Advances in Volcanology

Dmitri Rouwet
Bruce Christenson
Franco Tassi
Jean Vandemeulebrouck
Editors

Volcanic Lakes

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Advances in Volcanology

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Editors

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Editors
Dmitri Rouwet
Sezione di Bologna
Istituto Nazionale di Geofisica e Vulcanologia
Bologna
Italy

Bruce Christenson
GNS Science
Lower Hutt
New Zealand

Franco Tassi
Earth Sciences
University of Florence
Florence
Italy

Jean Vandemeulebrouck
Institut des Sciences de la Terre
Université de Savoie
Le Bourget du Lac
France

Videos to this book can be accessed at http://www.springerimages.com/videos/978-3-642-36833-2.

Advances in Volcanology
ISBN 978-3-642-36832-5 ISBN 978-3-642-36833-2 (eBook)
DOI 10.1007/978-3-642-36833-2

Library of Congress Control Number: 2014957163

Springer Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer-Verlag GmbH Berlin Heidelberg is part of Springer Science+Business Media (www.springer.com)

Foreword

Volcanic Lakes are fascinating. And useful. They trap. They integrate. They evaporate. They are dynamic balances of input, both volcanic and meteoric, and output (gas through-flux, evaporation, seepage and spillover). Changes in lake temperature or chemistry often, though not always, indicate changes in magma degassing; changes in lake level can indicate strain of the edifice; and bubbling in lakes can be recorded acoustically—all helpful in eruption forecasting. Lakes are windows into groundwater and many are windows into hydrothermal systems with a myriad of processes including chemical transport and deposition, self-sealing, transient pressurization, and explosive disruption. Seepage of acidic hydrothermal fluid weakens rock of volcanic edifices, making them prone to collapse. Accumulation of CO_2 and/or CH_4 deep within lakes creates the potential for overturn. Volcanic lakes that are suddenly breached or expelled scour channels to form sediment-rich lahars.

Volcanic lakes also record history. They preserve thin ash layers that are unlikely to survive erosion and bioturbation outside the lakes. Such ash can be from the host volcano or from afar, giving valuable information about eruptive histories in both instances. They preserve environmental indicators such as pollen, diatoms, and inorganic indicators. And, in some cases, they capture a history of unrest of the volcano itself—precious data that predate modern monitoring.

Some lakes are extreme environments—in acidity, sulfur, trace metals, and a primordial soup of extremophile organisms. Every volcanic lake, from acidic to alkaline, has its own story to tell about its host volcano and its surroundings. The chapters in this monograph tell some of those stories, but focus mainly on reviewing tools with which future workers can decipher stories by themselves. Enjoy the vast experience represented by these authors! Just as volcanic lakes are enriched by multiple inputs, so too will your enjoyment of the lakes be enriched by these chapters!

Chris Newhall

Contents

Volcanic Lakes

Bruce Christenson, Karoly Németh, Dmitri Rouwet, Franco Tassi, Jean Vandemeulebrouck, and Johan C. Varekamp

Abstract

Volcanic lakes are amongst the most spectacular natural features on the planet. These intersections of magmatic-hydrothermal systems and the Earth's surface are, poetically speaking, "blue windows" into the depth of a volcano (Fig. 1). The changing water compositions and colors of these lakes over time provide insights into the volcanic, hydrothermal and degassing processes of the underlying volcano.

Keywords

Volcanic lakes · Genetic classification · Chemical classification · Limnology · Volcanic lake color · Statement

B. Christenson
GNS, Lower Hutt, New Zealand

K. Németh
CS-INR, Volcanic Risk Solutions,
Massey University, Palmerston North, New Zealand

D. Rouwet (✉)
Istituto Nazionale di Geofisica e Vulcanologia,
Sezione di Bologna, Via Donato Creti 12 CAP,
40128 Bologna, Italy
e-mail: dmitri.rouwet@ingv.it

F. Tassi
Department of Earth Sciences, University of Florence, Florence, Italy

F. Tassi
CNR-IGG, Florence, Italy

J. Vandemeulebrouck
Laboratoire de Géophysique Interne et Tectonophysique, CNRS, Université de Savoie, Chambéry, France

J.C. Varekamp
Department of Earth and Environmental Sciences, Wesleyan University, Middletown, CT, USA

1 Introduction

Volcanic lakes are amongst the most spectacular natural features on the planet. These intersections of magmatic-hydrothermal systems and the Earth's surface are, poetically speaking, "blue windows" into the depth of a volcano (Fig. 1). The changing water compositions and colors of these lakes over time provide insights into the volcanic, hydrothermal and degassing processes of the underlying volcano. Volcanic lakes can be highly dynamic systems or pass through stages of relatively slow fluid exchanges, depending on the lake water residence time (RT), which is defined by the lake volume and the input (or output) fluxes ($RT = V/Q_{input}$); the larger the lake volume and the lower the input fluxes, the longer the RT will be (months to years), while smaller lakes affected by high fluid input will result in a short RT (weeks to months) (Varekamp 2003;

D. Rouwet et al. (eds.), *Volcanic Lakes*, Advances in Volcanology,
DOI 10.1007/978-3-642-36833-2_1,

Fig. 1 Yugama lake, Kusatsu-Shirane volcano, Honshu, Japan (26 June 2012) (picture by T. Ohba). Yugama lake is probably the most monitored crater lake in the world, with the record starting in the 1960s. Currently many small earthquakes happen under the Yugama crater. The area 1 km from the center of the crater is restricted to approach

Taran and Rouwet 2008; Taran et al. 2013; Rouwet et al. 2014). The RT thus controls (i) the lake's sensitivity to potential changes caused by processes external to the lake (e.g., fluid input from the volcano), and (ii) the frequency needed to effectively monitor the lake (Rouwet et al. 2014).

Many studies dealt with mass, energy, chemical or isotopic budget analyses, with the aim to combine the thermal and chemical behavior of lakes, often useful in volcanic monitoring setups (Hurst et al. 1991, 2012, this issue; Rowe et al. 1992a; Ohba et al. 1994, 1994; Pasternack and Varekamp 1997; Rouwet et al. 2004, 2008; Taran and Rouwet 2008; Rouwet and Tassi 2011; Varekamp, this issue). Lakes are approximated by a box of which the volume and temperature variations depend on heat and water entering (meteoric recharge, surface runoff, fluid input from the volcano) or exiting (evaporation, seepage, overflow) the lake. Fluid geochemistry is a common tool to study volcanic lakes, whereas subsurface processes may also be investigated by geophysical surveys (Rymer et al. 2000, 2009; Vandemeulebrouck et al. 2005; Fournier et al. 2009; Caudron et al. 2012), numerical modeling (Christenson et al. 2010; Todesco et al. 2012, this issue; Christenson and Tassi, this issue), and hydrogeology (Mazza et al., this issue).

Volcanic lake research was boosted after the August 1986 Lake Nyos limnic gas burst (Kling et al. 1987; Costa and Chiodini, this issue). This unfortunate event led to the foundation of the International Working Group on Crater Lakes (IWGCL), in the early 1990s re-baptized into the IAVCEI Commission on Volcanic Lakes (CVL). Former CVL-Leader JC Varekamp stated the multi-disciplinary character of CVL as follows: "the CVL has an important role to play within IAVCEI and a significant scientific mission in volcanology. Volcanic lakes are used to monitor volcanic activity, they harbor their own volcanic dangers (CO_2 explosions, lahars, phreatic explosions; Mastin and Witter 2000; Delmelle et al., this issue; Manville, this issue; Kusakabe, this issue; Rouwet and Morrissey, this issue), and may leak toxic fluids into the surface environment. In addition, they provide "deep blue" windows into the interior of volcanoes and even deeper into the magma source regions, with topical linkages towards ore deposition and geothermal energy development, all of which are reasons to pay substantial attention to volcanic lakes. In addition, many global change researchers use volcanic lakes for the study of environmental change. The sedimentary records are influenced both by climatic/hydrological parameters and volcanic inputs, and the expertise of CVL members can contribute to decipher these records. The CVL originators recognized that volcanic lakes provide a special field of endeavor, with intertwined aspects of volcanology, limnology, geochemistry, biology and toxicology."

This monograph on volcanic lakes touches on many of the above topics and aims to give an overview of the current state of volcanic lake research. We aim at offering an up-to-date manual on volcanic lake research, providing classic research methods as well as more high-tech approaches of future volcanic lake investigation and continuous monitoring. This chapter stresses the need to better define the various types of volcanic lakes, and provides a broad conceptual classification system based on the formation processes of lakes with respect to why, where, and how volcanic lakes form. Basic limnological aspects of lakes are reviewed, and color changes are explained, as not all volcanic lakes are just blue windows.

2 A Genetic Classification of Volcanic Lakes

For historical reasons, the nomenclature of volcanic lakes is thoroughly embedded in our geological vernacular, but may need some revisions. Tectonic, geomorphic and volcanologic processes all contribute to the formation of volcanic lakes as detailed below.

Classifying volcanic lakes can be based on the timing and status of volcanism of the region that hosts the volcanic lake. The temporal link between a volcanic event and lake formation provides one defining parameter for volcanic lake classification. A lake may develop inside the main active crater on a volcano or in a satellite vent that has only a minor role in the main volcanic structure. Alternatively, volcano/geomorphic processes (e.g., mudslides, lava flows, ash fall) may divert or block surface waters, or interfere gradually with drainage patterns far from an active vent. The latter may happen during volcanic activity or in a period following it. Areas with dispersed vents (e.g., cinder cone fields) can host maar lakes in active or long extinct craters, some with minor, other with major volcanic fluids inputs (Connor and Conway 2000; Németh 2010).

Before establishing an easy to follow matrix for volcanic lake genesis, some key questions should be addressed:

1. What is the status of the volcanic system associated with the lake?
2. Does magma reside close to the surface, and is eruption imminent?
3. How long after the last eruption did the volcanic lake form?
4. How strong is the genetic relationship between volcanic activity and the presence of a lake?
5. What is the role of the volcanic landform in providing the adequate basin for the volcanic lake?

So far, within this geotectonic perspective, there is no universal guideline on how such questions should be answered and, consequently, how lakes should be classified in relation to volcanic terrains. We suggest that the classification of volcanic lakes could follow a few main rules, based on four major variables:

1. the geotectonic assessment in which the lake is found (G), that can be expressed as monogenetic (0) or polygenetic (1) volcanic systems;
2. the relationship between the volcanism and the lake formation (R), that can be expressed as weak (0) or strong (1);
3. the timing of the volcanic lake formation in relationship to the volcanism (T), that can be expressed as long (0) or shortly (1) after the volcanic eruption;
4. the location of the volcanic lake in relationship to the volcanic center (L), that can be expressed as off (0) or over (1) the vent.

Such alpha-numerical expressions of lake types lead to a coding of volcanic lakes. The above suggested scheme can be combined with other aspects of the lakes that are more relevant to their chemical maturity (see below) and, eventually, biological status (Mapelli et al., this issue). Overall, we can say that deciphering the genetic background of volcanic lakes is often difficult, as the lake might literally cover part of the story to backtrack the formation history of some lakes (Marchetto et al., this issue). In the following sections some historically defined volcanic lake types are discussed in terms of the genetic classification issues outlined above.

2.1 Crater Lake (Code: G1, R1, T1, L1)

Volcanic lakes are often erroneously called crater lakes. Crater lakes are volcanic lakes typically associated with volcanoes that are classified as polygenetic from the genetic point of view (G1). Such volcanoes can form summit or central craters from explosive eruptive processes (e.g., Plinian eruptions, R1) that opened up deep and fairly large craters (Fig. 2). Soon after the crater forming eruptions (T1), due to climatic influences, local hydrogeology, and permanent degassing such craters can host deep and confined lakes that are eventually heated by the underlying magmatic-hydrothermal systems.

Crater lakes can be grouped into active versus inactive types as an expression whether the underlying vent is still considered to be connected with a magma reservoir or not. An active crater lake is located above an active vent (L1) producing continuous degassing during inter-eruptive periods. During eruptive periods such lakes can be totally or partially expelled and become the main water source of mass flow processes (e.g., lahars, Manville this issue) (Fig. 2).

Inactive crater lakes are associated with volcanic vents that are no longer attached to magma reservoirs. As a consequence such crater lakes are not influenced by degassing processes, nor significant hydrothermal activity. Beyond the scope of the genetic classification system, lake chemistry is the best means to provide information about the state of activity of the underlying vent (see below).

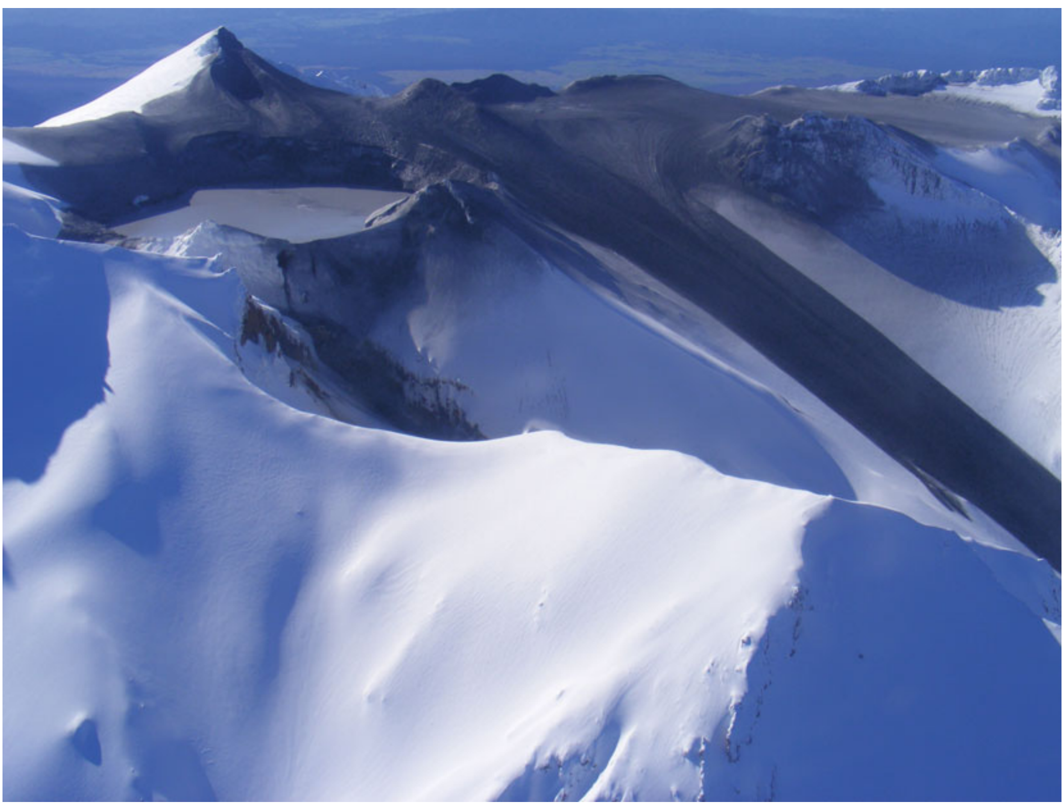


Fig. 2 Ruapehu Crater Lake after the September 2007 phreatomagmatic eruption and lahar (picture by K.N.)

Fig. 3 Crater Lake, Oregon, nearly 10 km in diameter, is actually a caldera lake formed after the 7700 y BP Mt Mazama eruption (Mandeville et al. 2009). In the front is Wizard Island (picture by D.R., August 2010)

2.2 Caldera Lake (Code: G1, R1, T0, L1)

Calderas are formed by collapse of the magma chamber after voluminous, often explosive eruptions in silicic volcanism (G1, R1) (e.g., Mt Masama-Crater Lake, Oregon, Fig. 3; Cosigüina lake, Nicaragua; Bolsena lake, Italy). They can have dimensions from kilometers to even tens of kilometers. The duration of the lake water fill after the eruption is unsure, but can be considerably long after (T0). Caldera lakes fill up these large calderas, most of the time entirely (L1).

2.3 Maar-Diatreme Lakes (Code: G0, R1, T1, L1)

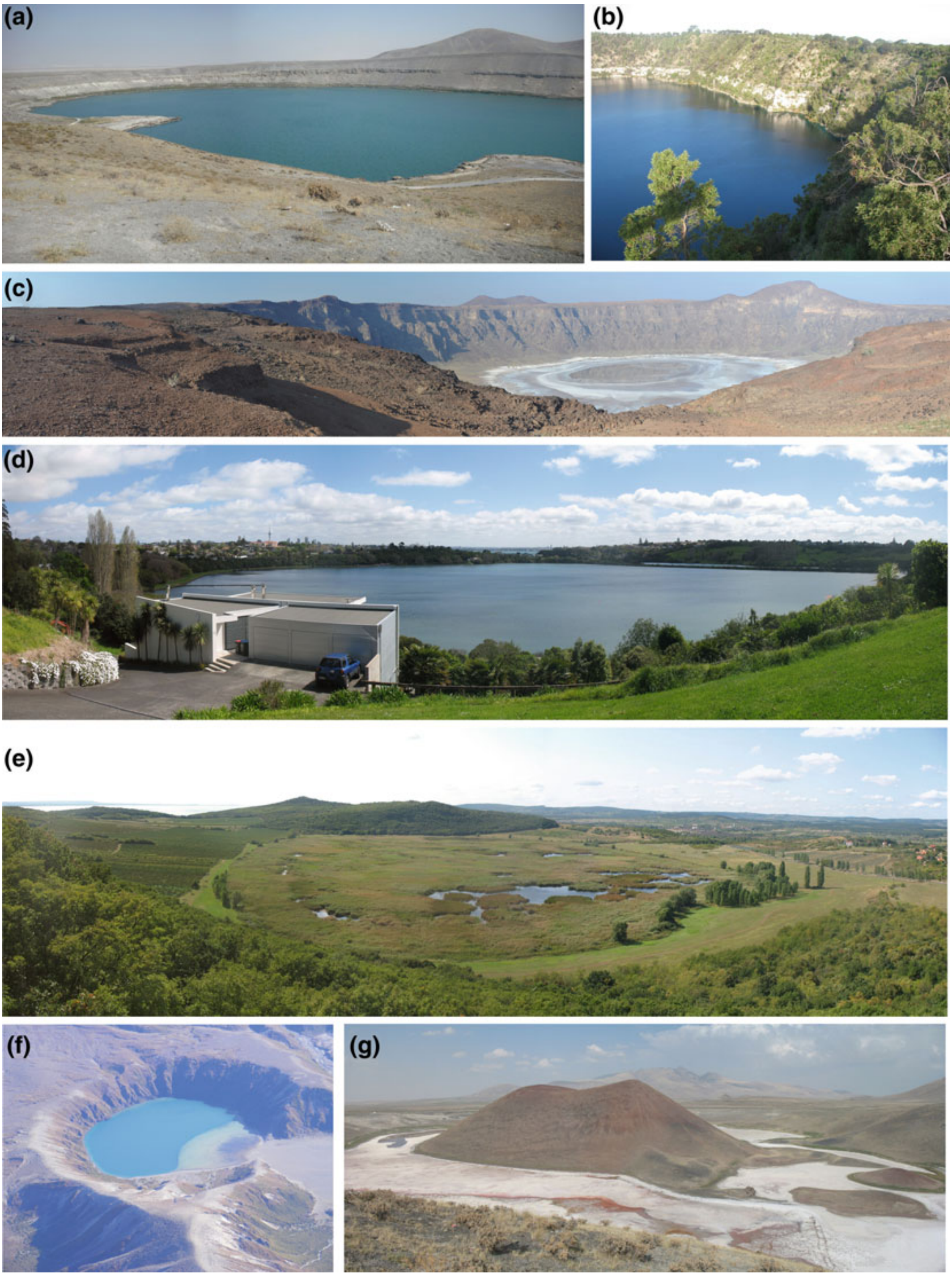
Maar volcanoes are typically formed by diatremes, and consist of maar craters surrounded by a relatively thin (few meters to over hundred meters) tephra rim. They are commonly associated with alkaline basaltic intra-continental volcanism (Lorenz 1986; White and Ross 2011; Kereszturi and Németh 2012; Aka, this issue). In such a scenario however, the erodible scoria deposits can be weathered significantly providing low permeable sediments, a necessary constraint to form a lake (Pasternack and Varekamp 1997). The lake can fill the gaps between the intra-crater scoria and lava spatter cone edifices and their remnants and the inner crater wall of the maar (Fig. 4).

2.4 Geothermal Lake (Code: G0-1, R1, T1, L0-1)

Geothermal lakes are formed in volcanic areas within explosion craters, but are not necessarily formed within a volcanic edifice as such (G0-1). A vent or crater formed during a phreatic eruption (R1), is filled by the geothermal aquifer fluid which gave rise to the eruption (T1). A clear example of a geothermal lake is Oyunama Lake, Noboribetsu geothermal area, Hokkaido, Japan (Fig. 5) (Delmelle and Bernard, this issue).

2.5 Lake in a Volcanic Environment (Code: G1, R0, T0, L0)

Lakes can form in depressions caused by active tectonics in volcanic areas (G1). The tectonics has a regional character, rather than being related to the volcano itself. The graben lakes of the East African Rift system, surrounded by volcanoes, are probably the best examples (e.g., Kivu lake, Vaselli et al.,


(a)
(b)
(c)
(d)
(e)
(f)
(g)

◀**Fig. 4** Volcanic lakes associated with maar-diatreme volcanoes such as in the case of the **a** Aci Gölü (Aci Lake) near Karapınar in Turkey (Keller 1975) represents a near perfect circular maar crater filled with deep water. The maar crater wall today represents the structural boundary of the maar-diatreme itself; **b** Blue Lake at Mt Gambier in South Australia (van Otterloo and Cas 2013) is a maar lake cut deeply into a limestone country rock. The lake level is controlled by karstic water systems of the limestone country rocks keeping the lake deep; **c** Al Wahbah crater is a maar volcano in Saudi Arabia that cut into a Proterozoic crystalline basement rock (Moufti et al. 2013). It hosts a temporal shallow lake that changes its level according to climatic conditions; **d** Orakei maar in Auckland, New Zealand (Németh et al. 2012) hosts a maar lake formed over alluvial, coastal deposits and it occupies the space between the erosionally retreated maar crater wall today. This means that the volcanic lake today has a larger surface area and shallower water depth than the original maar lake; **e** Külsö-tó in Tihany, Hungary (Németh et al. 2001) is a volcanic lake that is inferred to be formed more or less in the same area where a former volcano was located that was eroded later on and the created depression subsequently filled with water; **f** Tama Lakes near the Ruapehu volcano in New Zealand is another fine example for erosional enlargement of a maar crater lakes where the tuff ring has been eroded away completely; **g** Meke Gölü (Meke Lake) Konya near Karapınar in Turkey (Keller 1975) is a complex maar volcano. Its crater is partially filled with a large scoria cone (pictures by K.N.)

this issue). Volcanic activity does not play a role in the formation of the lake basin (R0), and the timing (T0) and spacing (L0) of the lake formation is unrelated to activity of a volcanic vent.

2.6 Lakes Dammed by Volcanic Deposits (Code: G0-1, R0-1, T0-1, L0)

Dammed lakes with a volcanic origin can be very diverse. Here we distinguish three types of such lakes:

1. when a volcanic edifice (Müller and Veyl 1956; Weinstein 2007) and/or associated lava field grow in a pre-existing fluvial network, water can be dammed creating lakes (e.g., Snag and Butte Lakes, California; Heiken 1978; Weinstein 2007) (G0-1, R1, T0-1, L0);
2. when active volcanic processes lead to failure of a volcanic edifice that dams or alters the pre-existing drainage network and forms or enlarges lakes (e.g., Spirit Lake near Mt St Helens, Washington; Zheng et al. 2014) (G1, R1, T0-1, L0);

Fig. 5 Oyunama lake, Noboribetsu geothermal area, Hokkaido, Japan, is a geothermal lake filling vents of previous phreatic eruptions (picture by D.R., July 2013)

3. when long-term geomorphological processes (e.g., landslides) lead to a change of the physiography of a volcanic terrain to cause damming of existing drainage patterns by non-volcanic surficial processes (G0-1, R0, T0, L0).

2.7 Volcanic Lakes After Snowmelting (Code: G0-1, R1, T1, L1)

Glaciers or snow caps topping volcanic craters can melt upon reactivation and form volcanic lakes. Such volcanic lakes can be the direct result of meltwater accumulation in the former crater of the volcano (G1), or fill other depressions of the volcanic system (G0). The relation with volcanic activity is clear as renewed heating is a must to melt the ice (R1), but eruptive activity is not necessarily involved. The lake formation is immediately after the ice melting phase, so T1. The lake forms on the vent (L1), the place where the heating phase starts. A clear example of the formation of a volcanic lake after snowmelting is Chiginagak lake, Alaska (Fig. 6), where a lake was formed in 2005, followed by snow dam breakage and a lahar (Schaefer et al. 2008). Many snow-capped volcanoes can potentially become the hosts of volcanic lakes after snow melting, when volcanic unrest resumes.

2.8 Volcanic Lake (Code: G0-1, R0-1, T0-1, L0-1)

A volcanic lake is a generic term incorporating all the above defined lake types. This explains the title of the here presented book issue: Volcanic Lakes.

Fig. 6 Chiginagak lake formed after snowmelting, Alaska (picture by G. Mc Gimsey, 21 August 2006, picture courtesy USGS, http://www.avo.alaska.edu/images/image.php?id=10973) (Schaefer et al. 2008). The depression in the crater rim on the *left* is filled by a snow dam

3 Classifying Volcanic Lakes from the Water Chemistry Perspective

As noted above, throughout history there has been some confusion and informal use of terms to describe the study objects of this monograph. Previously, volcanic lake classifications were based on water composition, especially lowered pH as a result of volcanic acid inputs (Delmelle and Bernard 2000a; Varekamp et al. 2000). A survey of the pH of volcanic lakes shows that many acid lakes have pH values below 3 and another suite has pH values between 5 and 8, whereas there is a paucity of lakes with pH values between 3 and 5. This duality in pH is most likely caused by the pH buffers of HSO_4^-/SO_4^{2-} and H_2CO_3/HCO_3^- (Marini et al. 2003). The lake classifications can be based on the character of the acidifying component (CO_2 versus the strong acids of S, Cl and F) or on general pH levels. Some volcanic lakes with carbonate inputs may have pH values >8, and evaporation processes may also lead to high pH values in some volcanic lakes (e.g., Farias et al. 2013; Pecoraino et al., this issue). As pointed out by Christenson and Tassi (this issue), lake compositional signatures are largely attributable to the age and depth of the degassing magma feeding the system.

A simple physical classification distinguishes volcanic lakes based on their water balance: those positioned inside a volcanic crater or caldera depression may have no surface outlets (Crater Lake, Oregon, Fig. 3; El Chichón lake, Mexico, Fig. 7) and are then terminal lakes where evaporation and eventually seepage has an important role in the water balance. Other lakes have subaqueous or surface geothermal or volcanic inputs but also an overflow or outlet system (Ruapehu, New Zealand, Christenson and Wood 1993; Kawah Ijen lake, Indonesia, Delmelle and Bernard 2000b; Caviahue lake, Argentina, Varekamp 2008). The lake water dynamics in these two types of lakes are fundamentally different: open lakes with an outlet experience only small variations in lake volume or mass, because the outflow term is constrained by the lake level. If, however, the lake level drops below the outlet, the lake then can shrink and become a closed, 'non-surface outlet' lake. Closed lakes have water outputs through seepage and evaporation and the seepage flux may vary with water level (hydraulic head, see e.g., Rouwet and Tassi 2011; Todesco et al. 2012, this issue).

Volcanic lakes can also be subdivided into several end member classes that reflect their origin, setting and the chemical composition of their waters. Lakes that occupy active volcanic craters or craters of recently active volcanoes will intercept the emitted volcanic gases directly in the lake environment, leading to very acid and sulfur-rich fluids. In many cases, the volcanic gases are intercepted in an underlying magmatic-hydrothermal system (Henley, this issue), where magma at several km depth is venting gases into a local groundwater layer of meteoric water. These acidified and mineralized waters may then enter the lake waters, creating a suite of lakes with different properties. The anion concentrations reflect the composition of the volcanic gas (Christenson and Tassi, this issue; Fig. 8a). Chloride loss as HCl vapor in hot concentrated lakes (e.g., Poás and Copahue lakes) is common (Rowe et al. 1992b; Rouwet and Ohba, this issue; Shinohara et al., this issue; Varekamp, this issue), leading to Cl depletion. Precipitation in the lakes of native sulfur, gypsum, anhydrite or jarosite, all common minerals in volcanic lakes, may deplete the waters in S (Delmelle and Bernard, this issue; de Ronde et al., this issue; Henley, this issue). The S–Cl–C diagram shows the clear partition in the acid S–Cl lakes with low pH values and the carbonate rich lakes with much higher pH values (Fig. 8b). Intermediate lakes are rare, which have an input of a mixed volcanic fluid but do not reach a pH low enough to let CO_2 escape. Concentrated pools of exotic S–Cl-rich water are found where the lake absorbs largely unprocessed raw volcanic gases, such as in the Keli Mutu lakes (Pasternack and Varekamp 1994) and Kawah Putih lake, both in Indonesia (Sriwana et al. 2000), and Poás and Rincón de la Vieja lakes in Costa Rica (Tassi et al. 2005, 2009).

Fig. 7 El Chichón crater lake, Chiapas, Mexico, was formed immediately after the March–April 1982 Plinian eruptions (picture by D.R., March 2004) (Rouwet et al. 2008; Taran and Rouwet 2008)

A second class of volcanic lakes receives hydrothermal fluids from underlying systems on active volcanoes, but here the fluids have already been processed extensively. These acid hydrothermal fluids may be strongly mineralized, but tend to be less rich in the volcanogenic volatile components (S+halogens). Examples are Taal lake, Phillipines (Delmelle et al. 1998; Zlotnicki et al. 2009; Gordon et al. 2009), the pre-2007 Kelut lake (Indonesia, Bernard and Mazot 2004; Mazot and Bernard, this issue), and El Chichón lake (1990–2013; Armienta et al. 2000; Rouwet et al. 2004, 2008; Peiffer et al. 2011).

The third class of volcanic lakes is contaminated with volcanic fluids that have largely lost their most reactive components such as the halogens and sulfur, and are CO_2 and/or carbonate rich. Their pH hovers from neutral to >7, tend to foster productive ecosystems, but their bottom waters may be charged with CO_2 that could lead to limnic eruptions (Nyos-type lakes, Tassi and Rouwet 2014; Costa and Chiodini, this issue; Kling et al., this issue; Kusakabe, this issue). Many of these lakes have a substantial diffusive CO_2 flux to the ambient atmosphere (Pérez et al. 2011; Mazot and Bernard, this issue) and some have direct bubble transport of CO_2 to the surface (Caudron et al. 2012). Examples are the African lakes Monoun, Nyos and Kivu, the carbonate lakes in Italy (Carapezza et al. 2008; Chiodini et al. 2012), Kelut lake on Java (Bernard and Mazot 2004; Caudron et al. 2012; Mazot and Bernard, this issue) and Quilotoa and Cuicocha lakes in Ecuador (Fig. 9, Aguilera et al. 2000; Gunkel et al. 2008; Gunkel and Beulker 2009).

The last class of lakes are dominated by meteoric fluids, either as a result of their sheer size (Toba lake, Indonesia; Bolsena lake, Italy; Crater Lake, Oregon) or because the volcanic/geothermal inputs are indeed very small (maar

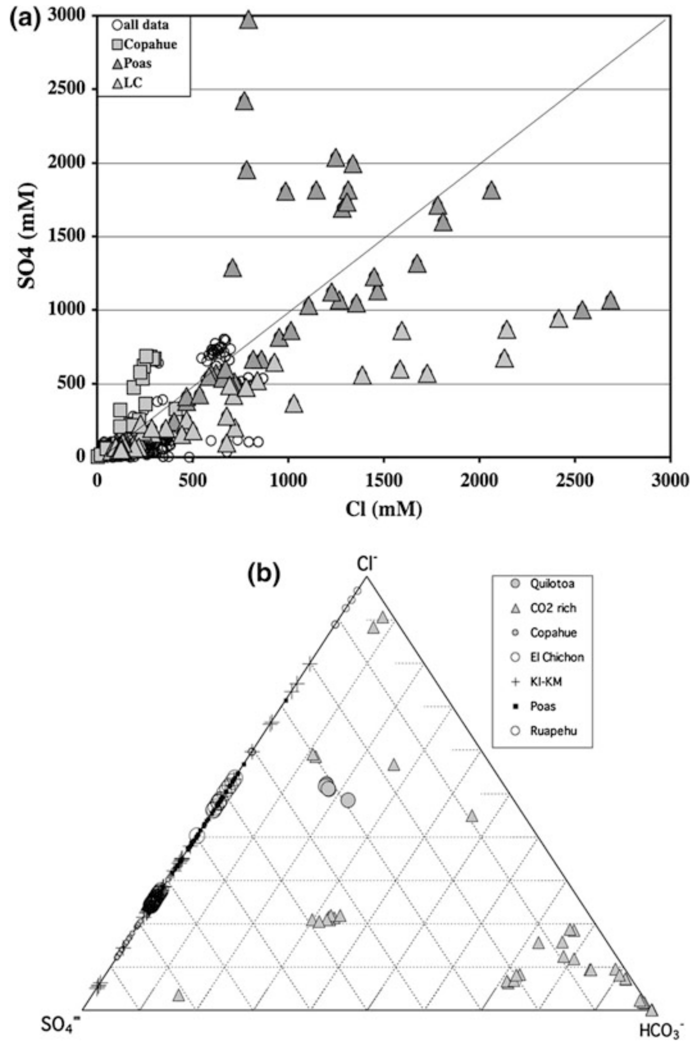


Fig. 8 **a**. Molar S/Cl is on average ∼1, but both S excess and deficits are common. The Poás crater lake samples (LC) probably suffered from sulfur loss through liquid sulfur formation and anhydrite crystallization. The Poás samples with excess sulfur (Poás lake) probably suffered from HCl loss through HCl vapor loss. **b**. The S–Cl–C diagram shows the acid lakes on the S–Cl axis, and the very CO_2 rich samples near the HCO_3 corner. Very few lakes have mixed S–Cl–HCO_3 compositions, and most of these have a relatively high pH values

lakes in the Eifel, FRG, Aeschbach-Hertig et al. 1996). Lakes that are non-volcanic in origin (e.g., some glacial lakes) may become contaminated through surface inflow of volcanically-contaminated rivers, with Caviahue lake in Argentina as an example (Varekamp 2008). An alternative volcanic lake classification based on lake water chemistry is proposed in a later chapter (Varekamp, this issue) grouping into active lakes, quiescent lakes and CO_2-rich lakes.

4 Limnology

The chemistry of lake water, including that of volcanic lakes, changes along the vertical profile when the heat budget results in a thermal gradient between the cooler surface waters and generally hotter bottom waters when affected by fluid input of volcanic origin (Boehrer and Schultze 2008; Kling et al., this issue). The thermal and chemical

Fig. 9 Laguna Cuicocha is a volcanic lake in the Andes of Ecuador, about 100 km north of Quito (the capital city) (picture by J. Ratner, University of Oxford)

stratification leads to the formation of different zones within a lake, characterized by distinct chemical-physical features and behavior (Fig. 10), as follows:

1. The epilimnion: the surface water layer sensitive to external temperature and solar radiation. Epilimnitic water exchanges heat and volatile substances (gases) with the atmosphere. The epilimnions recirculate episodically by wind and/or by changes of external temperatures.
2. The hypolimnion: the deep water layer showing the lowest temperature along the vertical lake profile, generally determined by the final water temperature during the spring

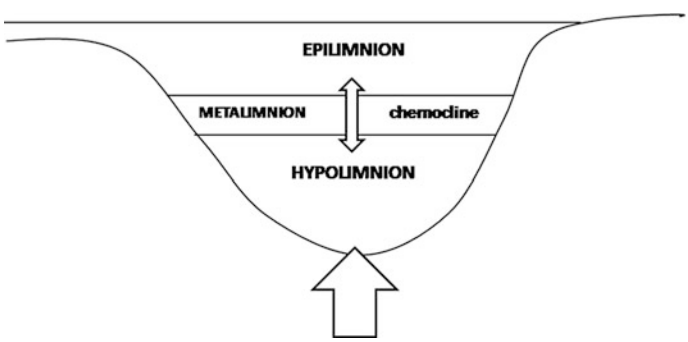


Fig. 10 Sketch of the lake stratification, simplified from Tassi and Rouwet (2014). The *lower arrow* indicates eventual heat and fluid input from the aquifer, the *double-arrow* indicates mixing processes (see text for further details)

lake turnover. Colder water is denser and tends to sink to the lake bottom.

3. The metalimnion: the water layer between the epilimnion and the hypolimnion, showing a marked thermal gradient. It basically corresponds to the thermocline which refers to the plane of maximum rate of temperature decrease with depth.

Different types of lakes can be recognized on the basis of thermal and water circulation features, basically depending on the lake's longitude and altitude.

Amictic lakes are lakes sealed off perennially by ice from annual variations in temperature. No vertical stratification occurs in these lakes. They are typical in the Antarctic.

Cold monomictic lakes are ice-covered lakes most of the year and experience complete mixing once a year during the summer. These lakes are found in the Arctic and high mountains.

Warm monomictic lakes show complete water circulation in winter and most stable stratification in summer. These lakes are common in warm regions of temperate zones.

Dimictic lakes experience complete mixing twice a year. These lakes are typical for cool temperate regions. Thermal stratification always has the 4 °C waters at the bottom and warmer waters higher up.

Oligomictic lakes mix completely irregularly, i.e., less than once a year. They can be found at low altitude in tropical regions (e.g., Hule and Río Cuarto lakes, Costa Rica; Cabassi et al. 2014).

Cold polymictic lakes a covered by lakes part of the year, and experience frequent or continuous complete mixing during the ice-free period. This behavior is typical for temperate lakes.

Warm polymictic lakes are never covered by ice, and show continuous complete mixing except for short (few hours) stratification periods. They are shallow lakes in tropical areas.

Meromictic lakes are those that do not undergo complete mixing, and are characterized by a permanent stratification (e.g., Lake Nyos, Kling et al., this issue). In meromictic lakes the monimolimnion is the deeper lake layer perennially isolated from the surface. Water chemistry in the monimolimnion is different with respect to the one of the shallower water layers.

The mixolimnion is the layer overlying the monimolimnion, where lake waters periodically circulate and mix. The chemolimnion is the layer separating the monimolimnion and the mixolimnion, characterized by a steep salinity gradient. The chemocline (Fig. 9) is the plane of density change; the pycnocline is the plane of density change which may be thermal or chemical in origin. The chemocline is a plane where a significant transition in composition occurs and may thus be also the pycnocline.

5 Volcanic Lake Colors

Lakes have a range of colors, dependent on their chemical composition or particular ecosystem. In general, oligotrophic lakes, i.e., those that are biologically unproductive, have a deep blue color (absorption of longer wavelengths, scattering of short wavelengths of the visible spectrum), somewhat similar to marine environments with limited productivity. Eutrophic lakes are rich in nutrients, carried in from local catchments, geothermal inputs or human contamination, and have a more greenish blue color, and in extreme cases may become truly green from algae in the water column. Brown lakes have high concentrations of dissolved organic matter, leading to brownish organic acids in the water. Some extreme lakes have a deep red color because of the presence of red algae in the water column.

Volcanic lakes may deviate from this four-color scheme of common lakes because of their sometimes unusual chemical inputs. Volcanic lakes dominated by meteoric waters are also often deep blue, because they tend to be oligotrophic with their very small catchment areas (e.g., Crater Lake, Oregon, Fig. 3). Three other 'color groups' of volcanic lakes exist:

1. Lakes with a geothermal or volcanic nutrient input, usually phosphorous;
2. Lakes with a colored dissolved substance, usually Fe or sulfur;
3. Lakes with a suspended substance or chemical precipitate with a specific color.

Some volcanic lakes have a P-rich input, which are usually relatively low pH systems, where the P is derived from the dissolution of volcanic rocks. Phosphorous is removed once a phosphate mineral becomes saturated or the P-oxyanion is removed by adsorption onto a host phase that precipitates (usually an Fe-rich phase). If the P enters a volcanic lake, it may stimulate the biotic productivity, which could create a green lake. Geothermal nitrogen fluxes tend to be relatively small, although traces of ammonia and nitrate occur in geothermal systems and may provide the basis of the local food chains (Pedrozo et al. 2001, 2008). These lake colors are common compared to non-volcanic lakes, except that the source of the nutrients is here geothermal or volcanic and not anthropogenic.

Fundamentally different are volcanic lakes that contain a dissolved substance that lends a color to the water. Waters rich in Fe^{2+} may be deep green, whereas Fe^{3+} in water may produce a violet to brownish water color, depending on speciation and complexation.

The third group of volcanic lakes may have colors that reflect the presence of a suspended solid, be it a colloid or a fine mineral precipitate. Some acid volcanic lakes are deep gray (e.g., Poás lake, Costa Rica, Fig. 11) when the grey bottom sediments are stirred up by convection currents. Other acid lakes are saturated in elemental sulfur, which in hot lakes may form a pool of liquid sulfur at the bottom (e.g., Poás lake; Oppenheimer and Stevenson 1989; Yugama lake, Kusatsu Shirane, Japan; Takano et al. 1994). Gas percolation through this liquid layer may bring up small spheres of molten sulfur that chills in the cooler surface waters and may float as small suspended masses partly due to its hydrophobic nature. Small colloids of sulfur may form as well, which will give the water a blue white tinge, which together with the other constituents (green from ferrous ions) may create the turquoise colored lakes (e.g., middle Keli Mutu lake, Indonesia; Pasternack and Varekamp 1994) (Fig. 12). The crater lake of Aso volcano, Japan (Yudamari lake, Fig. 13, Shinohara et al., this issue) changes its color from blue-ish green to more deep green colors, the result of the disappearance of the blue color component (Ohsawa et al. 2010). The presence of the sulfur colloids creates the blue color, and with diminishing concentrations of colloidal sulfur, the lake turns greener. In the case of Yudamari lake, the disappearance of colloidal sulfur is caused by enhanced SO_2 inputs into the system (Delmelle and Bernard, this issue), and

Fig. 11 Laguna Caliente, Poás, Costa Rica (picture by R. Mora-Amador, 11 April 2007). The *grey color* of the lake is due to strong lake water convection, mixing lake bottom sediments with the water. Note the *yellow mats* of floating sulphur spherules

Fig. 12 Keli Mutu volcano, Flores, Indonesia (picture by R. Campion, 22 August 2011), with its three colorful lakes. From *left* to *right*: Tiwu ata Polo, Tiwu Nuwa Muri Khoofai, and Tiwu ata Mbupu. The three lakes are known for their occasional changes in color, believed to be the result from the modification of the size and composition of mineral precipitates suspended in their waters

Fig. 13 Yudamari crater lake, Mt Nakadake, Aso volcano, Kyushu, Japan (picture by N. Vinet, 5 December 2011). Intense degassing from the turquoise lake and fumaroles (right of Yudamari lake). The stratified, steep cliffs of the crater well illustrate the sustained volcanic activity of Aso volcano. Lake-derived plume and fumarole gas measurements using a portable Multi-Gas station are conducted (Shinohara et al., this issue)

as such, color changes may have a role in eruption monitoring. Colloidal silica is found in silica-rich geothermal pools which tend to have a specific blue color as a result of the scattering of light on these tiny colloids (Ohsawa et al. 2010).

Changes in color of crater lakes are sometimes related to the precipitation of new mineral phases. A most striking example was Voui lake in 2005, which changed from a deep blue, rather dilute lake at the top of Ambae volcano (Vanuatu) into a pool of blood red, very acidic water, with a small new island volcano in the middle (Fig. 14). Water analyses and saturation calculations suggest that the red color of the lake was the result of the precipitation of jarosite and hematite (Bani et al. 2009). The three Keli Mutu lakes on Flores, Indonesia are also famous for their colors and color changes with the seasons (Fig. 12). The three lakes have pH values ranging from 3 to <1, with the smallest, and most dilute lake being black, and the center, most acidic lake being turquoise (and saturated with sulfur). The first lake is green in the dry season (with Fe contents dominated by Fe^{2+}) and red to brown during the wet season (November–April), possibly the result of a pH increase with rainwater dilution and oxidation of Fe^{2+} into Fe-oxide phases (hematite, Pasternack and Varekamp 1994).

6 Statement of This Monograph

This first monograph on volcanic lakes aims to give an overview on the present state of volcanic lake research, covering topics such as volcano monitoring, the chemistry, dynamics and degassing of acidic crater lakes, mass-energy-chemical-isotopic balance approaches, limnology and degassing of Nyos-type lakes, the impact on the human and natural environment, the eruption products and impact of crater lake breaching eruptions, numerical modeling of gas clouds and fluid migrations, CO_2 fluxes from lakes, biological activity, monitoring techniques, and some aspects more. We aim to offer an updated manual

Fig. 14 Voui lake, Ambae volcano, Vanuatu, before the 2005 eruptions (picture by K.N.) (Bani et al. 2009). The *darker blue* lake behind Voui lake is the inactive Manaro lake

on volcanic lake research, providing classic research methods, and point towards a more high-tech approach of future volcanic lake research and continuous monitoring.

The target audience of the book is strictly scientific, composed of volcanologists, limnologists, and biologists, among other volcano-phyles. Despite this scientific focus, we would like to leave a visually attractive, illustrated handbook to all people interested in one of the most extreme and spectacular features on the Earth's surface: volcanic lakes.

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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

V. Manville (✉)
School of Earth and Environment,
University of Leeds, Leeds LS2 9JT, UK
e-mail: v.r.manville@leeds.ac.uk

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