geol Soc Am Bull 90:827–838

Kusakabe M, Ohba T, Yoshida Y, Satake H, Ohizumi T, Evans WC, Tanyileke G, Kling GW (2008) Evolution of CO2 in Lakes Monoun and Nyos, Cameroon, before and during controlled degassing. Geochem J 42:93–118

Lagmay AMF, Rodolfo KS, Siringan FP, Uy H, Remotigue C, Zamora P, Lapus M, Rodolfo R, Ong J (2007) Geology and hazard implications of the Maraunot notch in the Pinatubo caldera, Philippines. Bull Volcanol 69:797–809

Larson GL (1989) Geographical distribution, morphology and water quality of caldera lakes: a review. Hydrobiologia 171:23–32

Latter JH (1981) Tsunamis of volcanic origin: summary of causes, with particular reference to Krakatoa, 1883. Bull Volcanol 44:467–490

Le Guern F, Tazieff H, Pierret RF (1982) An example of health hazard: people killed by gas during a phreatic eruption: Dieng Plateau (Java, Indonesia), February 20th 1979. Bull Volc 45:153–156

Lipman PW, Mullineaux DR (1981) The 1980 eruptions of Mount St. Helens, Washington. United Stated geological survey, Professional Paper, vol 1250, 844 p

Lliboutry L, Arnao BM, Pautre A, Schneider B (1977) Glaciological problems set by the control of dangerous lakes in Cordilerra Blanca, Peru 1. Historical failures of morainic dams, their causes and prevention. J Glaciol 18:239–254

Lockwood JP, Costa JE, Tuttle ML, Nni J, Tebor SG (1988) The potential for catastrophic dam failure at Lake Nyos maar, Cameroon. Bull Volcanol 50:340–349

Lorenz V (1973) On the formation of maars. Bull Volcanologique 37:183–204

Lowe DJ, Green JD (1992) Lakes. In: Soons JM, Selby MJ (eds) Landforms of New Zealand. Longman Paul Ltd., pp 107–143

Lube G, Cronin SJ, Manville V, Procter JN, Cole SE, Freundt A (2012) Energy growth in laharic mass flows. Geology 40:475–478

Machado F, Parsons WH, Richards AF, Mulford JW (1962) Capelinhos eruption of Fayal volcano, Azores, 1957–1958. J Geophys Res 67:3519–3529

Macías JL, Capra L, Scott KM, Espíndola JM, García-Palomo A, Costa JE (2004) The 26 May 1982 breakout flows derived from failure of a volcanic dam at El Chichón, Chiapas, Mexico. Geol Soc Am Bull 116:233–246

Magnússon E, Gudmundsson MT, Roberts MJ, Sigurðsson G, Höskuldsson F, Oddsson B (2012) Ice-volcano interactions during the 2010 Eyjafjallajökull eruption, as revealed by airborne imaging radar. J Geophys Res 117:B07405

Mann CP, Stix J, Vallance JW, Richer M (2004) Subaqueous intracaldera volcanism, Ilopango Caldera, El Salvador, Central America. In: Rose WI Jr, Bommer JJ, López DL, Carr MJ, Major JJ (eds) Natural hazards in El Salvador. Geological Society of America, Special Paper, vol 375, pp 159–174

Manville VR (2001) Sedimentology and history of Lake Reporoa: an ephemeral supra-ignimbrite lake, Taupo Volcanic Zone, New Zealand. In: White JDL, Riggs NR (eds) Volcanogenic sedimentation in lacustrine settings. International association of sedimentologists, Special Publication, vol 30, pp 109–140

Manville V (2002) Sedimentary and geomorphic responses to a large ignimbrite eruption: readjustment of the Waikato river in the aftermath of the A.D. 181 Taupo eruption, New Zealand. J Geol 110:519–542

Manville V (2004) Palaeohydraulic analysis of the 1953 Tangiwai lahar: New Zealand's worst volcanic disaster. Acta Vulcanol XVI(1/2):137–152

Manville V (2010) An overview of break-out floods from intracaldera lakes. Glob Planet Change 70:14–23

Manville V, Cronin SJ (2007) Break-out lahar from New Zealand's Crater Lake. EOS Trans AGU 88:441–442

Manville V, Wilson CJN (2003) Interactions between volcanism, rifting and subsidence: implications of intracaldera palaeoshorelines at Taupo volcano, New Zealand. J Geol Soc London 160:3–6

Manville V, Wilson CJN (2004) The 26.5 ka Oruanui eruption, New Zealand: a review of the roles of volcanism and climate in the post-eruptive sedimentary response. NZ J Geol Geophys 47:525–547

Manville VR, White JDL, Houghton BF, Wilson CJN (1999) Paleohydrology and sedimentology of a post-1800a breakout flood from intracaldera Lake Taupo, North Island, New Zealand. Geol Soc Am Bull 111:1435–1447

Manville V, Newton EH, White JDL (2005) Fluvial responses to volcanism: resedimentation of the 1800a Taupo ignimbrite in the Rangitaiki River catchment, North Island, New Zealand. Geomorphology 65:49–70

Manville V, Hodgson KA, Nairn IA (2007) A review of break-out floods from volcanogenic lakes in New Zealand. NZ J Geol Geophys 52:131–150

Massey C, Manville V, Hancox GT, Keys HJR, Lawrence C, McSaveney MJ (2010) Out-burst flood (lahar) triggered by retrogressive landsliding, 18 March 2007 at Mt. Ruapehu, New Zealand—a successful early warning. Landslides 7:303–315

Mastin LG (1995) Thermodynamics of gas and steam-blast eruptions. Bull Volcanol 57:85–98

Mastin LG (1997) Evidence for water influx from a caldera lake during the explosive hydromagmatic eruption of 1790, Kilauea volcano, Hawaii. J Geophys Res 102:20093–20109

Mastin LG, Witter JB (2000) The hazards of eruptions through lakes and seawater. J Volcanol Geoth Res 97:195–214

McClelland L, Simkin T, Summers M, Nielsen E, Stein TC (1989) Global volcanism, 1975–1985. Prentice-Hall, Englewood Cliffs, 655 p

McCoy FW, Heiken G (2000) The late-bronze age explosive eruption of Thera (Santorini), Greece: regional and local effects. In: McCoy FW, Heiken G (eds) Volcanic hazards and disasters in human antiquity. Geological Society of America, Special Publication, vol 345, pp 43–70

McGimsey RG, Waythomas CF, Neal CA (1994) High stand and catastrophic draining of intracaldera Surprise Lake, Aniakchak Volcano, Alaska. U.S. Geol Surv Bull 2107:59–71

McGuire WJ (1996) Volcano instability: a review of contemporary issues. In: McGuire WJ, Jones AP, Neuberg J (eds) Volcano instability on the Earth and other planets. Geological Society of London, Special Publication, vol 110, pp 1–23

Meier MF, Carpenter PJ, Janda RJ (1981) Hydrologic effects of Mount St. Helens' 1980 eruptions. EOS Trans AGU 62(33):625–626

Meyer DF, Martinson HA (1989) Rates and processes of channel development and recovery following the 1980 eruption of Mount St. Helens, Washington. J Hydrol Sci 34:115–127

Meyer W, Sabol MA, Schuster RL (1986) Landslide dammed lakes at Mount St. Helens, Washington. In: Schuster RL (ed) Landslide dams—process, risk, and mitigation. American society of civil engineers geotechnical Special Publication, vol 3, pp 21–41

Miller TP, Smith RL (1977) Spectacular mobility of ash flows around Aniakchak and Fisher calderas, Alaska. Geology 5:173–176

Miura K, Ban M, Ohba T, Fujinawa A (2012) Sequence of the 1895 eruption of the Zao volcano, Tohuku Japan. J Volcanol Geoth Res 247–248:139–157

Moore JG (1967) Base surge in recent volcanic eruptions. Bull Volcanol 30:337–363

Moore JG, Nakamura K, Alcarez A (1966a) The September 28–30, 1965 eruption of Taal Volcano, Philippines. Bull Volcanol 29:75–76

Moore JG, Nakamura K, Alcarez A (1966b) The 1965 eruption of Taal Volcano. Science 151:955–960

Mooser F, Meyer-Abich H, McBirney AR (1958) Central America. Catalogue of active volcanoes of the world including solfatara fields, Part VI, International Association of Volcanology and Chemistry of the Earth's Interior, Rome, Italy, 146 p

Morimoto R (1948) Submarine eruption of the Myôjin reef. Bull Volcanol 23:151–160

Morrissey M, Gisler G, Weaver R, Gittings ML (2010) Numerical model of crater lake eruptions. Bull Volcanol 72:1169–1178

Motyka RJ (1977) Katmai caldera: glacier growth, lake rise, and geothermal activity. Short Notes Alaskan Geol 55:17–21

Nairn IA (1979) Rotomahana-Waimangu eruption, 1886. base-surge and basalt magma. NZ J Geol Geophys 22:363–378

Nairn IA (2002) Geology of the Okataina volcanic centre. Institute of Geological and Nuclear Sciences, geological map no. 25 (1:50 000). Lower Hutt, New Zealand, 1 sheet + 156 p

Nairn IA, Wood CP, Hewson CAY (1979) Phreatic eruptions of Ruapehu: April 1975. NZ J Geol Geophys 22:155–173

Nairn IA, Self S, Cole JW, Leonard GS, Scutter C (2001) Distribution, stratigraphy and history of proximal deposits from the—AD 1305 Kaharoa eruption of Tarawera volcano, New Zealand. NZ J Geol Geophys 44:467–484

Nakagawa M, Wada K, Thordarson T, Wood CP, Gamble JA (1999) Petrological investigations of the 1995 and 1996 eruptions of Ruapehu volcano, New Zealand: formation of discrete and small magma pockets and their intermittent discharge. Bull Volcanol 61:15–31

Nayar A (2009) A lakeful of trouble. Nature 460:321–333

Neall VE (1996) Hydrological disasters associated with volcanoes. In: Singh VP (ed) Hydrology of disasters. Kluwer, Dordrecht, pp 395–425

Nelson CH, Bacon CR, Robinson SW, Adam DP, Bradbury JP, Barber JH Jr, Schwartz D, Vagenas G (1994) The volcanic, sedimentologic, and paleolimnologic history of the Crater Lake caldera floor, Oregon: evidence for small caldera evolution. Geol Soc Am bull 106:684–704

Németh K, Cronin SJ, Charley D, Harrison M, Garae E (2006) Exploding lakes in Vanuatu—"Surtseyan-style" eruptions witnessed on Ambae Island. Episodes 29:87–92

Németh K, Cronin SJ, Smith IEM, Flores JA (2012) Amplified hazard of small-volume monogenetic eruptions due to environmental conditions, Orakei Basin, Auckland Volcanic Field, New Zealand. Bull Volcanol 74:2121–2137

Newhall CG, Dzurisin D (1988) Historical unrest at large calderas of the world. US Geol Surv Bull 1855:1108 p

Newhall CG, Punongbayan RS (1996) Fire and mud: eruptions and lahars of Mount Pinatubo, Philippines. University of Washington Press, Seattle, 1126 p

O'Connor JE, Beebee RA (2009) Floods from natural rock-material dams. In: Burr DM, Carling PA, Baker VR (eds) Megaflooding on Earth and Mars. Cambridge University Press, Cambridge, pp 128–171

O'Connor JE, Clague JJ, Walder JS, Manville V, Beebee RA (2013) Outburst floods. In: Shroder JF (ed) Treatise on geomorphology. Academic Press, San Diego, pp 475–510

Oppenheimer C (1993) Infrared surveillance of crater lakes using satellite data. J Volcanol Geoth Res 55:117–128

O'Shea BE (1954) Ruapehu and the Tangiwai disaster. NZ J Sci Technol B36:174–189

Otway PM (1986) Vertical deformation associated with the Taupo earthquake swarm, June 1983. In: Reilly WI, Harford BE (eds) Recent crustal movements. Royal Society of New Zealand Bulletin, vol 24, pp 187–200

Pain CF, Blong RJ, McKee CO, Polach HA (1981) Pyroclastic deposits and eruptive sequences of Long Island. In: Johnson RW (ed) Cooke-Ravian volume of volcanological papers. Geological Survey of Papua New Guinea, Port Moresby, Memoir, vol 10, pp 101–113

Park C, Schmincke H-U (1997) Lake formation and catastrophic dam burst during the Late Pleistocene Laacher See eruption (Germany). Naturwissenschaft 84:521–525

Pierson TC (1985) Initiation and flow behavior of the 1980 Pine Creek and Muddy River lahars, Mount St. Helens, Washington. Geol Soc Am Bull 96:1056–1069

Pierson TC (1997) Transformation of water flood to debris flow following the eruption-triggered transient-lake breakout from the crater on 19 March 1982. In: Pierson TC (ed) Hydrologic consequences of hot-rock/snowpack interactions at Mount St. Helens volcano, Washington, 1982–1984. United States geological survey open-file report, vol 96–179, pp 19–36

Pierson TC, Janda RJ, Thouret J-C, Borrero CA (1990) Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Columbia, and consequent mobilization, flow and deposition of lahars. J Volcanol Geoth Res 41:17–66

Pierson TC, Janda RJ, Umbal JV, Daag AS (1992) Immediate and long-term hazards from lahars and excess sedimentation in rivers draining Mt. Pinatubo, Philippines. U.S. Geol Surv Water-Resour Invest Rep 92–4039:183–203

Procter JN, Cronin SJ, Fuller IC, Lube G, Manville V (2010) Quantifying the geomorphic impacts of a lake break-out flood, Mt. Ruapehu. NZ Geol 38:67–70

Pulgarin B, Macías JL, Cepeda H, Capra L (2004) Late Pleistocene deposits associated with a southern flank collapse of the Nevado del Huila volcanic complex (Colombia). Acta Vulcanolgica 16:37–58

Pullar WA, Selby MJ (1971) Coastal progradation of Rangitaiki Plains, New Zealand. NZ J Sci 14:419–434

Ramos EG (1986) Lakeshore landslides: unrecognised hazards around Taal volcano. Philippine J Volcanol 3:28–53

Reid ME, Sisson TW, Brien DL (2001) Volcano collapse promoted by hydrothermal alteration and edifice shape, Mount Rainier, Washington. Geology 29:779–782

Reynolds MA, Best JG, Johnson RW (1980) 1953–57 eruption of Tuluman volcano: rhyolitic volcanic activity in the northern Bismarck sea. Geol Surv P N G Mem 7:5–44

Richer M, Mann CP, Stix J (2004 Mafic magma injection triggers eruption at Ilopango Caldera, El Salvador, Central America. In: Rose WI Jr, Bommer JJ, López DL, Carr MJ, Major JJ (eds) Natural hazards in El salvador. Geological Society of America, Special Paper, vol 375, pp 175–189

Riggs NR, Ort M, White JDL, Wilson CJN, Clarkson R (2001) Post-1.8-ka marginal sedimentation in Lake Taupo, New Zealand: effects of wave energy and sediment supply in a rapidly rising lake. In: White JDL, Riggs NR (eds) Volcanogenic sedimentation in lacustrine settings. International Association of Sedimentologists, Special Publication, vol 30, pp 151–177

Rodolfo KS (2000) The hazard from lahars and jökulhlaups. In: Sigurdsson H, Houghton B, McNutt S, Rymer H, Stix J (eds) Encyclopedia of volcanoes. Academic Press, New York, pp 973–995

Rodolfo KS, Umbal JV (2008) A prehistoric lahar-dammed lake and eruption of Mount Pinatubo described in a Philippine aborigine legend. J Volcanol Geoth Res 176:432–437

Rodolfo KS, Umbal JV, Alonso RA, Remotigue CT, Paladio-Melosantos ML, Salvador JHG, Evangelista D, Miller Y (1996) Two years of lahars on the western flank of Mount Pinatubo: Initiation, flow processes, deposits, and attendant geomorphic and hydraulic changes. In: Newhall CG, Punongbayan RS (eds) Fire and Mud, eruptions and lahars of Mount Pinatubo. University of Washington Press, Seattle, Philippines, pp 989–1013

Rose WI (1972) Notes on the 1902 eruption of Santa María Volcano, Guatemala. Bull Volcanol 36:1–17

Rose WI, Conway FM, Pullinger CR, Deino CR, McIntosh WC (1999) An improved age framework for late quaternary silicic eruptions in northern Central America. Bull Volcanol 61:106–120

Rowe GLJ, Ohsawa S, Takano B, Brantley SL, Fernandez JF, Barquero J (1992) Using crater lake chemistry to predict volcanic activity at Poás volcano, Costa Rica. Bull Volcanol 54:494–503

Schaefer JR, Scott WE, Evans WC, Jorgenson J, McGimsey RG, Wang B (2008) The 2005 catastrophic acid crater lake drainage, lahar, and acidic aerosol formation at Mount Chiginagak volcano, Alaska, USA: field observations and preliminary water and vegetation chemistry results. Geochem Geophys Geosyst 9:Q07018

Schuster RL (2000) Outburst debris-flows from failure of natural dams. In: Wieczorek G, Naeser N (eds) Debris-flow hazards mitigation: mechanics, prediction, and assessment. Balkema, Rotterdam, pp 29–42

Schuster RL, Evans SG (2011) Engineering measures for the hazard reduction of landslide dams. In: Evans SG, Hermanns RL, Strom A, Scarascia-Mugnozza G (eds) Natural and artificial rockslide dams. Springer, Berlin, pp 77–100

Scott KM (1988) Origin, behavior, and sedimentology of prehistoric catastrophic lahars at Mt. St. Helens, Washington. Geological Society of America, Special Paper, vol 229, pp 23–36

Scott KM (1989) Magnitude and frequency of lahars and lahar-runout flows in the Toutle-Cowlitz River system. United States geological survey, Professional Paper, vol 1447-B, 33 p

Scott KM, Hoblitt RE, Torres RC, Self S, Martinez MML, Nillos T Jr (1996a) Pyroclastic flows of the June 15, 1991, climactic eruption of Mount Pinatubo. In: Newhall CG, Punongbayan RS (eds) Fire and Mud, eruptions and lahars of Mount Pinatubo, Philippines. University of Washington Press, Seattle, pp 545–570

Scott KM, Janda RJ, De La Cruz EG, Gabinete E, Eto I, Isada M, Sexon M, Hadley KC (1996b) Channel and sedimentation responses to large volumes of 1991 volcanic deposits on the east flank of Mount Pinatubo. In: Newhall CG, Punongbayan RS (eds) Fire and Mud, eruptions and lahars of Mount Pinatubo. University of Washington Press, Seattle, Philippines, pp 971–988

Segschneider B, Landis CA, Manville V, White JDL, Wilson CJN (2002) Environmental response to a large, explosive rhyolite eruption: Lithofacies and physical sedimentology of post-1.8 ka pumice-rich Taupo volcaniclastics in the Hawke's Bay region. NZ Sediment Geol 150:275–299

Self S, Rampino MR (1981) The 1883 eruption of Krakatau. Nature 294:699–704

Shepherd JB, Aspinall WP, Rowley KC, Pereira J, Sigurdsson H, Fiske RS, Tomblin JF (1979) The eruption of Soufrière volcano, St Vincent April–June 1979. Nature 282:24–28

Sheridan MF, Wohletz KH (1983) Hydrovolcanism: basic considerations and review. J Volcanol Geoth Res 17:1–29

Siebert L (1984) Large volcanic debris avalanches: characteristics of source areas, deposits, and associated eruptions. J Volcanol Geoth Res 22:163–197

Siebert L (1996) Hazards of large volcanic debris avalanches and associated eruptive phenomena. In: Scarpa R, Tilling RI (eds) Monitoring and mitigation of volcano hazards. Springer, Berlin, pp 541–572

Siebert L, Begét JE, Glicken H (1995) The 1883 and late-prehistoric eruptions of Augustine volcano, Alaska. J Volcanol Geoth Res 66:367–395

Sigurdsson H, Devine JD, Tchoua FM, Presser TS, Pringle MKW, Evans WC (1987) Origin of the lethal gas burst from Lake Monoun, Cameroon. J Volcanol Geoth Res 31:1–16

Silva L, Cochemé JJ, Canul R, Duffield W, Tilling R (1982) El Chichón Volcano. SEAN Bulletin, Smithsonian Institution 7(5):2–6

Simkin T, Siebert L (1994) Volcanoes of the world. Smithsonian institution, global volcanism program. Geoscience press, Tucson, Arizona, 349 p

Simmons SF, Keywood M, Scott BJ, Kearn RF (1993) Irreversible change of the Rotomahana-Waimangu hydrothermal system (New Zealand) as a consequence of a volcanic eruption. Geology 21:643–646

Smart GM (1981) Volcanic debris control, Gunung Kelud, East Java. In: Erosion and transport in Pacific Rim steeplands. International Association of Hydrological Sciences Publication, vol 134, pp 604–654

Smith RCM (1991a) Landscape response to a major ignimbrite eruption, Taupo Volcanic Center, New Zealand. In: Fisher RV, Smith GA (eds) Sedimentation in volcanic settings. Society of Economic Paleontologists and Mineralogists Special Publication, vol 45, 123–137

Smith RCM (1991b) Post-eruption sedimentation on the margin of a caldera lake, Taupo Volcanic Centre, New Zealand. Sed Geol 74:89–138

Smith RT, Houghton BF (1995) Vent migration and changing eruptive style during the 1800a Taupo eruption: new evidence from the Hatepe and Rotongaio phreatoplinian ashes. Bull Volcanol 57:432–440

Sparks RSJ (1976) Grain size variations in ignimbrites and implications for the transport of pyroclastic flows. Sedimentology 23:147–188

Stelling P, Gardner J, Begét JE (2005) Eruptive history of fisher Caldera, Alaska, USA. J Volcanol Geoth Res 139:163–183

Stilwell WF, Hopkins HJ, Appleton W (1954) Tangiwai railway disaster: report of board of inquiry, Wellington, NZ, 31 p

Stimac JA, Goff F, Counce D, Larocque ACL, Hilton DR, Morgenstern U (2004) The crater lake and hydrothermal system of Mount Pinatubo, Philippines: evolution in the decade after the eruption. Bull Volcanol 66:149–167

Stoopes GR, Sheridan MR (1992) Giant debris avalanches from the Colima volcanic complex, Mexico: implications for long runout landslides (>100 km) and hazard assessment. Geology 20:299–302

Suryo I, Clarke MCG (1985) The occurrence and mitigation of volcanic hazards in Indonesia as exemplified at the Mount Merapi, Mount Kelut and Mount Galunggung volcanoes. Q J Eng Geol 18:79–98

Swift CHI, Kresch DL (1983) Mudflow hazards along the Toutle and Cowlitz rivers from a hypothetical failure of Spirit Lake blockage. U.S. geological survey, water-resources investigation report, vol 82–4125. Tacoma, Washington, 10 p

Taig T (2002) Ruapehu lahar residual risk assessment. TTAC Limited, 77 p. and 8 appendices

Tanguy J-C, Ribière C, Scarth A, Tjetjep WS (1998) Victims from volcanic eruptions: a revised database. Bull Volcanol 60:137–144

Tazieff H (1989) Mechanisms of the Nyos carbon dioxide disaster and of co-called phreatic steam eruptions. J Volcanol Geoth Res 39:109–116

Thiele R, Moreno H, Elgueta S (1998) Quaternary geological-geomorphological evolution of the uppermost course of the Río Laja valley. Rev Geol Chile 25:229–253

Thorarinsson S, Einarsson T, Sigvaldason GE, Elisson G (1964) The submarine eruption off the Vestmann Islands 1963-64. Bull Volcanol 27:434–445

Thouret JC, Abdurachman KE, Bourdier J-L, Bronto S (1998) Origin, characteristics, and behaviour of lahars following the 1990 eruption of Kelud volcano, eastern Java (Indonesia). Bull Volcanol 59:460–480

Tinti S, Pagnoni G, Zaniboni F (2006a) The landslides and tsunamis of the 30th December 2002 in Stromboli analysed through numerical simulations. Bull Volcanol 68:462–479

Tinti S, Maramai A, Armigliato A, Graziani L, Manucci A, Pagnoni G, Zaniboni F (2006b) Observations of physical effects from tsunamis of December 30, 2002 at Stromboli volcano, southern Italy. Bull Volcanol 68:450–461

Tómasson H (1996) The jökulhlaup from Katla in 1918. Ann Glaciol 22:249–254

Tómasson H (2002) Catastrophic floods in Iceland. In: Snorrason Á, Finnsdóttir HP, Moss ME (eds) The extremes of the extremes: extraordinary floods. International Association of Hydrological Sciences publication, vol 271, pp 121–126

Torsvik T, Paris R, Didenkulova I, Pelinovsky E, Belousov A, Belousova M (2010) Numerical simulation of a tsunami event during the 1996 eruption in Karymskoye lake, Kamchatka, Russia. Nat Hazards Earth Syst Sci 10:2359–2369

Turner G, Ingham M, Bibby H (2007) Electrical resistivity monitoring of seepage and stability of the tephra barrier at Crater Lake, Mt Ruapehu, New Zealand. Geophys Res Abstr 9:11630

Tweed FS, Russell AJ (1999) Controls on the formation and sudden drainage of glacier-impounded lakes: implications for jökulhlaup characteristics. Prog Phys Geogr 23:79–110

Umbal JV, Rodolfo KS (1996) The 1991 lahars of southwestern Mount Pinatubo and evolution of the lahar-dammed Mapanuepe Lake. In: Newhall CG, Punongbayan RS (eds) Fire and Mud, eruptions and lahars of Mount Pinatubo. University of Washington Press, Seattle, Philippines, pp 951–970

van Padang MN (1951) Indonesia. Catalogue of active volcanoes of the world including solfatara fields, part I, International Association of Volcanology and Chemistry of the Earth's Interior, Rome, Italy, 271 p

Varekamp JC, Ouimette AP, Herman SW, Bermúdez A, Delpino D (2001) Hydrothermal element fluxes from Copahue, Argentina: a "beehive" volcano in turmoil. Geology 29:1059–1062

Vidal N, Merle O (2000) Reactivation of basement faults beneath volcanoes: a new model of flank collapse. J Volcanol Geoth Res 99:9–26

Voight B, Glicken H, Janda RJ, Douglass PM (1981) Catastrophic rockslide avalanche of May 18. In: Lipman PW, Mullineaux DR (eds) The 1980 eruptions of Mount St. Helens, Washington. United States geological survey professional paper, vol 1250, pp 347–377

Wagner TP, McKee CO, Kuduon J, Kombua R (2003) Landslide-induced wave in a small volcanic lake: Kasu Tephra Cone, Papua New Guinea. Int J Earth Sci 92:405–406

Waitt RB Jr, Pierson TC, MacLeod NS, Janda RJ, Voight B, Holcomb RT (1983) Eruption-triggered avalanche, flood, and lahar at Mount St. Helens—effects of winter snowpack. Science 221:1394–1397

Walder JS, Costa JE (1996) Outburst floods from glacier-dammed lakes: the effect of mode of drainage on flood magnitude. Earth Surf Proc Land 21:701–723

Walder JS, Watts P, Sorensen OE, Janssen K (2003) Tsunamis generated by subaerial mass flows. J Geophys Res 108:EPM 2.1–2.19

Walder JS, Watts P, Waythomas CF (2006) Case study: mapping tsunami hazards associated with debris flow into a reservoir. J Hydraul Eng 132:1–11

Walker GPL (1981) Characteristics of two phreatoplinian ashes, and their water-flushed origin. J Volcanol Geoth Res 9:395–407

Walker GPL, Self S, Wilson L (1984) Tarawera 1886—a basaltic plinian fissure eruption. J Volcanol Geoth Res 21:61–78

Ward RH (1922) A note on the significance of the recent subsidence of the shore of Lake Taupo. NZ J Sci Technol 5:280–281

Ward SN (2001) Landslide tsunami. J Geophys Res 106:11201–11215

Waters AC, Fisher RV (1971) Base surges and their deposits: Capelinhos and Taal volcanoes. J Geophys Res 76:5596–5614

Watts P, Waythomas CF (2003) Theoretical analysis of tsunami generation by pyroclastic flows. J Geophys Res 108(B12):EPM 4.1–4.4.21

Waythomas CF (2001) Formation and failure of volcanic debris dams in the Chakachatna river valley associated with eruptions of the Spurr volcanic complex, Alaska. Geomorphology 39:111–129

Waythomas CF, Neal CA (1998) Tsunami generation by pyroclastic flow during the 3500-year B.P. caldera-forming eruption of Aniakchak Volcano, Alaska. Bull Volcanol 60:110–124

Waythomas CF, Walder JS, McGimsey RG, Neal CA (1996) A catastrophic flood caused by drainage of a caldera lake at Aniakchak Volcano, Alaska, and implications for volcanic-hazards assessment. Geol Soc Am Bull 108:861–871

Webb TH, Ferris BG, Harris JS (1986) The Lake Taupo, New Zealand, earthquake swarms of 1983. NZ J Geol Geophys 33:377–389

Wei H, Sparks RSJ, Liu R, Fan Q, Wang Y, Hong H, Zhang HW, Chen H, Jiang C, Dong J, Zheng Y, Pan Y (2003) Three active volcanoes in China and their hazards. J Asian Earth Sci 21:515–526

Wei H, Hong H, Sparks RSJ, Walder JS, Han B (2004) Potential hazards of eruptions around the Tianchi caldera lake, China. Acta Geol Sinica 78:790–794

White JDL (1996) Impure coolants and interaction dynamics of phreatomagmatic eruptions. J Volcanol Geoth Res 74:155–170

White JDL, Houghton BF, Hodgson KA, Wilson CJN (1997) Delayed sedimentary response to the A.D. 1886 eruption of Tarawera, New Zealand. Geology 25:459–462

Williams H (1941) Calderas and their origins. Univ Calif Bull Geol Sci 25:239–346

Wilson CJN (1993) Stratigraphy, chronology, styles and dynamics of late Quaternary eruptions from Taupo volcano, New Zealand. Philos Trans R Soc Lond A343:205–306

Wilson CJN (2001) The 26.5 ka Oruanui eruption, New Zealand: an introduction and overview. J Volcanol Geoth Res 112:133–174

Wilson CJN, Walker GPL (1985) The Taupo eruption, New Zealand. I. General aspects. Philos Trans R Soc Lond A314:199–228
Wilson CJN, Riggs NR, Ort MH, White JDL, Houghton BF (1997) An annotated atlas of post-1.8 ka shoreline features at Lake Taupo, New Zealand. Institute of Geological and Nuclear Sciences, Science Report, vol 97, no 19, Lower Hutt, New Zealand, 35 p
Witham CS (2005) Volcanic disasters and incidents: a new database. J Volcanol Geoth Res 148:191–233
Wohletz KH (1986) Explosive magma-water interactions: thermodynamics, explosion mechanisms, and field studies. Bull Volcanol 48:245–264
Wolfe BA, Begét JE (2002) Destruction of an Aleut village by a catastrophic flood release from Okmok caldera, Umnak Island, Alaska. In: Proceedings of GSA Denver annual meeting. Division of Geological and Geophysical Surveys, Denver, CO
Yasui M, Koyaguchi T (2004) Sequence and eruptive style of the 1783 eruption of Asama Volcano, central Japan: a case study of an andesitic explosive eruption generating fountain-fed lava flow, pumice fall, scoria flow and forming a cone. Bull Volcanol 66:243–262
Youd TL, Wilson RC, Schuster RL (1981) Stability of blockage in North Fork Toutle river. In: Lipman PW, Mullineaus DR (eds) The 1980 eruptions of Mount St. Helens, Washington. United States Geological Survey Professional Paper 1250, pp 821–828
Zen MT, Hadikusumo D (1965) The future danger of Mt. Kelut (eastern Java—Indonesia). Bull Volcanol 28:275–282