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Review

Past, present and future of volcanic lake monitoring

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ABSTRACT

Volcanic lake research boosted after lethal gas burst occurred at Lake Nyos (Cameroon) in 1986, a limnic rather than a volcanic event. This led to the foundation of the IAVCEI-Commission on Volcanic Lakes, which grew out into a multi-disciplinary scientific community since the 1990s. We here introduce the first data base of volcanic lakes VOLADA, containing 474 lakes, a number that, in our opinion, is surprisingly high. VOLADA could become an interactive, open-access working tool where our community can rely on in the future. Many of the compiled lakes were almost unknown, or at least unstudied to date, whereas there are acidic crater lakes topping active magmatic–hydrothermal systems that are continuously or discontinuously monitored, providing useful information for volcanic surveillance (e.g., Ruapehu, Yugama, Poás). Nyos-type lakes, i.e. those hosted in quiescent volcanoes and characterized by significant gas accumulation in bottom waters, are potentially hazardous. These lakes tend to remain stably stratified in tropical and sub-tropical climates (meromictic), leading to long-term build-up of gas, which can be released after a trigger. Some of the unstudied lakes are possibly in the latter situation. Acidic crater lakes are easily recognized as active, whereas Nyos-type lakes can only be recognized as potentially hazardous if bottom waters are investigated, a less obvious operation. In this review, research strategies are lined out, especially for the "active crater lakes". We make suggestions for monitoring frequency based on the principle of the "residence time dependent monitoring time window". A complementary, multi-disciplinary (geochemistry, geophysics, limnology, statistics) approach is considered to provide new ideas, which can be the bases for future volcanic lake monitoring. More profound deterministic knowledge (e.g., precursory signals for phreatic eruptions, or lake roll-over events) should not only serve to enhance conceptual models of single lakes, but also serve as input parameters in probabilistic approaches. After more than 25 years of pioneering studies on rather few lakes (~20% of all), the scientific community should be challenged to study the many poorly studied volcanic lakes, in order to better constrain the related hazards.

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1. Introduction

Volcanic lake research boosted after the unfortunate limnic gas bursts occurred at Lake Monoun and Lake Nyos, Cameroon, in August 1984 and 1986, respectively (Kerr, 1987; Kling et al., 1987). These events were followed by an International Conference in 1987 in Cameroon's capital, Yaounde (JVGR, Special issue 1989), and gave way to a spicy discussion on the causes of the CO_2 eruptions from these Cameroonian volcanic lakes. This discussion is still ongoing and divides the scientific community in two "schools": the Lake Nyos event was triggered by a phreatic eruption, and thus volcano-related (Barberi et al., 1989; Tazieff, 1989) vs. the Lake Nyos event was a limnic event, releasing gas stored in bottom waters after lake overturn (Kling et al., 1987, 1989; Kanari, 1989; Kusakabe et al., 1989). Post-1986 monitoring of the evolution of water and dissolved gas chemistry of Lake Nyos strongly supports the latter theory (Evans et al., 1993, 1994; Kling et al., 2005; Kusakabe et al., 2008; Kusakabe, 2014), now also observed at other lakes worldwide (e.g., Lago Albano, the two Monticchio lakes, Italy; Laguna Hule and Río Cuarto, Costa Rica; Lac Pavin, France; and, of course, Lake Monoun, Cameroon) (Aeschbach-Hertig et al., 1999; Kusakabe et al., 2000; Carapezza et al., 2008; Chiodini et al., 2012; Cabassi et al., 2013a,b; Caracausi et al., 2013). The group of people attending the 1987 meeting were soon named the International Working Group on Crater Lakes (IWGCL). Despite the "limnic origin" of IWGCL, the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) soon recognized the status of this working group, leading to the incorporation of IWGCL as a IAVCEI Commission, re-baptized in 1993 as the IAVCEI Commission on Volcanic Lakes (CVL).

After the "limnic start" of CVL, volcanic lake research has become more "acidic", more "active" (in any sense), and more "geochemical" and "volcanogical". This logical trend had its roots even before Nyos-1986, remembering the pioneering work on the acidic and frequently erupting Lake Yugama (Kusatsu-Shirane Volcano, Japan; Ohashi, 1919; Minakami, 1939; Satake and Saijo, 1974; Ossaka et al., 1980; Takano, 1987), Ruapehu's Crater Lake, New Zealand (Giggenbach, 1974; Giggenbach and Glover, 1975; Hurst and Dibble, 1981), Poás' Laguna Caliente, Costa Rica (Brantley et al., 1987; Brown et al., 1989; Mora-Amador, 2010, and references therein), and El Chichón's post-1982 active crater lake, Mexico (Casadevall et al., 1984). Many fluid geochemists have worked at least once at volcanic lakes, making CVL a "niche-commission" within the larger fluid community. In recent years, CVL has opened up to other research approaches stimulating multi-disciplinary and intertwined research: from the start in limnology (e.g., Schmid et al., 2004, 2005, 2010; Boehrer and Schultze, 2008; Tassi et al., 2009a,b; Cabassi et al., 2013a), over the dominating (fluid) geochemistry (Rowe et al., 1992a,b, 1995; Christenson and Wood, 1993; Christenson, 1994, 2000; Delmelle and Bernard, 1994; Pasternack and Varekamp, 1994; Rowe, 1994; Takano et al., 1994; Taran et al., 1998; Delmelle et al., 2000; Kempter and Rowe, 2000; Kusakabe et al., 2000, 2008; Martínez et al., 2000; Ohba et al., 2000, 2008; Sriwana et al., 2000; Varekamp and Kreulen, 2000; Varekamp et al., 2000, 2001; Bernard et al., 2004; Stimac et al., 2004; Tassi et al., 2005; Christenson et al., 2007, 2010a; Rouwet et al., 2008, 2009; Bani et al., 2009; Arpa et al., 2013), to mass and energy balance studies (Brown et al., 1989; Hurst et al., 1991, 2012; Ohba et al., 1994; Pasternack and Varekamp, 1997; Rouwet et al., 2004; Fournier et al., 2009; Terada et al., 2012), biology (Pedrozo et al., 2001; Löhr et al., 2005; Pasche et al., 2009, 2010; Mapelli et al., 2014), geophysics (Vandemeulebrouck et al., 1994, 2000; Rymer et al., 2000, 2009; Fournier et al., 2004; Werner et al., 2006; Caudron et al., 2012), and numerical (Todesco et al., 2012, 2014) and analog modeling (Vandemeulebrouck et al., 2005). In 2013, CVL exists twenty years, but volcanic lake research started more than fifty years ago. Many detailed reviews on various specific topics will soon be published in the first book on volcanic lakes (Springer-Heidelberg).

This review paper will present the state-of-the-art of volcanic lake research throughout the past five decades, and will blink an eye towards the future. The most important volcanic lake classification schemes will be discussed, lake-related hazards will be overviewed and the two potentially most hazardous lake types will be deepened out. New and innovative monitoring strategies, based on the concept of "residence time dependent monitoring time window" will be lined out to make volcanic lake monitoring safer and more efficient. As a première, we here introduce the first data base on volcanic lakes (VOLADA), which is available for the research community through IAVCEI's VHub network. VOLADA aims to become as complete as possible, and constantly updated with the collaboration of all lake researchers.

2. Classification schemes of volcanic lakes revisited

In science, a large variety of manifestations of a similar feature inevitably leads to classification systems. Pasternack and Varekamp (1997) introduced a physical–chemical classification scheme for volcanic lakes, with six subclasses. The first subclass includes the *erupting lakes* (class 1, Fig. 1), characterized by a variable volume, a relatively high temperature and strong acidity. Within erupting craters, it is generally difficult for a lake to survive as water loss upon evaporation tends to outweigh the meteoric water recharge, the respectively two major out- and input water fluxes for volcanic lakes. Some lakes, however, have survived upon invasion of a lava flow (Rinjani effusive eruption 2009, Indonesia; Alain Bernard written communication), phreatomagmatic eruptions (Lake Voui eruption 2005, Vanuatu; Bani et al., 2009), or adjacent high-temperature fumarolic degassing (Poás, Santa Ana, Gorely, Aso; Brantley et al., 1987; Bernard et al., 2004; Scolamacchia et al., 2010; Melnikov and Ushakov, 2011; Shinohara et al., 2014). When volcanic activity increases, lake water temperature rises: it is found that when the lake water temperature exceeds 45 °C a meteoric water recharge of >5000 mm/y is needed to avoid the lake from shrinking and eventually disappearing. In practice, this requires tropical climatic conditions. Current examples of erupting crater lakes are Poás' Laguna Caliente (Costa Rica, 2006–ongoing phreatic eruption cycle; Rouwet et al., 2010a) and Copahue crater lake (Argentina), both doomed to disappear if volcanic activity will not decrease. Copahue crater lake actually disappeared

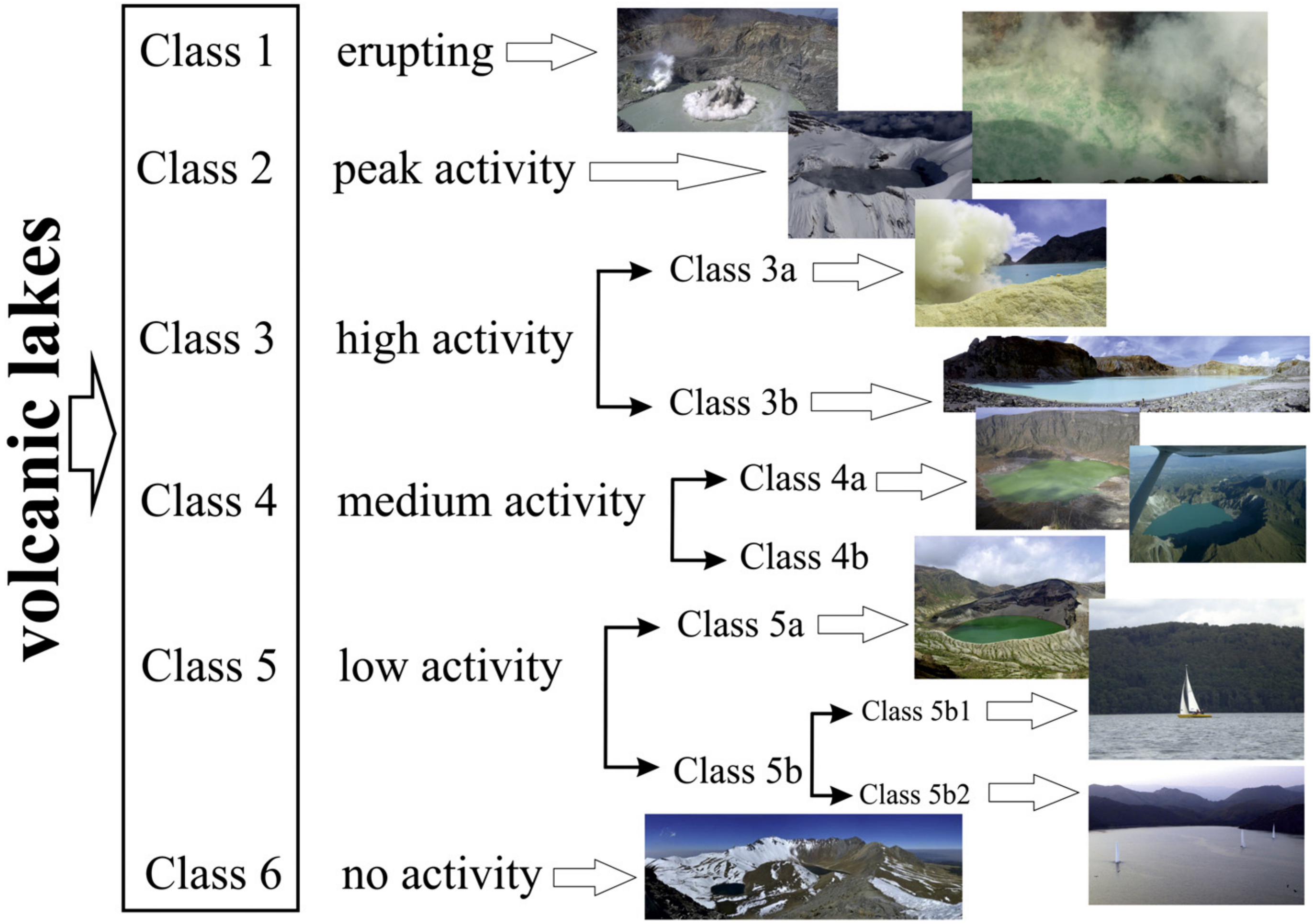

Fig. 1. Physical–chemical classification scheme for volcanic lakes (simplified from Pasternack and Varekamp, 1997). The lakes in the pictures are, from top to bottom: Poás' Laguna Caliente, Costa Rica (A.B. Castro), Aso's Yudamari lake, Japan (G. González-Ilama), Ruapehu, New Zealand (V.C.), Kawah Ijen, Indonesia (R. Campion), Kusatsu Shirane's Yugama, Japan (R.M.-A.), El Chichón, Mexico (D.R.), Pinatubo, Philippines (B. Fontaine, LAVE Belgium), Zao, Japan (J.M. Bardintseff), Laacher See, Germany (D.R.), Lake Nyos, Cameroon (Y. Yoshida), Nevado de Toluca, Mexico (V. Smith).

after the December 2012 phreatomagmatic eruptions, but restored soon after due to meltwater refill (Fig. 2) (Agusto et al., 2013).

Besides the *erupting* and *peak activity lakes* (class 2, Fig. 1), i.e. hyperacidic and highly saline (TDS >300 g/L) volcanic lakes, the lakes pertaining to the other four classes are all in a steady state equilibrium. This means that water in- and output fluxes are equal (Varekamp, 2002), and consequently, the residence time (R, in s) of lake water can be calculated as

$$R = V_L / Q \quad (1)$$

where V_L is the lake water volume (in m^3 or L) and Q (m^3/s or L/s) is the flux of water into (or out of) the lake (see also Taran and Rouwet, 2008). Varekamp (2002) found that "chemical contaminants" are flushed out of the lake after six residence times. This has important consequences for crater lake monitoring (see Section 4). Peak activity lakes are generally related to a state of volcanic unrest, often leading into (phreatic) eruption cycles.

High activity lakes (class 3, Fig. 1) are perfectly mixed lakes when a permanent jet inlet at the lake bottom is wide and powerful enough to overcome the lake depth (Pasternack and Varekamp, 1997). Such lakes are hot (class 3a, Fig. 1; $150 < TDS(g/L) < 250$ and $35 < T(°C) < 45$), or cool (class 3b, Fig. 1; $40 < TDS(g/L) < 150$ and $20 < T(°C) < 35$) acidic lakes. The high salinities imply a significant fluid contribution from magmatic/hydrothermal origin, also rich in acidic volatiles (SO_2, HCl, HF) causing very low pH values (pH < 1.5). Marini et al. (2003) described a bimodal pH distribution for volcanic lake waters, with an acidic mode for a pH of 0.5–1.5 and a near-neutral mode for a pH of 6–6.5. Class 1 to 3 lakes are part of the acidic-mode lakes in the Marini et al. (2003) classification.

Medium activity lakes (class 4, Fig. 1) do show a stable buoyant inlet jet near the lake bottom, but lack the clear magmatic volatile input. They are rather underlain by an active hydrothermal system, releasing CO_2- and H_2S-rich vapor into the lake. Oxidation of H_2S to SO_4 leads to pH values near 2–2.5. At these conditions, CO_2 is insoluble and mainly released as bubbles at the lake surface. The lake behaves as a large steam-heated, SO_4-rich, Cl-poor pool and exhibits salinities ($10 < TDS(g/L) < 40$) significantly lower with respect to those of the previous classes. Oxidized acid-saline lakes (class 4a, Fig. 1) are most frequent (surface oxidation), although reduced acid-saline lakes (class 4b, Fig. 1) exist (Pasternack and Varekamp, 1997). The temperature of class 4 lakes can be highly variable, but are generally well above the ambient temperature.

Low activity lakes (class 5, Fig. 1) basically consist of (1) steam-heated pools without a clear jet-like inlet (acid sulfate lake with a TDS < 10 g/L, class 5a, Fig. 1), or (2) CO_2-dominated lakes (class 5b, Fig. 1). In the latter case, the presence of significant amounts of dissolved CO_2 and the absence of SO_2–H_2S imply a relatively high pH, coinciding with the near-neutral mode of Marini et al. (2003). CO_2-dominated lakes are generally not underlain by a degassing

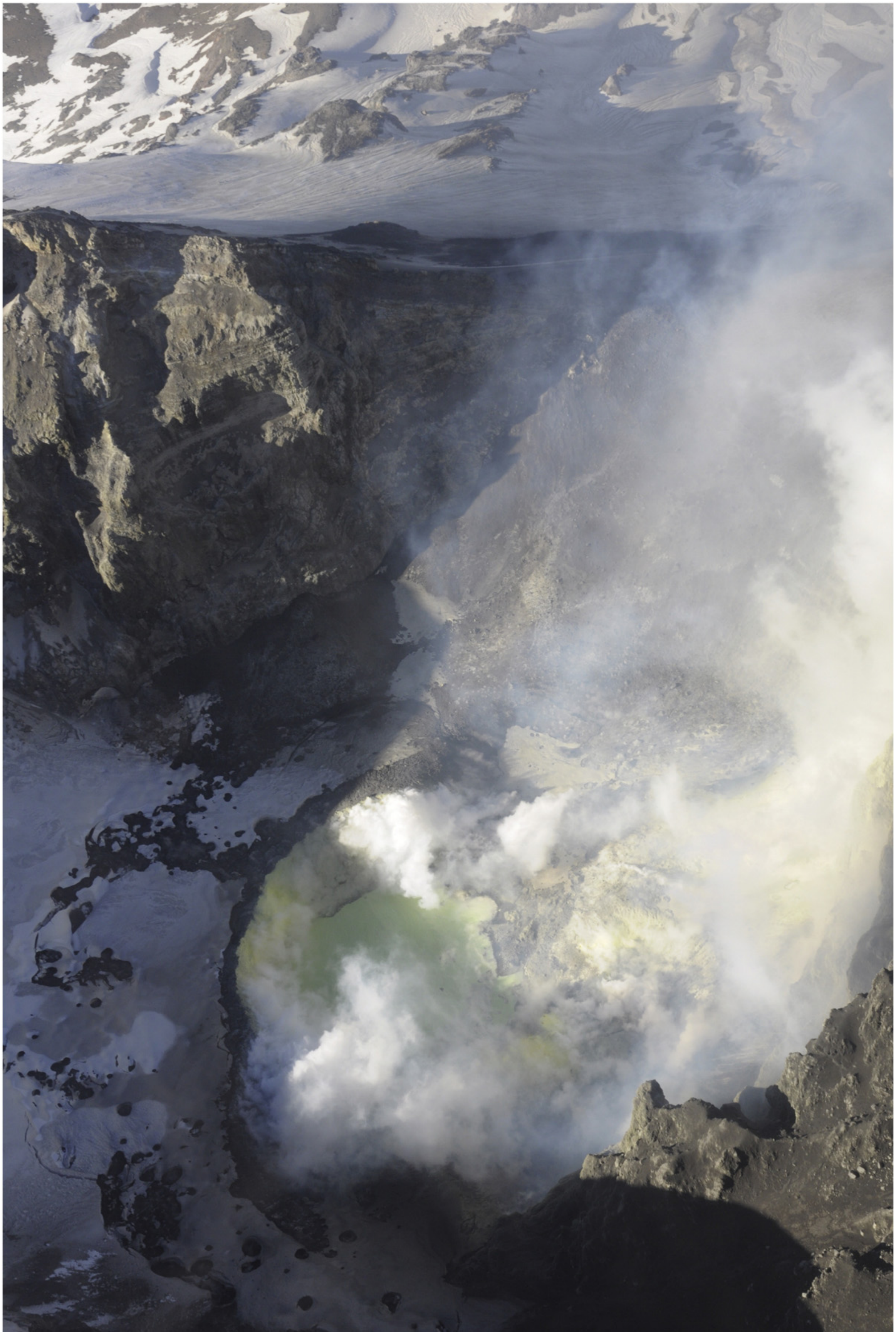

Fig. 2. Copahue crater lake restoring after the December 2012 phreatomagmatic eruption. The yellow froth is sulfur slick massively floating on the lake surface, indicating a lake water bottom temperature >116 °C (picture: A.T. Caselli).

magmatic or hydrothermal system, but are rather recharged by CO_2-rich ground waters resulting from regional scale CO_2-degassing, an ubiquitous process in most volcano-tectonic settings. In shallow lakes (class 5b1, Fig. 1), dissolved CO_2 can (at least partly) reach the surface through diffusion or bubbling degassing, whereas in stratified deep lakes (class 5b2, Fig. 1) it mostly remains trapped in the hypolimnion (bottom layer in thermally stratified lakes; Boehrer and Schultze, 2008). The latter class is more familiarly called "Nyos-type lakes" (Sections 3.3 and 4.3), or bursting, CO_2-dominated volcanic lakes.

The remaining lake class probably contains most volcanic lakes: *no activity lakes*, containing neutral-dilute waters of purely meteoric origin (class 6, Fig. 1). Fig. 1 represents the Pasternack and Varekamp (1997) classification scheme, and provides examples of each lake class.

Beyond this physical–chemical classification, Varekamp et al. (2000) took the effort to better distinguish the chemical systematics in the various types of volcanic lakes. Based on their $SO_4 + Cl$ concentrations and pH values they first subdivided volcanic lakes in three classes: (1) CO_2-dominated lakes ($SO_4 + Cl < 10$ mg/L, $5 < pH < 9$), (2) quiescent lakes (10 mg/L $< SO_4 + Cl < 3000$ mg/L, $1.5 < pH < 9$), and (3) "active" crater lakes ($SO_4 + Cl > 3000$ mg/L, $-1 < pH < 3$) (Fig. 3a). The CO_2-dominated lakes are mainly "Nyos-type" lakes, while the "active" crater lakes coincide with the erupting, peak-activity and some high-activity lakes (classes 1, 2, 3).

A third classification scheme is based on the "percentage residual acidity" (PRA, Varekamp et al., 2000), or the capacity of lake water to neutralize, i.e. counterbalancing water–rock neutralization reactions involving lake sediments with magmatic volatiles entering the lake (Fig. 3b). Lakes with high-PRA waters are gas-dominated lakes (G); lakes with low-PRA waters are rock-dominated lakes (R) (Varekamp et al., 2000) (Fig. 3b).

Most volcanic lakes fit one of the above classification schemes, which thus become useful to get a first glance on how volcanic lakes work, and why. We later adopt the Pasternack and Varekamp (1997) and Varekamp et al. (2000) classification schemes for the VOLADA data base (Section 6). Nevertheless, some lakes are hardly classable, as their physical–chemical properties reflect "non-classical" dynamics, depending on particular hydrothermal dynamics of lake systems (e.g., spring water input, special buffer capacities, influence of marine or evaporite-conate waters). These lakes deserved specific attention in the past (e.g., pre-2007 Kelut crater lake, Indonesia; Pinatubo and Taal crater lakes, both in the Philippines; El Chichón crater lake, Mexico) (Delmelle et al., 1998; Bernard and Mazot, 2004; Stimac et al., 2004; Peiffer et al., 2011).

3. Hazards related to volcanic lakes

3.1. Phreatic and phreatomagmatic eruptions

The sudden input of fluids and heat from a magmatic source into a more superficial aquifer can trigger phreatic eruptions (Rouwet and Morrissey, 2014, and references therein). A volcanic lake topping an active magmatic–hydrothermal system in a crater structure (= active crater lake) is the maximum expression of such a phreatic eruption-prone aquifer. Despite the apparently obvious idea that the physical–chemical parameters characterizing a volcanic lake can act as precursory signals for rejuvenating eruptive activity, it remains extremely difficult, in practice, to forecast single phreatic eruptions (Christenson et al., 2007, 2010a; Jolly et al., 2010; Kilgour et al., 2010). Phreatic eruptions do not expel juvenile material, as only magma-derived fluids and not the magma itself are involved. Phreatic eruptions, however, can be extremely violent (i.e., a high release rate of kinetic energy for short duration eruptions), and destructive. Morrissey et al. (2010) and Rouwet and Morrissey (2014) discussed that phreatic eruptions are rather *implosions* than explosions. Phreatic eruptions are generally low-VEI events (corresponding to VEI 1-2; Newhall and Self, 1982), and do not relict voluminous eruption deposits, making them hard to study retrospectively in the geological record.

A rigorous classification system for phreatic eruptions does not exist, and phreatic eruptions from crater lakes are often grouped by their eruption column heights above the lake surface (e.g., <50 m, 50–250 m, >250 m; Mora-Amador et al., 2010), a classification that is mostly specific for each case. Phreatic eruptions breach a crater lake surface if the fluid pressure beneath the lake exceeds the hydrostatic pressure of the lake water column. Lower lake levels could thus lead to less violent but eventually more frequent phreatic eruptions, as pressure thresholds are lower and hence are more easily reached. A lake level drop (e.g., upon prolonged high evaporative water loss) or the phreatic eruptions themselves yield a pressure drop in the underlying magmatic–hydrothermal plumbing system, which could result in magma rise. This is the reason why phreatic eruptions often anticipate more violent and explosive phreatomagmatic eruptions.

At active crater lakes, the temporal evolution from phreatic to phreatomagmatic eruption activity can be highly variable. Besides the different dynamics of the magma plumbing system, it is not yet clear why some crater lake pass through year-long phreatic eruption cycles with very frequent, mainly small phreatic eruptions (e.g., Poás 2006–ongoing and Rincón de la Vieja 2011–ongoing eruption cycles; Rouwet

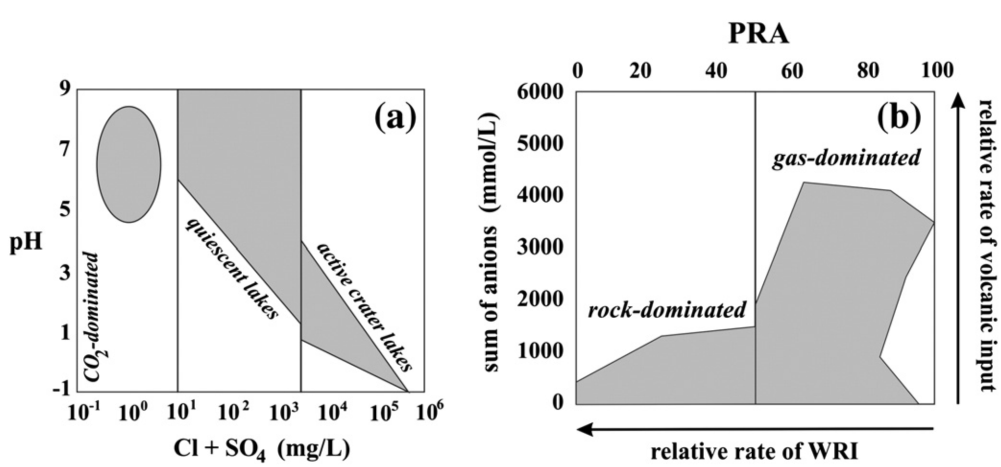

Fig. 3. Chemical classification systems based on a data compilation of 373 lake water samples (gray shaded areas), modified from Varekamp et al. (2000). (a) Three subclasses based on the $Cl + SO_4$ content and pH of lake waters, and (b) rock-dominated vs. gas-dominated volcanic lakes, a classification based on the concept of percentage residual acidity (PRA). WRI = water–rock interaction.

et al., 2010a; González et al., 2013), while other lakes evolve extremely fast from the phreatic stage to the phreatomagmatic stage (e.g., Ruapehu 1995–1996 eruptions, Copahue December 2012 eruption; Christenson, 2000; Agusto et al., 2013). Phreatomagmatic activity often leads to a complete dry out of the lake, evolving towards a pure magmatic stage. Both phreatic and phreatomagmatic crater lake breaching eruptions can be accompanied by base surges after column collapse, or tsunamis or seiches which can be the most hazardous outcomes for people near the lake shore (i.e., volcanologists) (Mastin and Witter, 2000).

On the other hand, the evolution from quiescence to unrest in a volcanic lake has generally easily recognizable indicators, such as: (1) a long-term lake water temperature increase, (2) lake level rising, due to a pushing vapor front beneath the lake, and (3) appearance of floating sulfur spherules on the lake surface (testifying the input of a >116 °C fluid, Hurst et al., 1991; Takano et al., 1994). Contrarily, once phreatic activity is resumed, eruptive events are sometimes preceded by lake water cooling, suggesting vent blocking at the fluid inlet at the lake bottom (Werner et al., 2006; Christenson et al., 2010a). This process is probably induced by the self-sealing capacity of elemental sulfur when input fluid temperature exceeds 160 °C, inhibiting an efficient heat and mass dissipation throughout the lake water column. It remains challenging to forecast both the major "Ruapehu-style" surprise phreatic eruptions and the minor "Poás-style" frequent phreatic eruptions within an ongoing eruption cycle.

3.2. Lahars

Phreatic or phreatomagmatic eruptions can generate sudden water expulsion from the lake basin, eventually out of the crater. Some crater lakes are naturally dammed by pyroclastic deposits from previous eruptions (e.g., Ruapehu, Lake Nyos, Rincón de la Vieja; Lockwood et al., 1988; Lockwood and Rubin, 1989; Freeth and Rex, 2000; Aka et al., 2008; Christenson, 2013), which increases lake basin vulnerability. Massive water expulsion from lakes can easily form high volume lahars (Cronin et al., 1997; Schaefer et al., 2008; Carrivick et al., 2009; Kilgour et al., 2010). Sudden snow melt after heating is an efficient trigger mechanism (Schaefer et al., 2008). Where phreatic and phreatomagmatic activity mainly affects the summit areas of lake hosting volcanoes, posing a risk for volcanologists and tourists, lahars can be destructive up to tens of kilometers down slope the volcano, posing a risk for larger numbers of people (Manville, 2014).

3.3. Limnic gas bursts

In volcano-tectonic settings, large amounts of CO_2 released from deep magmatic sources can be stored in the hypolimnion of meromictic (permanently stratified) volcanic lakes. Different triggering mechanisms to release the CO_2 from bottom waters are proposed, based on observations from the August 1984 Lake Monoun and August 1986 Lake Nyos gas bursts: (1) a landslide slumped into deep lake waters (Kling et al., 1987, 1989; Sigurdsson et al., 1987), (2) supersaturation of CO_2 (Kanari, 1989; Evans et al., 1994; Kusakabe, 2014), (3) a seasonal decline in the stability of lake stratification (Kling et al., 1987), (4) an internal wave (Kling et al., 1987), or (5) climatic factors (Giggenbach, 1990). A combination of some of the trigger mechanisms is probably true, for which they should be treated equally. Fact is that both Lake Monoun and Lake Nyos gas bursts occurred in August, the period during which lake stratification is less stable, at least in water close to the surface. As solar heating of lake surface water is blocked by clouds, which also directly feed the lake with colder rain water, colder and denser surface waters tend to sink into deeper strata of the lake. Especially in tropical regions, where the difference between lake surface water temperature during summer and winter is small, deep stratified lakes do not tend to turn over yearly, while in temperate regions the large seasonal difference of lake water temperature provokes lake overturn during the cold period. Paired to this overturn, CO_2 is released at the lake surface: if CO_2 release is frequent (yearly), resulting hazards will be small, or even inexistent; if CO_2 release is infrequent related hazards will be high. The reason CO_2 release is hazardous is that it is an odorless, colorless, but asphyxiating gas. Moreover, CO_2 is denser than air and will disperse at breathing height hovering over the earth's surface (Costa and Chiodini, 2014).

3.4. Acid gas attack

Besides the direct impact of a CO_2 limnic gas burst, prolonged release of acidic gas species from the surface of "active" crater lakes (Varekamp et al., 2000) can lead to "acid gas attack" of the surrounding lands. Moreover, in the high-humidity environments the acidic gas species will be absorbed in clouds, creating acid rain. Despite the presence of a water body (the lake), if the input of magmatic volatiles beneath the lake is high and continuous, scrubbing of acidic gas species such as SO_2, HCl and HF cannot outweigh the continuous recharge from below the lake (Symonds et al., 2001). For extremely acidic waters (pH 0 or below), HCl does not behave as a conservative species, especially when acidity is continuously provided by SO_2, the more abundant acidic species at actively degassing volcanoes. On their turn, sulfur gases also degas from the lake surface, although a large part of the originally entering SO_2 will be involved in more complex sulfur dynamics in active crater lakes (see Delmelle and Bernard, 2014, for a thorough review). Stronger acid degassing from lakes is favored by (1) a higher lake water temperature, (2) a higher acidic recharge from below, (3) bubbling degassing at the lake surface, (4) strong lake convection, and (5) strong winds at the lake surface (Rouwet and Ohba, 2014). A clear example of acidic gases creating a "death zone" downwind a strongly degassing active crater lake is Laguna Caliente at Poás, Costa Rica (Fig. 4).

3.5. Water contamination and wall rock failure after seepage of acidic lake water

Even if the acid remains in the liquid phase in a lake system, acidic fluids can become hazardous when prolonged lake water dispersion into the volcanic edifice occurs. The possible hazards related to lake water seepage are two: (1) the lake water will end up into the hydrological network, leading to contamination of aquifers, rivers, and farmland (Sriwana et al., 1998; Delmelle and Bernard, 2000; van Rotterdam-Los et al., 2008; van Hinsberg et al., 2010), and (2) prolonged water–rock interaction under extremely acidic conditions will dissolve the wall rock, leading to a decrease of the mechanical stability of the volcanic edifice, eventually leading to flank failure (Kempter and Rowe, 2000; Wagner et al., 2003; Rouwet et al., 2010b; Delmelle et al., 2014).

The most striking example of contamination by a seeping acidic crater lake of the natural environmental is Kawah Ijen (Java, Indonesia), discharging through the Banyupahit river (Heikens et al., 2005; Löhr et al., 2005; Delmelle et al., 2014). This acidic river contains high concentrations of toxic elements such as SO_4, NH_4, PO_4, Cl, F, Fe, Cu, Pb, Zn and Al. These elements will form a threat to people as they enter the food-chain in a direct (drink water from wells) or indirect way (irrigation waters entering crops). Fluorisis, a bone disease following F contamination, is common in this area. Healing of soils and rivers seems to be the only remediation strategy, although in practice this is hardly possible.

Within the lifetime of hydrothermal systems (hundreds to thousands of years), mass removal after prolonged chemical and physical rock leaching can weaken the mechanical stability of the volcanic edifice, increasing the risk for avalanches and lahars, even during periods of volcanic quiescence (Voight et al., 1983; López and Williams, 1993; Kerle and van Wijck de Vries, 2001; Reid, 2004). Within this long-term time scale, the alteration of basement rocks to clay minerals by magmatic–hydrothermal activity may create clay-rich sliding plains at depth, which can escalate into major landslides, a kind of volcanic

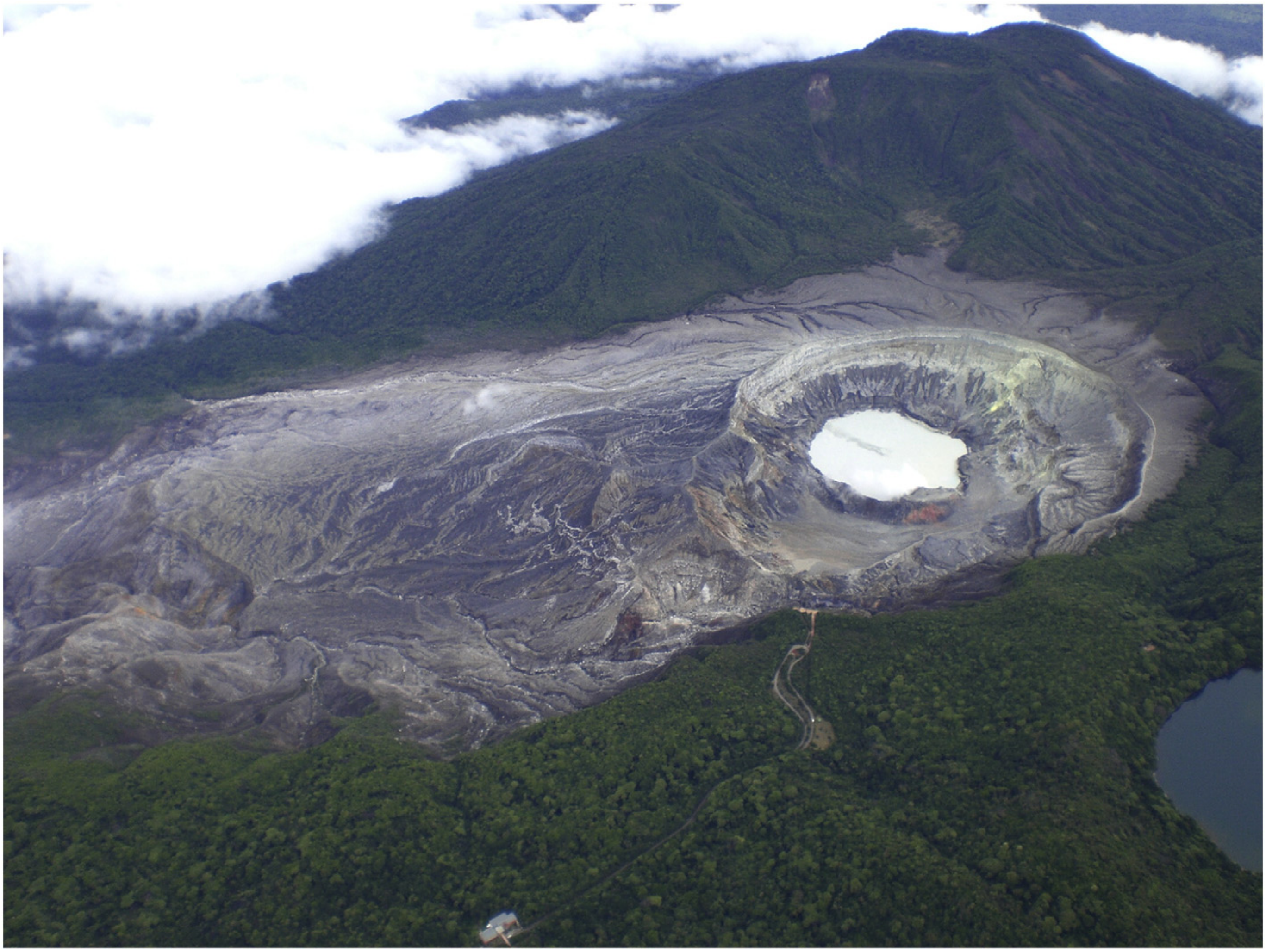

Fig. 4. Aerial photograph of Poás volcano, Costa Rica (picture by D.R., 6 April 2007). The gray lake is Laguna Caliente, the source of the acidic plume degassing and resulting acid rain, affecting the west side of the volcano (left). The lake in the foreground in the non-active Laguna Botos, with pH ~4 water due to the influence of the acid rain.

disaster (Sato et al., 2013). As volcano flanks are intrinsically metastable structures (del Potro and Hürlimann, 2009), the presence of soils or altered areas weaken the geomechanical characteristics of volcanic materials (Delmelle et al., 2014). Such massive rock mass removal is visualized by the Río Sucio, discharging the northern fumarolic field and thermal springs of Irazú volcano (Costa Rica), presently in a state of quiescence (Fig. 5 inset). During heavy rain events, the altered areas of volcano flanks can be easily moved. In the case of Irazú, a massive avalanche could destroy the bridge of the highway connecting the capital area with the main commercial harbor of the Atlantic Ocean, paralyzing the country's economic activities (Fig. 5).

4. Lake monitoring and hazard mitigation: "active" crater lakes vs "Nyos-type" lakes

4.1. The residence time dependent monitoring time window

The first obstacle to bypass when monitoring volcanic lakes is to find the adequate frequency to carry out measurements and observations related to lake activity, teasing the residence time dependent monitoring time window (RTDMTW hereafter). This is especially valid for tracking changes in the chemical composition of lake waters, as aqueous species tend to be highly conservative within volcanic lakes. High-frequency geochemical monitoring, considering the entire lake as representative for the change in activity or dynamics, does not necessarily increase its quality, as obtained information will often be over-detailed with respect to fluid dynamics within the lake system. Nevertheless, a high-frequency data gathering will be useful to decipher specific, especially physical events, e.g.: the fine structure of fluid flushing detected by high-frequency gravimetry surveys (Rymer et al., 2000), daily T-gauging to detect effects on lake water evaporation regime, or lake convection. Some possibly hazardous events (e.g., phreatic eruptions) are seen to be only precursored on the very short term (minutes) and local scale, and do require a high-frequency monitoring.

On the other hand, too low-frequency geochemical or geophysical monitoring will inevitably lead to missed signals of significant past events that changed the chemical and physical properties of the lake. If this signal is preserved in time and overprinted with more recent, but undetected additional signals, it will be extremely difficult to distinguish which process caused which change. Table 1 summarizes the four possibilities of monitoring strategies based on the RTDMTW. Details and concrete examples are provided in the next section.

4.2. Geochemical monitoring of active crater lakes

Active crater lakes (erupting, peak- and high-activity lakes) are one of the most dynamic manifestations of volcanic activity, besides being a picturesque "blue window" into the magmatic–hydrothermal system. Contrary to open-conduit degassing volcanoes, which will lose an eventual indicative precursory signal to the atmosphere often without being

Fig. 5. Río Sucio draining the northern thermal springs and near-summit fumarolic field of Irazú volcano, Costa Rica (pictures by D.R., December 2009). Inset: inlet of Río Sucio into the Río Hondura, a fresh water river originating from lower elevations of Irazú's northern flank. The main picture shows the bridge of HW32 (Carretera Braulio Carrillo), connecting the metropolitan area of the Valle Central with the Atlantic coast.

detected, active crater lakes can preserve a chemical or physical marker for a certain period of time after the indicative event occurred. This particular property can become both an advantage as a disadvantage, largely depending on the lake volume and related residence time. When the residence time of an active crater lake is sufficiently short (i.e., the lake has a small volume and/or the total water input flux is high), monitoring frequency must be high enough to detect sudden changes in the lake's physical and chemical properties, in the same time window as magmatic dynamics (e.g., weeks or few months). When lake water residence time is large, less details can be provided for the RTDMTW, and only long-term trends can become insightful. Unfortunately, long-term trends are less useful in deterministic eruption forecasting. This means that small, dynamic crater lakes are most sensitive, and more easily monitored, if they are able to resist against magmatic heat input before they dry out completely.

"Easily" is a relative term. Rather than investigating temporal evolutions of absolute concentrations of major anion or cation species, a common used method to be found more effective in some active crater lakes is the temporal evolution of ratios between major species, e.g., Mg/Cl and SO_4/Cl ratios (Giggenbach, 1974; Ohba et al., 2008) (Fig. 6). Anionic species in volcanic lakes mostly originate from an underlying degassing magmatic ($HCl–SO_2–HF$ dominant) or hydrothermal system ($CO_2–H_2S$ dominant), whereas cationic species originate from the leaching of metals from the rock. The acidic gas species are absorbed in the lake water as Cl^-, SO_4^{2-} (or HSO_4^-), and F^-, releasing protons to the water yielding extreme acidities (pH ~ 0 or below). H^+ reacts with metal oxides in the neutralizing reactions:

$$M_2O + 2H^+ = 2M^+ + H_2O \quad (1)$$

$$MO + 2H^+ = M^{2+} + H_2O \quad (2)$$

$$M_2O_3 + 6H^+ = 2M^{3+} + 3H_2O \quad (3)$$

Table 1
Four monitoring strategies based on the residence time dependent monitoring time window.

1. Residence time ≫ monitoring time window:	over-detailed, only useful for short-term precursors
2. Residence time ≥ monitoring time window:	representative for the observed lake dynamics
3. Residence time < monitoring time window:	risk of unobserved signals, no detection short-term precursors
4. Residence time ≪ monitoring time window:	lack of detail possible

where M is the cationic species (rock forming element, i.e. Na, K, Ca, Mg, Fe, Al, etc.). As acidic crater lake brines are highly "immature waters" (Giggenbach, 1988), far from thermodynamic equilibrium, the cation content reflects isochemical dissolution of the wall rock. As such, Mg is a highly mobile element in the aquatic environment (Pasternack and Varekamp, 1994; Takano et al., 2004). An increase in Mg/Cl is thought to correspond to an enhanced interaction with a recently intruded, but crystallizing magma (Mg increase), relative to the degassing state of the magma (stable HCl degassing). Chloride ion is generally considered a "conservative" element: once HCl encounters a water body, it will be efficiently scrubbed and remain in the water phase without posterior degassing (Symonds et al., 2001). The contradiction in "Cl is a highly volatile lithophile but hydrophile element" (Sharp et al., 2010) shows that less is true. Under extremely acidic and hot conditions (≈active crater lake), HCl tends to degas from water bodies (Truesdell et al., 1989). An increase in the Mg/Cl ratio in the lake water of the most active crater lakes will thus often refer to enhanced "evaporative degassing", rather than "fresh magma near the surface", making correct interpretations of Mg/Cl ratios unstraightforward. A long-term increasing trend in the Mg/Cl ratio at Poás' Laguna Caliente in the 1980s and during the 2006–ongoing peak-activity periods did perfectly mimic the strong evaporation from the lake surface, and did not necessarily indicate the presence of magma near the surface (Rowe et al., 1992b) (Fig. 6). On the other hand, at Ruapehu Crater Lake where less extreme conditions reign, the Mg/Cl ratio has demonstrated to be useful in eruption forecasting since the 1970s (Giggenbach, 1974).

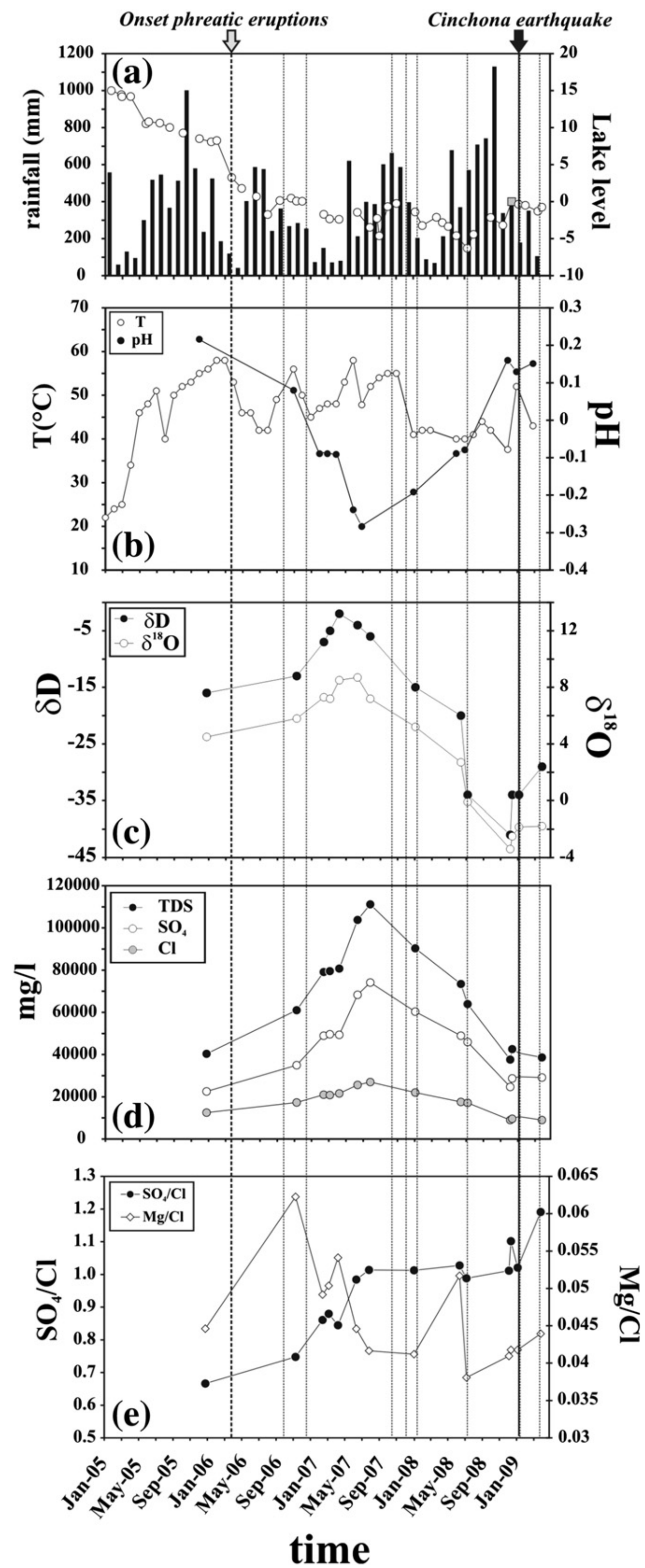

Fig. 6. An example of discontinuous monitoring of Poás' Laguna Caliente, Costa Rica, for the period 2005–2009 during the March 2006–ongoing phreatic eruption cycle (based on D.R. and R.M.-A. personal data, to be published elsewhere). The vertical gray lines indicate phreatic eruptions; the vertical black line indicate the occurrence of a tectonic Earthquake (Mw 6.2), 6 km from Poás volcano (Cinchona, 8 January 2009), (a) Rainfall gauged near the Poás summit and lake level variations, (b) lake water temperature and pH variations, as measured directly in the field, (c) variations in the lake water isotopic composition (δD and $\delta^{18}O$), higher values often indicate increased evaporation, (d) variations in SO_4, Cl and Total Dissolved Solids content in lake water, (e) variations in SO_4/Cl and Mg/Cl ratios. The temporal variations of monitored parameters indicate that relationships with the phreatic activity are not unequivocal.

With the peculiar hydrophile–volatile behavior of HCl, the SO_4/Cl ratios in crater lake water should also be approached cautiously. Moreover, according to the solubilities in magmas of the various volatile species, during magma uprising SO_2 degassing occurs at greater depth with respect to HCl (and HF) (Carroll and Webster, 1994). In open-conduit degassing, this fact has lead to efficient monitoring preluding eruptions (Aiuppa et al., 2002, 2004, 2009). When SO_2 will rise through crater lake water it will easily be absorbed and, depending on the T-E_h conditions of the lake water, SO_2 will undergo complex speciations: (1) native sulfur pools at the lake bottom, (2) SO_4^{2-} (or HSO_4^- in extremely acidic environments), (3) thiosulfates (Takano, 1987), (4) H_2S, (5) sulfate–sulfide mineral precipitation, and (6) products of reactions among these species. It is hard to quantify "SO_4^{2-}" (the measured concentration in lake water) as solid sinks and gaseous S will be lost from the water phase. Combining this complexity together with the behavior of HCl at varying pH, SO_4/Cl ratios will be difficult to interpret (Fig. 6). It is observed that the evaporative degassing of HCl is often dominant, and even favored by an enhanced SO_2 input providing the necessary proton for HCl to degass, making SO_4 and Cl interdependent. Although ratios between species are more indicative as absolute concentrations, which strongly depend on dilution and evaporation effects, care should be taken when interpreting them within a monitoring strategy.

If even the gases are not able to close the puzzle, maybe it is worth studying the water in se: does the isotopic composition of crater lake water mirror the magmatic dynamics beneath crater lakes (Fig. 6)? Magmatic water (defined "andesitic water" by Taran et al., 1989) can be recognized only in vapors from high temperature fumaroles (T > 800 °C) (Taran et al., 2013). When high temperature degassing takes place beneath a crater lake, the magmatic water end member will be likely masked, although a major challenge in crater lake monitoring is to quantify the input rate of hot magmatic fluids. Isotope balance approaches for crater lakes were effectively applied to medium-activity crater lakes (e.g., El Chichón, Taran and Rouwet, 2008), but seem less appropriate for more dynamic crater lakes. These calculations are based on the box model, i.e. the total lake water volume at a certain period of observation results from the balance between water input and water output fluxes (Hurst et al., 1991; Rowe et al., 1992a; Ohba et al., 1994; Pasternack and Varekamp, 1997; Rouwet et al., 2004, 2008, 2009; Rouwet and Tassi, 2011), as follows:

$$V_L = V_{L0} + (Q_m \cdot dt + Q_{hmf} \cdot dt + Q_{ro} \cdot dt) - (Q_s \cdot dt + Q_e \cdot dt + Q_{of} \cdot dt) \quad (4)$$

where V_L is the lake water at the period of observation (in m^3 or L); V_{L0} is the lake water volume at the previous period of observation (in m^3 or L); Q_m is the input rate of meteoric water (in m^3/s or L/s), Q_{hmf} is the input rate of the hot magmatic fluid end member (in m^3/s or L/s), Q_{ro} is the input rate of runoff water (in m^3/s or L/s), Q_s is the output rate of water due to seepage (in m^3/s or L/s), Q_e is the rate of water loss due to evaporation (in m^3/s or L/s); Q_{of} is the output rate of water due to lake overflow (in m^3/s or L/s); and dt is the period of observation (in s). The volume of the crater lake can be estimated by sonar reflection surveys (Takano et al., 2004), photographical methods (Rouwet, 2011), or lake level gauging (Terada et al., 2012). Q_m, Q_{ro} and Q_{of} can be gauged or measured and Q_e can be calculated using equations of energy loss by evaporation (see Hurst et al., 2012, for a review). The sublacustrine processes, lake seepage rate and the input rate of the hot magmatic fluid end member, have to be calculated from Eq. (4), as they are not measurable in the field. Recent modeling procedures (TOUGH2; Todesco et al., 2012, 2014) attempted to estimate Q_s within reasonable assumptions for pressurized systems beneath lakes (Section 5.4). For monitoring purposes, Q_{hmf} is the major unknown which we desire to track with time. Multiplying every parameter with its corresponding isotopic composition, we add additional unknowns, of which some can be estimated within reasonable assumptions. As such, the hot magmatic fluid end member has an assumable isotopic composition equal to Taran's "andesitic water" ($\delta D = -25‰$ V-SMOW and $\delta^{18}O = +7.5 \pm 1.5‰$ V-SMOW). If this is true, and with a Q_s obtained from numerical modeling, and all other parameters and corresponding isotopic compositions covering known or measurable values, Q_{hmf} can be calculated. Nevertheless, the "hot magmatic fluid end member" venting at the bottom of active crater lakes often results from multi-step boiling off of recycled seeped lake water, rather than a continuous deep input flux of "andesitic water" directly originating from the magma. The top of the magmatic–hydrothermal system underlying active crater lakes is often a highly dynamic flushing of the lake water itself. If both Q_{hmf} and its isotopic composition are unknown parameters, chemical modeling strategies are the only means to better quantify the counterbalancing Q_{hmf} and Q_s.

4.2.1. Case studies of geochemical monitoring

The 1994–1996 Ruapehu Crater Lake monitoring (New Zealand; Christenson, 2000) tends towards a strategy-1 monitoring (Table 1), because of the high-volume of the lake (130 m deep, 9×10^6 m^3; Christenson, 1994), and thus generally long residence time of lake water. During the observation period, fluid input was high enough (lower residence time, due to faster fluid cycling) to observe several trends precursory to the September 1995 phreatomagmatic eruptions by several months: Mg/Cl, T, SO_4 and Cl increased since 6, 9 and 10 months before the event, respectively (Christenson, 2000). Such detail lead to efficient monitoring.

Yugama Lake (Kusatsu-Shirane, Japan) has been monitored with a monthly frequency since 1989 (and since 1966 on a less frequent basis, Ohba et al., 2008). This frequency corresponds to strategy-2 monitoring (Table 1), as the residence time of Yugama lake water is in the order of one to two years. Despite the slightly over-detail of this monitoring it permits to observe seasonal trends, important for Yugama Lake as the lake is near freezing in winter. Important changes in the dynamics of the underlying magmatic–hydrothermal system should be observed adequately, especially tracking the Mg/Cl ratios.

It is needless to say that sampling frequency also depends on a budget available to the researchers involved. This non-scientific, but important factor, inevitably leads to strategy-3 monitoring (Table 1). An example is the 1995–2008 discontinuous monitoring of El Chichón crater lake (Mexico, Taran et al., 1998; Rouwet et al., 2004, 2008, 2009). This shallow, low-volume crater lake is affected by high-rate fluid input (meteoric as well as spring waters), leading to an extremely short residence time of 2 months (Taran and Rouwet, 2008), which would require a monitoring frequency of at least monthly, if not weekly. Instead, El Chichón lake was sampled 2–4 times a year. Logistical issues (distance from observatory, 4000 mm/year rainfall with a rainy season in summer) impeded consistent lake sampling, especially during the rainy season. Nevertheless, with this monitoring frequency, a non-seasonal, long-term cyclic trend was recognized, resulting from the lake's relationship with a geyser-like spring occasionally feeding the lake with water and solutes (mainly Cl).

Most of the studied lakes follow a strategy-4 monitoring (Table 1), with occasional or discontinuous observations or sampling surveys. For these lakes it is often difficult to link observed changes to effective changes in the magmatic–hydrothermal system. Despite this monitoring inconsistency, abrupt clear indicators (e.g., sudden T rise or drop, vigorous degassing from a previously quiescent lake, drastic lake level drop, appearance of sulfur spherules on the lake surface) can become precursory signals. Recent examples of successful strategy-4 lake monitoring leading to an eruptive period are Copahue's crater lake (Argentina-Chile, December 2012 eruption, Agusto et al., 2013) and Poás' Laguna Caliente (Costa Rica, 2006–ongoing phreatic eruption cycle; Rouwet et al., 2010a; González et al., 2013).

4.3. Monitoring Nyos-type lakes and hazard mitigation

After the 1986 Lake Nyos gas burst concern gradually raised on the fact if other volcanic lakes are able to release a CO_2 cloud in a similar way. Especially in the 2000s, deep waters of meromictic (constantly stratified) volcanic lakes were sampled and gauged to detect CO_2 accumulation, e.g.: Albano, Monticchio and Averno lakes (Italy, Caliro et al., 2008; Carapezza et al., 2008; Chiodini et al., 2012; Cabassi et al., 2013a; Caracausi et al., 2013), Lake Kivu (DRC-Rwanda; Schmid et al., 2005; Tassi et al., 2009b), Río Cuarto and Laguna Hule (Costa Rica; Cabassi et al., 2013b). As residence time of lake water in Nyos-type lakes (high volume) is very long (years–decades), the monitoring frequency often seems to higher than needed. As Nyos-type lakes are not affected by highly dynamic fluid fluxes or phreatic eruption dynamics, the only scope of the monitoring is to estimate the recharge rate of CO_2-enriched ground waters with time, beyond any RTDMTW frame. For this reason, a 1–2 year monitoring frequency is highly recommended (Minoru Kusakabe written communication), especially when artificial degassing is undertaken.

On Lake Nyos, hazard mitigation actions are developed by liberating the stored CO_2 from the bottom layers, lowering degassing tubes to the lake maximum depths (Halbwachs et al., 2004; Kusakabe, 2014). After instigation, the principle of gas self-lifting fountains CO_2-rich mineralized water to the surface (Fig. 7). A similar strategy is undertaken at Lake Kivu (Schmid et al., 2004, 2005), where the CH_4-enriched deep waters additionally house an energy source, mostly for Rwanda. At Lago Albano, during Roman times, a drainage tunnel was engineered to (1) avoid direct overflow, causing eventual floods and lahars on the outskirts of the Colli Albani volcano, or (2) decrease the lake depth to avoid large volume storage of CO_2 in bottom waters, eventually released during catastrophic events (Funiciello et al., 2003). A recent review on monitoring methods and mitigation strategies for Nyos-type lakes can be found in Tassi and Rouwet (2014).

Fig. 7. Degassing pipes in action at Lake Nyos, Cameroon. Deep lake water is fountained to the surface in order to liberate CO_2. Lake surface water turned red by iron oxide after oxidation of iron dissolved in bottom water, contemporaneously pumped to the surface (picture by Y. Yoshida).

5. Strategies for future volcanic lake monitoring

5.1. Temperature gauging and FLIR imagery

During the last decade or so, thermal camera imagery has been efficiently applied in volcano monitoring set-ups (Oppenheimer, 1993; Calvari et al., 2005; Harris et al., 2005, 2012; Lodato et al., 2007; Spampinato et al., 2012; Witter et al., 2012). Continuous monitoring of fumaroles, erupting volcanoes or lava flows has enabled to estimate output rates and thermal energy release from volcanoes. As lake systems are sensitive to thermal variations caused by fluid input from the underlying magmatic–hydrothermal environment, thermal imagery has recently become a promising tool for volcanic lake monitoring. A major technical inconvenience when imaging high-T lakes is the air humidity created by the evaporation from the lake surface. Corrections for the air humidity effect on thermal images should be made in order to provide realistic estimates of lake water surface temperatures. Nevertheless, to obtain a continuous T-recording of active crater lakes, thermal imagery from a distance is adequate, as the acidic conditions and eventual phreatic activity has previously shut down T-probes submerged in the lake (Hurst, 2013).

Space-borne infrared (IR) imagery of crater lakes was first experimented in the late-1980s for Poás' Laguna Caliente, Costa Rica (Oppenheimer, 1993). The lake surface temperatures measured by satellite imaging resulted 3 °C lower than those contemporaneously measured in the field. Despite this discrepancy, IR temperatures could be more representative as they are lake-dimension pixel sized, rather than a point measurement in the field. A more recent study of satellite IR imagery (Trunk and Bernard, 2008) on four well-known crater lakes (Poás, Ruapehu, Kawah Ijen and Lake Yugama) reached similar conclusions: the error in the temperature measurements (<1 °C) are below the usual indicative temperature variations in crater lakes (>1 °C). They also noticed that lake water heating often anticipates increases in seismic activity, converting the method in an eventual early warning sign prior to increased volcanic unrest.

During the last three of years, ground-based thermal images of the phreatic eruptions at Poás and Rincón de la Vieja volcanoes, Costa Rica, were collected (Ramírez et al., 2013) (Fig. 8). Beyond the RTDMTW, generally in the order of weeks to months, and in need of considering the entire lake to be representative of the temporal variation, phreatic eruptions are local phenomena originating from well located vents, consequently following specific temporal and spatial dynamics. Some minutes before such phreatic eruptions, increased fluid jetting occurs from the eruptive vents which is visualized as a synoptic view by FLIR imagery. Although an acid-proof temperature sensor immerged as some depth coupled with a telemetry system can provide a more precise "point temperature" in real time at a fraction of the cost of a FLIR system, we believe this is probably the most adequate and maybe only short-term precursor phreatic eruptions will reveal. Needless to say that thermal imagery of crater lake water temperatures

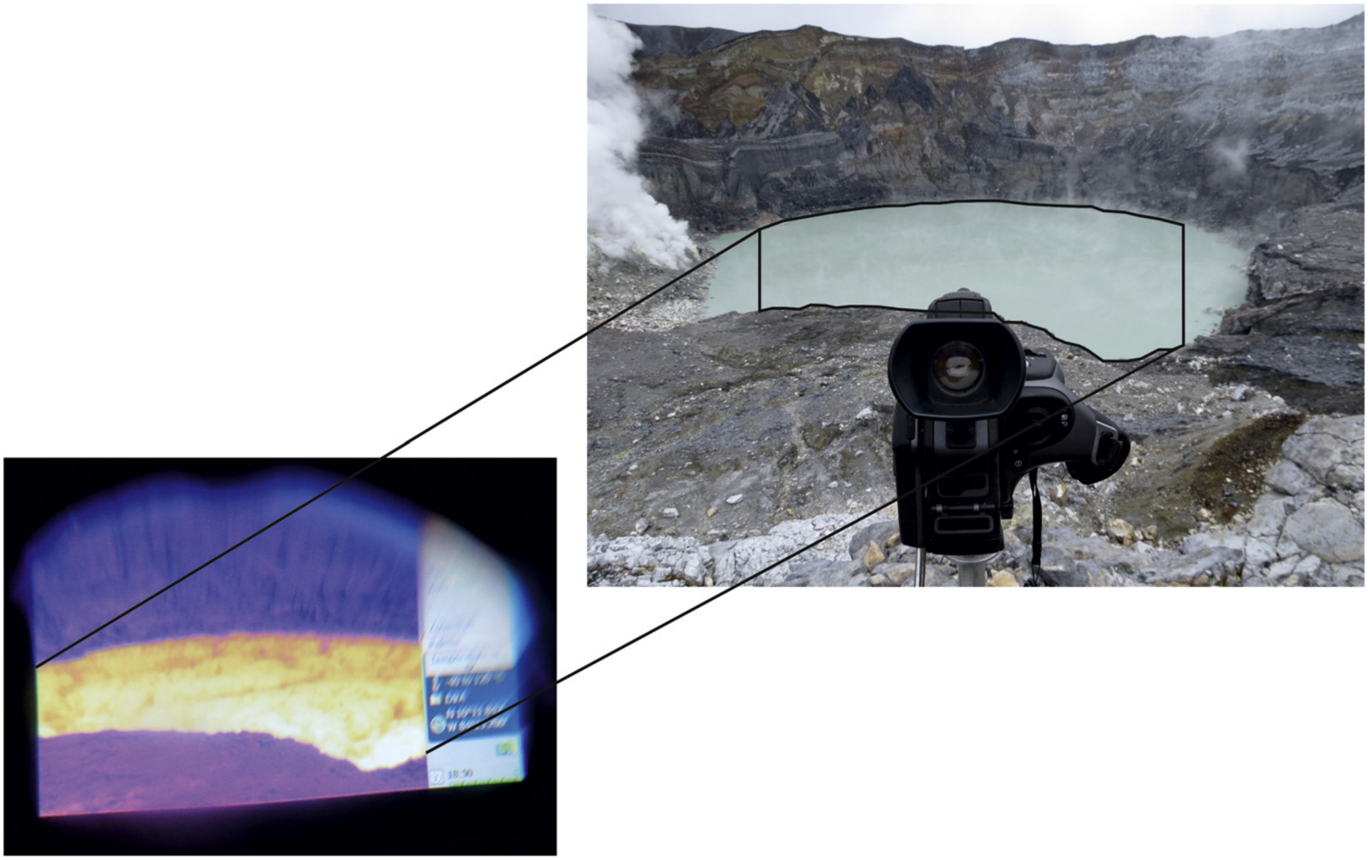

Fig. 8. FLIR imaging at Poás' Laguna Caliente in May 2012, by C. Ramírez (RSN-UCR, Costa Rica) (picture D.R.) (Ramírez et al., 2013).

from a distance (satellite or ground-based) will make thermal tracking a lot safer and faster (real-time), especially for frequently erupting lakes, when lake water sampling or T-gauging at the lake shore will become too risky, or practically impossible.

5.2. Measuring gas fluxes

When a volcano resumes a state of volcanic unrest after a period of quiescence, degassing is often the first process to occur. Providing qualitative (chemical composition) as well as quantitative (output rate) insights in early degassing will serve as an early warning system. The same principle counts for re-activation at crater lake bearing volcanoes. The behavior of CO_2, the most abundant "dry" species in magmatic gas, when reaching a water body (i.e., crater lake) depends on the pH: (1) it will be at least partially dissolved in near-neutral pH waters, or (2) it will bubble through the lake water column for acidic ($pH < 4$) waters. Due to its relatively low solubility in magmas, degassing CO_2 can take place at great depth, and will thus reach the surface before many other species. The other gas species indicative of magmatic degassing (SO_2, HCl, HF) will be scrubbed in the lake water and underlying magmatic–hydrothermal system, and will only be partly released at the lake or crater surface. The latter species will provide qualitative details, using solute geochemistry of crater lake waters (Section 4.2), or multi-gas detection above/near the crater lake surface (next section).

If we consider the crater lake as the intersection between the magmatic–hydrothermal system/aquifer and the surface, installing a continuous CO_2-flux station (e.g., accumulation chamber method; Chiodini et al., 1998) right next to an active crater lake will practically give similar flux rates as having it installed on the lake water itself (as a floating accumulation chamber; Mazot and Taran, 2009; Mazot et al., 2011; Pérez et al., 2011; Arpa et al., 2013), especially if the crater lake and surrounding aquifer is hyper-acidic. This is a good hint to monitor very active and erupting crater lakes, as a floating accumulation chambers will not have much longevity on the lake surface. Nevertheless, the degassing conditions from an open-air lake surface will be different than degassing through a porous medium next to the lake, but building a time-record of CO_2 gas fluxes from the same spot, will quantify deep CO_2 degassing affecting the lake as well as its surroundings (Fig. 9). For practical purposes, installing fixed CO_2-flux stations on land is more straightforward than on the surface of an acidic and eventually erupting crater lake.

Besides tracking the most abundant gas species in a chemical way (CO_2 accumulation chamber method), gas flow can be detected in a physical way by underwater hydroacoustic monitoring (Vandemeulebrouck et al., 1994, 2000), or echo sounding surveys from the lake surface (Caudron et al., 2012). The former method distinguishes boiling, bubbling and rock-cracking processes, as a low-frequency (1–50 Hz), high-frequency (500–5000 Hz) or ultrasonic (20–100 kHz) acoustic signal, respectively. As such, when a volcanic lake resumes activity, the acoustic signal will evolve from low-frequency (boiling), over high-frequency (bubbling degassing), to eventually ultrasonic acoustic signals (rock cracking). This trend was observed prior to the 1990 Kelut eruption (Vandemeulebrouck et al., 2000). On the other hand, Ruapehu crater lake in the early 1990s (note: before the 1995–1996 phreatomagmatic eruptions) did not show any sign of bubbling degassing, but rather low-frequency noise generated by liquid flow to and from the crater lake (Vandemeulebrouck et al., 1994).

The latter method, combined with CO_2-flux records carried out on the lake surface using the floating accumulation chamber method, gives, besides quantifying the gas flux, insights into the degassing style of gas entering the pre-2007 eruption at Kelut crater lake (Caudron et al., 2012). The gas (CO_2) flux is quantified using an empirical equation based on the backscatter signal reaching the echosounder after hitting a train of rising bubbles through the lake water column. It is

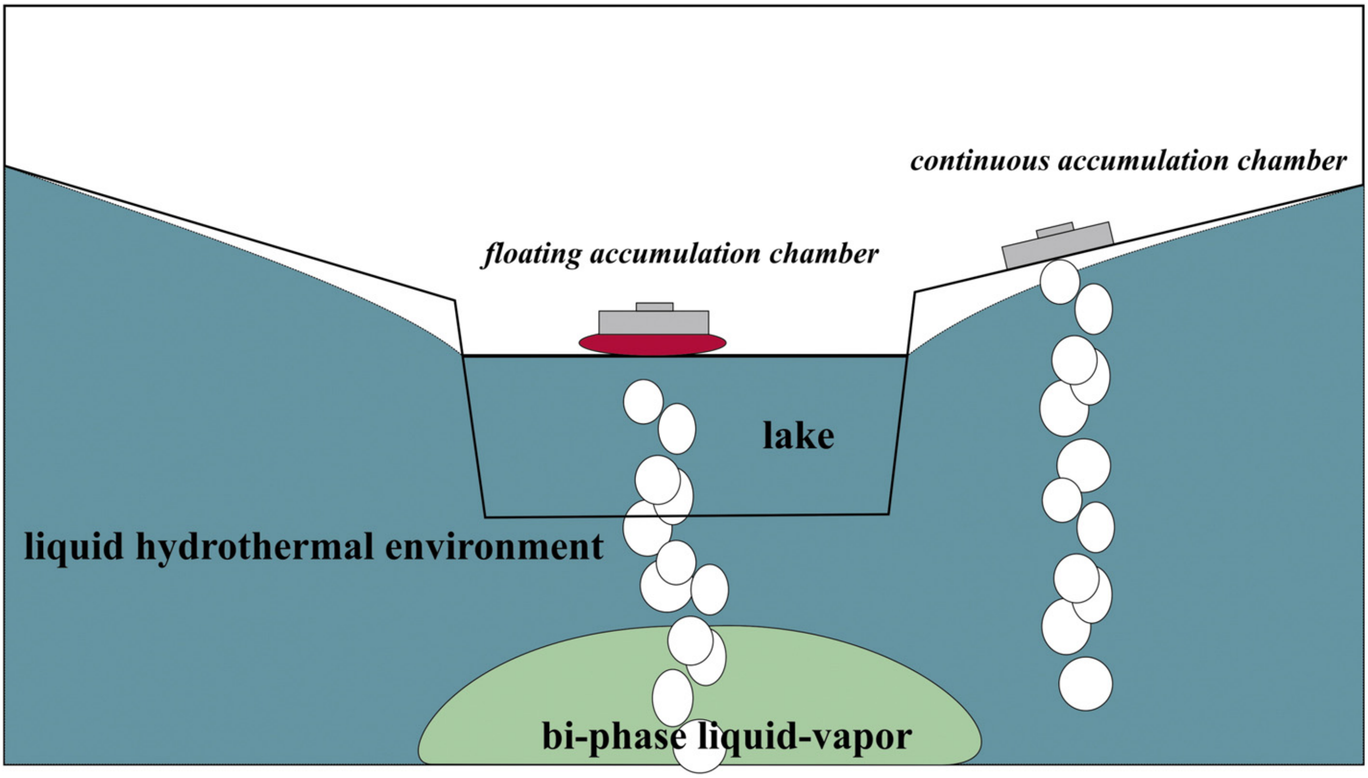

Fig. 9. CO_2 monitoring strategy, using the accumulation chamber method. Gas bubbles (predominantly CO_2) are in white. As the liquid hydrothermal environment surrounding an active crater lake can be considered a proxy of the lake water itself (hyper-acidic, highly saline brine), an increased degassing spot near the lake shore can be used to track temporal variations in CO_2 gas efflux in a more practical way, with respect to the "aggressive" crater lake surface (acidic degassing, eventual phreatic eruptions). A major issue is to not lose the gas flux station when monitoring is most needed, during eruptive activity.

noticed that bubble signals sometimes disappear along their rise towards the surface, meaning that CO_2 dissolves in the water, afterwards partly liberated at the lake surface by diffuse degassing.

We suggest to apply the three methods (floating accumulation chamber, hydroacoustic monitoring, echosounder surveys), preferably in a continuous set-up, in order to quantify gas fluxes from active crater lakes, as they have shown to be ideal tools in early warning detection of volcano reawakening.

5.3. Multigas measurements

As earlier emphasized, volcanic lake bearing volcanoes do not behave as open-conduit volcanoes, but can manifest active degassing from the crater lake surface, even to such a degree that real volcanic plumes exit their craters (e.g., Poás, Aso, Copahue). Recently, efforts have been made to measure gas concentrations in situ in such evaporative degassing plumes by using multi-gas portable analyzers (Di Napoli et al., 2013; Shinohara et al., 2014). Remember that, for an active crater lake: (1) the colder lake water will easily condense incoming water vapor, (2) CO_2 will merely bubble through the lake or will degas by diffusion without being scrubbed in the lake, (3) "magmatic" SO_2 or "hydrothermal" H_2S will be absorbed in the lake water, followed by complex S-speciation reactions, strongly altering the original signal, and (4) HCl (and HF-less treated here, although not less useful in lake monitoring) will easily be absorbed in lake water, but will be effectively released as a gas at the lake surface, especially under hot and hyper-acidic conditions. The alkaline trap method (passive or active), previously used in monitoring of volcanic plumes (Aiuppa et al., 2002; Shinohara and Witter, 2005), is complicated by the intrinsically extreme humidity in plumes coming off crater lakes, which will lead to large analytical uncertainties.

Measurements carried out with multi-gas analyzers (Aiuppa et al., 2005; Shinohara, 2005) are promising. This technique is based on the direct detection of gas concentrations using species-specific gas analyzers or sensors. To the best of our knowledge, so far two multi-gas experiments have been carried out. On Aso's acidic Yudamari crater lake (Japan) the scrubbing and speciation effect described above is strong compared to adjacent high-temperature fumaroles (Shinohara et al., 2014). On the other hand, the hydrothermal-dominant Boiling Lake (Dominica; Fournier et al., 2009) rather behaves as an "open-air fumarole" with its gas coming off the lake very similar in composition as the boiling-temperature fumaroles in the adjacent Valley of Desolation (Di Napoli et al., 2013).

Another experiment, detecting CO/CO_2 ratios from a degassing crater lake, was carried out on Ruapehu (Christenson et al., 2010b): higher CO/CO_2 ratios indicate a higher temperature of the underlying magmatic–hydrothermal system.

Building long time series of multi-gas measurements is still a void to be filled before declaring its usefulness in volcano monitoring (Fig. 10). Major questions to be answered are: (1) What is the exact relationship between the lake water chemistry and the chemical composition of the evaporative degassing plume? (2) Is the gas coming off the lake representative for the original magmatic marker, after having passed several scrubber-system, i.e. the magmatic–hydrothermal system, and the lake itself? (3) Will the gas composition be overprinted by more superficial factors, such as humidity, lake water T, pH and salinity? Nevertheless, the system has already proven its robustness in extremely acidic and humid environments, which is not an obvious constraint when studying volcanic lakes (Fig. 10).

5.4. Numerical modeling

Quantifying the main driving agent in crater lake dynamics (i.e., the input rate of the hot magmatic fluid), is the major challenge in volcanic lake monitoring. This process can only be indirectly deduced from the effects it causes (i.e., changes in lake water chemistry and temperature, bubbling degassing, enhanced evaporation, etc.), but can hardly be detected directly, for being a sublacustrine process. In mass and energy balance approaches, the input flux of the hot magmatic fluid is the major unknown which is counterbalanced by another unknown and sublacustrine factor, the water seepage rate out of the lake (Section 4.2, Eq. (4)). As a consequence, two unknowns in one equation automatically leads to the need of modeling, by fixing one of the unknowns, considering the other one as the variable parameter.

During the last twenty years, numerical modeling simulations at magmatic–hydrothermal systems were successfully elaborated (Hayba and Ingebritsen, 1994; Todesco, 1997; Todesco et al., 2003, 2004; Todesco and Berrino, 2005; Hurwitz et al., 2007; Ingebritsen et al., 2010; Rinaldi et al., 2012; Petrillo et al., 2013). The first application of this kind on an active crater lake tried to give insight into the seepage from the Poás' Laguna Caliente crater lake towards the Río Agrio watershed (Sanford et al., 1995). They obtained water travel times from the lakes to the springs in the range of 1–30 years, coinciding with tritium-based water residence times of Río Agrio thermal spring waters (3–17 years; Rowe et al., 1995). A more lake-focused numerical simulation (TOUGH2) for Laguna Caliente was recently developed by Todesco et al. (2012, 2014). They discovered net seepage output fluxes in the order of 1–10 L/s, an order of magnitude lower than previous estimates from mass balance approaches (Brown et al., 1989; Rowe et al., 1992a).

A major concern in active crater lakes building up towards phreatic activity is to discover if physical mineral seals are present (e.g., the role of molten sulfur pools at the lake bottom). The importance of CO_2 in numerical simulations is once again straightforward, as CO_2, together with vapor, is a pressure increasing agent in the hydrothermal environment beneath the lake. If a high-permeability in the porous medium cannot account for a sufficient pressure build-up beneath the lake, a low-permeability seal needs to be present to explain the pressure build-up anticipating phreatic eruptions (Ruapehu Crater Lake; Christenson et al., 2010a). Although a direct monitoring application is ruled out for numerical modeling, the outcomes can be highly insightful to better understand fluid flushing in and out of active crater lakes. Especially, quantifying the seepage output and hot magmatic input fluxes, tracked with time, can be of help in active crater lake monitoring.

5.5. Monitoring indirect hazards

Quiescent volcanoes are often neglected in volcano monitoring. The presence of a "stable" acidic crater lake is often no cause of concern (no volcanic unrest; Phillipson et al., 2013), if it is considered as the background behavior of the specific volcano (e.g., Kawah Ijen, Indonesia; Yugama, Japan, El Chichón, Mexico; Irazú, Costa Rica). Nevertheless, within the lifetime of hydrothermal systems (decades to centuries) the presence of acidic fluids permeating into the volcanic edifice can alter its mechanical stability (Section 3.5). Acidic crater lakes offer the perfect scenario for this process (see Delmelle et al., 2014, for a thorough review). Highly altered sectors, flank deformation, lack of

Fig. 10. A hypothetical multi-gas monitoring setup for Poás' Laguna Caliente (Costa Rica) (picture by R. M.-A., February 2007). MG = multi-gas sensor.

vegetation in certain areas, fumarolic activity and thermal springs at flanks, chemical and physical rock removal through thermal springs, drastic level drops in crater lakes (e.g., 2010–2013 Irazú) are apparently innocuous indicators which should raise concern instead (~volcanic unrest).

Recognizing these features is relatively easy, but which specific indicators leading into related hazardous events, such as flank failure, sector collapse, lahars or floods can be revealed? Rock mass removal rates can be estimated by the "Cl-inventory method" (Ingebritsen et al., 2001):

$$Q_t = [Q_r(Cl_d - Cl_u)]/[Cl_t - Cl_u] \quad (5)$$

where Q_t is the discharge of the thermal spring group (L/s), charged with solutes after rock leaching; Q_s is the discharge of the river downstream the thermal spring group (L/s); Cl_d is the Cl content in the river downstream of the thermal spring group (mg/L); Cl_u is the Cl content in the river upstream of the thermal spring group (mg/L); and Cl_t is the Cl content in the thermal spring group (mg/L). In some cases, the thermal spring is the head of the river, without any thermal or cold springs more upstream, reducing Cl_u to zero in Eq. (5), and thus simplifying (Fig. 11):

$$Q_t = [Q_r Cl_d] / Cl_t.$$

Measuring Q_t in the field is practically impossible, as (1) the numerous springs are sometimes hidden at the river bed, and (2) spring outlets are too ragged to enable direct flux measurements. If we assume that no solutes are lost downstream from the original thermal spring waters by seepage, and if we know the total dissolved solids content in the spring waters (TDS), it is possible to calculate the rate of solute loss, and the rock mass removal rate, through the thermal springs (Rowe et al., 1995; Taran and Peiffer, 2009) (Fig. 11). Building a temporal record of these estimates will eventually reveal rock mass removal rates from volcano flanks through springs up to worrying levels. Such variations can have seasonal trends, and should be related to the monitoring of climatic parameters, especially rainfall.

Rainfall gauging is also necessary to reveal anomalous rain events which can rise to alarming rates when hitting such unstable volcanic flanks. Extremely hazardous lahars and floods can be easily triggered, without the necessity of a volcanic eruption or even volcanic unrest. Crater lake bearing volcanoes are more prone to such disasters, for just containing an extra amount of "free water".

5.6. Statistical approaches

5.6.1. Pattern recognition

At this point of this review paper, it has become clear that unambiguous precursory signals of phreatic eruptions from active crater lakes have not yet been recognized in the purely deterministic way. Sometimes phreatic eruptions occur without a precursory signal, sometimes after (prolonged) lake heating, sometimes during periods of lake water cooling, and sometimes after a peak in the Mg/Cl ratio in the lake water, among other scenarios. Often, such studies examine only one crater lake at a time, and thus may focus on the peculiar behavior of the studied lake, which is the intrinsically correct way to do.

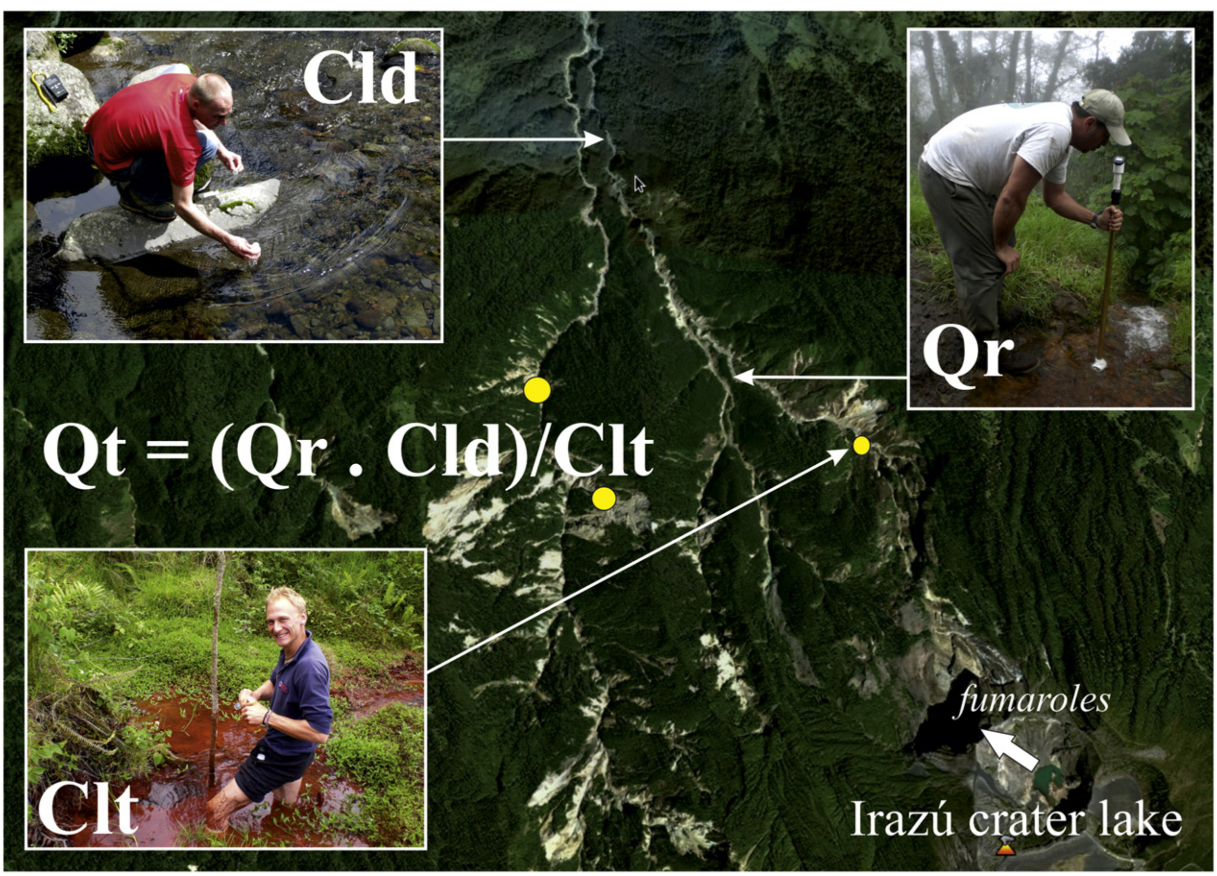

Fig. 11. Hypothetical application of the Cl-inventory method of Ingebritsen et al. (2001) for Irazú volcano, Costa Rica. The pictures and locations of the springs do not coincide with the real situation. Yellow dots indicate thermal springs. The upper right picture in the inset shows the measuring of the river discharge with a flow meter; the upper left picture shows river water sampling downstream; the lower left picture shows thermal spring water sampling. Up is North in the GoogleEarth map. Repeating this procedure for all rivers and thermal springs discharging at Irazú will result in a total Cl-budget of the volcano. Knowing the TDS/Cl ratios in thermal spring waters and Q_t enables to calculate the chemical removal rate from thermal springs.

Pattern recognition is an objective statistical technique that has been previously used to approach geophysical problems (Sandri et al., 2004, 2005; Mendoza-Rosas and De la Cruz-Reyna, 2008) searching for common and general patterns in precursory activity within a set of "objects" (e.g., time intervals preceding earthquakes or eruptions), neglecting the physical peculiarity of single objects on purpose. For the most studied and frequently erupting crater lakes (e.g., Ruapehu, Poás, Yugama, Copahue, Aso), pattern recognition of large data sets (VOLADA, Section 6) appears to be a promising tool to objectively identify possible common schemes in the various potential precursors, on the long and short term. For the above mentioned lakes the available data cover several decade-long time series, including various eruptive phases which could be of help to discover eventual precursory signals, helpful in future monitoring of those and other lake-hosting volcanoes. This research branch is still completely virgin, but could surprisingly give new insights, even without the additional collection of information (literature-based).

5.6.2. Event trees

As discussed earlier, the presence of a volcanic lake increases the probability of certain types of volcanic hazard with respect to volcanoes without a lake. Again, this topic has only been approached in a purely deterministic way. Newhall and Hoblitt (2002) introduced the application of event trees in probabilistic eruption forecasting, which has been followed in more recent approaches, such as the Bayesian Belief Network (BBN; Aspinall et al., 2003), the Bayesian Event Tree (BET; Marzocchi et al., 2004, 2008; Sandri et al., 2009, 2012; Selva et al., 2010, 2012), and HASSET (Sobradelo et al., 2013). An important paradigm is that, for volcanic lakes, hazard does not necessarily has to be induced by an increase in magmatic activity, as often is the case for purely magmatic systems and erupting volcanoes. Thus far, the statistical codes based on the event trees do hardly include such "non-magmatic unrest scenarios", most of the active lakes pass through. Nevertheless, for instance, BET represents a flexible tool to provide probability distributions of any specific event, linked to volcanic unrest, which we are interested in (magmatic or non, eruptive or non), by merging all the relevant available information such as theoretical models, a priori beliefs, monitoring measures, and any kind of past data (Marzocchi and Bebbington, 2012). In a future version, BET will be adapted to consider such "non-magmatic lake scenarios", given an appropriate selection of "monitoring parameters" at each node of the event tree (Rouwet et al., in prep.).

Deterministic knowledge, discussed above, should now be properly translated into adequate monitoring parameters with specific thresholds to be introduced within the event tree structure, in order to provide, for each specific lake, Probability Density Functions (PDFs) for specific hazardous events. The numerical outcome will provide (1) a guideline for future deterministic research, in search of the "missing link", (2) a less subjective, less "emotion or philosophy based" frame for volcanologists deciding to descend active craters or not, increasing the operator's safety, (3) a structured, science-based bridge between volcanologists, the population and decision-maker (e.g., civil protection officers), during periods of unrest, (4) a tool to organize and protect future land-use, tourism and urbanization near a lake-hosting volcano, and, last but not least, (5) a tool to quantify probabilities of possible occurrences of lake-related hazards, useful in volcanic surveillance. Let's not forget though that any statistical approach cannot stand on its own: without the high quality and extensive series of input data, originating from deterministic research, the epistemic uncertainty of the calculated probabilities will be high (Marzocchi and Bebbington, 2012).

5.7. Concluding remarks: choosing safety

Until present, crater lake monitoring has been mainly based on direct measurements and sampling of crater lake waters. This implies the physical presence of the volcanologist near the lake shore, or even *on* the lake with a raft. For highly active or erupting crater lakes – the ones most in need of an efficient monitoring – it implies an increased risk (high vulnerability), especially when the monitoring time window becomes shorter (higher frequency monitoring) to eventually detect the key short-term precursor. The proposed monitoring setups aim to increase monitoring frequency by eventual automatic transmission data from remotely sensed instruments (short- as well as long-term monitoring), decrease exposure time of volcanologists, and thus increase safety. Confronting the outcomes of these methods with "more classical" field-based methods (e.g., water chemistry) will correlate earlier, useful interpretations with the safer monitoring approach. The above mentioned future monitoring methods will not compromise the quality and, even less, quantity of information.

6. VOLADA: the first collaborative data base for volcanic lakes

There are more volcanic lakes on Earth than previously thought. We here introduce a data base – the first in its kind – compiling the available information on 474 volcanic lakes worldwide. It aims to become a complete and interactive tool, in which researchers can add, extract and use data in a dynamic matter. The data base will be available online for members of the VHub "iavceicvl" group, and is controlled and protected by the authors (DR and VC): https://vhub.org/resources/2822.

The lakes are alphabetically ordered by continent-country, by coordinates, and by the volcano it belongs to. The coordinates are linked to GoogleEarth to easily locate each of the lakes on a map, and pictures will be added where available. So far, 86 lakes were recognized in Europe (30 in the Azores), 97 in Africa (29 in Cameroon), 51 in North America (21 in Mexico), 58 in Central America (27 in Costa Rica), 28 in South America (18 Chile-Argentina), 111 in Asia (33 in Indonesia), and 43 in Oceania (27 in New Zealand). In a first step, the lakes are classified following the classification systems by Pasternack and Varekamp (1997) and Varekamp et al. (2000) (Section 2), for their physical (10 sub-classes, from erupting to no-activity lakes) and chemical (rock-dominated or gas-dominated) characteristics, respectively.

The "level of study" is number-coded and ranges from "constantly/continuously monitored-well studied-studied-poorly studied-not studied". The number of "poorly studied" and "not studied" lakes is still very high; future research strategies should also focus on tackling these lakes. The data of the last eruptions of the lake or related volcano is indicated. Lake basin characteristic parameters are provided (depth, surface area, volume), together with basic physical–chemical parameters of lake waters (pH, T, Conductivity).

Where available, we aim to add temporal variations of the chemical and eventually isotopic composition of lake waters, based on literature or unpublished data (with permission of the contributor). This last task requires major effort and time, for which we invite all group members to insert data of "their preferred volcanic lake". Outcomes of mass and/or energy budget analyses of lakes can be considered as well. Suggested literature can be added for each lake. The data base will be updated, when scientific literature and research evolves. VOLADA will not only be of great help in deterministic approaches and volcano monitoring, but the large amount of data will also permit statistical or probabilistic research approaches.

7. Conclusions

This review paper on the state-of-the-art of volcanic lake research can become a guideline for future monitoring strategies. A main concept introduced here, the relationship between the lake water residence time and the monitoring time window, implies that the lake's sensitivity in revealing indicators of variations in magmatic input strongly depends on the duration lake water remains in the lake basin. The longer the residence time (~the larger the lake volume and/or the lower the water input rate), the less sensible the lake will be, and the longer the monitoring time window should be. For those lakes, long-term monitoring can only be ambitioned (monthly trends). On the other hand, small and dynamic lakes (high input rates) are more sensitive, and short-term monitoring is feasible (weekly to daily trends). The decade-long fluid geochemical monitoring efforts of active volcanic lakes have been insightful to better understand fluid dynamics in the surrounding magmatic–hydrothermal environment, but, due to the "time scale problem", it has unfortunately not led to unambiguous precursory signals for lake-related hazards.

A major direct hazard related to volcanic lakes are phreatic eruptions, which eventually evolve into phreatomagmatic activity. Such eruptions are often localized and do not necessarily need the lake as a whole to show a precursory signal; sudden variations in magmatic fluid input rate (gas, vapor or liquid water) from well localized vents can precursor phreatic eruptions by minutes. Visual and thermal imagery is a promising monitoring tool to detail such dynamic venting. Indirect hazards related to volcanic lakes (e.g., lahars after water expulsion, prolonged lake seepage and resulting rock mass removal from the volcanic edifice leading to eventual occurrence of rain-triggered lahars, acid dispersion in the air and hydrologic network) can be monitored by localizing "weak sectors" of the volcano on the long-term scale.

A major challenge in future monitoring is increasing safety for lake-volcanologists, used to sample at lake shores, and surrounding people (tourists, farmers). Besides instrumental implementations, and real-time monitoring by remotely sensed methods, critically revised in this study (e.g., FLIR, Multi-gas measurements, echosounding, hydroacoustic monitoring, CO_2 flux measurements), a re-interpretation of existing data sets by means of statistical approaches, such as pattern recognition or event tree-based quests after the right precursor, can surprisingly reveal earlier unobserved trends in certain monitored parameters prior to variations in volcanic activity. Long time records exist for the most monitored and frequently erupting lakes (Ruapehu, Yugama, Poás), which can become particularly useful to better understand pre-eruptive behavior of such peak activity lakes. We would like to invite the scientific community to (1) collaborate in the implementation of the VOLADA data base on volcanic lakes, introduced here, and (2) focus future research efforts to the many poorly studied lakes worldwide.

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