IAVCEI Commission of Volcanic Lakes

8th Workshop on Volcanic Lakes

25th to 31st July 2013, Aso volcano and Hokkaido Island, JAPAN

平成**25**年度東京大学地震研究所共同利用（研究集会：**2013-W-06**）
「火山熱水系構成要素としての火口湖の特徴と挙動：***Properties and behavior of volcanic lake as a constituent in the magma-hydrothermal system***」講演要旨集
研究代表者：大場武

ABSTRACT BOOK

IAVCEI

TOKAI UNIVERSITY

EARTHQUAKE RESEARCH INSTITUTE UNIVERSITY OF TOKYO

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Preface

The former workshop (7th) was successfully held at Costa Rica in 2010 hosted by researchers in University of Costa Rica and National University. I sincerely thank their kindness to all of the participants. The 7th workshop was initially planned by Dr Dmitri Rouwet as the leader of IAVCEI Commission of Volcanic Lakes. At the 7th workshop, the Japanese group proposed the 8th workshop at Aso Volcano of Japan in 2013. Fortunately, the proposal was accepted by the majority of participants.

For support to the 8th workshop, IAVCEI and Earthquake Research Institute University of Tokyo (ERI) has provided 3,000 Euro and JPY 582,000, respectively. I sincerely thank their consideration to the workshop. The above money was used for the grant to participants from overseas especially for young researchers and students. In order to write the application form submitted to ERI, Prof. M. Ichihara of ERI guided me as the coordinator. I sincerely thank her contribution.

40 abstracts have been submitted and an attendance of up to 50 people is expected. This participant number reflects a consistency in the activity of CVL members during the last couple of years (since CVL7-2010). CVL8 will obviously be the key event of our community.

The crater lake on the top of Aso Volcano is the main target of this workshop. Aso Volcano is composed of many volcanic cones surrounded by a huge caldera rim. The Nakadake peak is one of the cones, hosting a deep pit crater in which high temperature and hyper acidic lake water has been sustained. I wish we exchange the knowledge on volcanic lake inspired by the appearance and the smell of energetic hot lake. Volcanic lakes could be a unique resource for tourism as same as Aso Volcano. However, some volcanic lakes could be hazardous to the resident near the lake. One important goal of our study on volcanic lake is the mitigation of hazard generated by volcanic lake. I hope this workshop could be a great step attaining the goal.

Prof. Takeshi OHBA
Host of the 8th Workshop on Volcanic Lakes

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Theme 1: Hazard mitigation involving crater lakes

New findings at Lake Monoun in 2013 by the cooperative research project between Japan and Cameroon under "SATREPS†" program

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The explosive discharge of CO_2 gas (limnic eruption) in the middle of 1980s at Lakes Nyos and Monoun in Cameroon killed about 1800 people. The driving force of the limnic eruptions was the sudden exsolution of CO_2 gas dissolved in the lake water. To understand the mechanism during the limnic eruption, and to mitigate the impact of similar phenomena in the future, the project entitled "Magmatic fluid supply into Lakes Nyos and Monoun, and mitigation of natural disasters through capacity building" was launched in 2011 with the cooperation between Japanese and Cameroonian researchers within the framework of SATREPS, financially supported by Japan International Cooperation Agency (JICA), Japan Science and Technology agency (JST) and Institute for Geological and Mining Research, Cameroon (IRGM). The duration of the project is 5 years, and it will end in March 2016. The project consists of two major components, which are the collaborative research component and a capacity building component. The project carries the following studies; (1) annual sampling and analysis of lake waters, (2) rock-water interaction beneath lake floor, (3) computer simulation of limnic eruption, (4) hydrology around the lakes Nyos and Monoun but also in other part of the Cameroonian Volcanic Line (CVL), (5) eruptive history of volcanoes that host the lakes (e.g. Nyos and Barombi Mbo), (6) geochemical survey of the lakes along CVL, (7) petrology of volcanic rocks around the lakes, (8) microbiological study of water in the lakes, and (9) removal of the bottom water in Lake Monoun. The capacity building component is already training 6 Cameroonian in various Japanese universities for PhD. The results of their researches would contribute to the progress of the project and the mitigation of hazards involving the lakes. Moreover, 5 Cameroonian laboratory workers undertook short term training at cutting edge laboratories in Japan.
The accumulation of CO_2 in the bottom water of lakes resulted from continuous discharge of CO_2-rich fluid. Previous studies have shown that the CO_2 originates from mantle based on $^3He/^4He$ ratios. In that case, there might be magma degassing beneath the lakes although the depth and size of the magma chamber remains unknown. In 2001 and 2003, a degassing pipe was installed at Lakes Nyos and Monoun, respectively. In 2006, two additional pipes were installed at Lake Monoun. The three pipes have dramatically accelerated the gas removal. Most of the CO_2 was removed at Lake Monoun by 2001. Two additional pipes were installed in Lake Nyos, in 2011, also accelerating the removal of CO_2. The installation of pipes has greatly reduced the risk of recurrence of limnic eruption. However, the supply of CO_2 rich fluid is expected to continue over a long time, because the life of magma is generally longer than 10^4 years. In this context, monitoring of lakes is prerequisite and imperative. In the project, the capacity building of IRGM, which

should be responsible for the monitoring, has been attempted through donation of analytical and field equipment.

In Lake Monoun, the removal of CO_2 rich bottom water has stopped since 2011 because the concentration of CO_2 in the bottom water has decreased. The 2011, 2012 and 2013 surveys suggest the CO_2 concentration in the bottom water at the east basin started to increase (Fig.1). This observation suggests the necessity of another method to remove the bottom CO_2-rich water. We are planning an installation of a system to pump the bottom water driven by solar panels.

Lake Monoun is made up of three basins (Fig. 1): the main basin at the east measures 100 m, the central with about 50 m depth and the west basin with 40 m depth. In March 2012, sounds velocity depth profiles were taken in the central and west basins of Lake Monoun. The sound velocity distribution is related to the CO_2 distribution. The profiles revealed significant positive anomalies in the central and west basins. These findings have never been observed yet. In March 2013, the temperature and conductivity profiles were acquired at the central basin. The lake water was also sampled at various depths. In the water significant enrichment was detected in the following components, CO_2, Cl^-, Br^-, Na^+, K^+, Mg^{2+}, Ca^{2+}, Mn^{2+}, Fe^{2+} and SiO_2. The CO_2 concentration was high in the range between -30 to -40m and low at the bottom (-50m) of the central basin (Fig. 1). It is interesting to note that the concentration of CO_2 was decoupled with that of the other chemical species. An explanation of this decoupling may be possible by assuming the existence of CO_2 bubbles supplied at the bottom, where water is saturated with respect to CO_2 gas. The bubbles separated from the recharge fluid ascend through water, and then dissolve in lake water generating the concentration peak at the mid depth of the central basin.

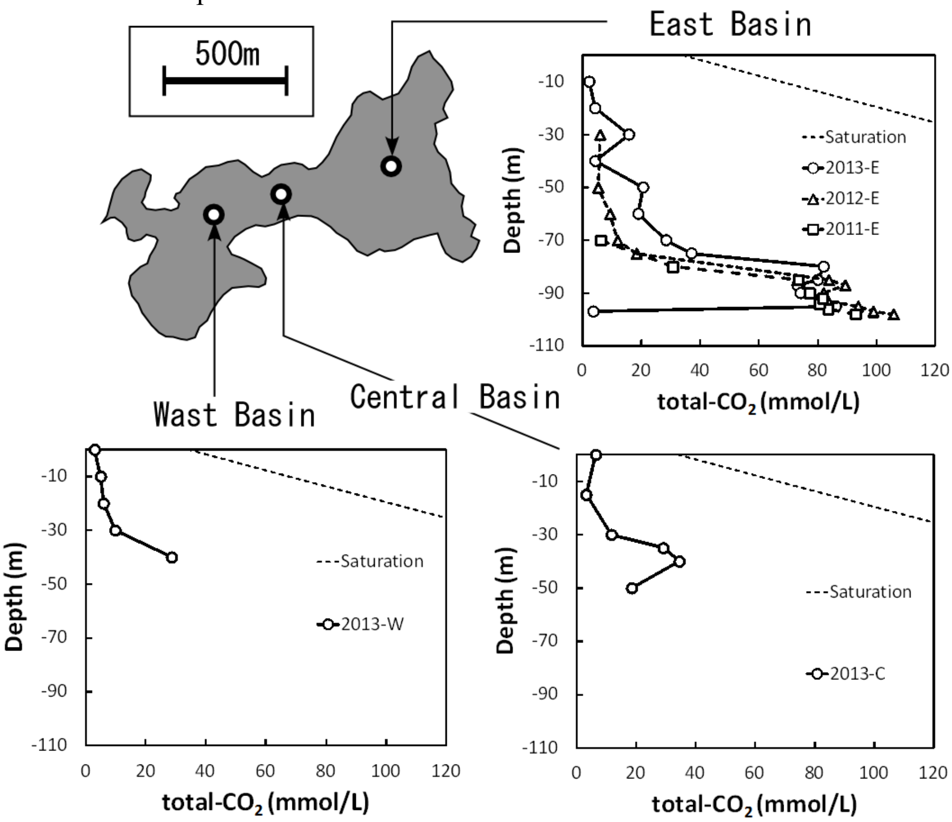

Fig. 1. CO_2 concentration profiles at three basins in Lake Monoun

Diffuse CO_2 emission from certain crater lakes located on the Cameroon Volcanic Line (CVL): A contribution to global carbon cycle budget and CO_2-related hazard assessment in Cameroon

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Tectonically controlled CO_2 degassing structures regrouped under the appellation of diffuse degassing structures (DDS) is considered as one of the sources of atmospheric CO_2. Among the DDS are crater lakes which release CO_2 to the atmosphere through massive exhalation (e.g. lakes Nyos and Monoun mid-80s deadly events) and/or in a passive way, at water/atmosphere interface. In recent years, monitoring of CO_2 generated by DDS has received growing attention both to quantify their contribution to the global carbon cycle and also to serve as proxies for volcanic activities surveillance. This work aims at (1) contributing to the global carbon cycle budget refinement and (2) attempts to generate baseline data to assess the risk related with hazardous CO_2 emission from crater lakes in Cameroon. It reports diffuse CO_2 from 10 crater lakes of the CVL. Using the accumulation chamber technique, diffuse CO_2 surveys at water/atmosphere interface were conducted at lakes Nyos and Monoun in January 2009 and at these and 8 other lakes in March-May 2012 and 2013. Our results reveal that 3 lakes are in equilibrium with atmospheric CO_2, 3 are *CO_2-phagic* (consume atmospheric CO_2) while remaining 5 are net CO_2 contributors to the atmosphere. We have, conservatively, estimated that about 105 tons.day^{-1} CO_2 is released to the atmosphere from the about 7.64 km^2 surveyed area. Extrapolating the precedent result to the about 38 crater lakes of the CVL, gives an amount of about 471 tons CO_2 emitted to the atmosphere per day. Comparison between net diffuse CO_2 degassing measured in 2009 and 2012 indicates that CO_2 flux at Lakes Nyos has dramatically increased (from about 16.7 tons.day^{-1} to about 112 tons.day^{-1}) concomitantly with the installation of additional degassing pipes while, it has meantime remarkably decreased (from about 19.1 tons.day^{-1} to about 2.3 tons.day^{-1}) at Lake Monoun where the piping process has ended. This observation suggests that siderite contained in bottom water that is released at the surface of lakes Nyos and Monoun by the degassing pipes is oxidized to amorphous hydroxide and/or hematite following: $FeCO_3 + \frac{1}{4}O_2 + \frac{3}{2}H_2O \rightarrow Fe(OH)_3 + CO_2$ and/or $2FeCO_3 + \frac{1}{2}O_2 \rightarrow Fe_2O_3 + 2CO_2$. It is thus believed that, the CO_2 produced via above reactions might be the source of the observed variation of the CO_2 flux at the lakes. Since that source is not a permanent one, it is suggested that account for the diffuse CO_2 from those two lakes in the global carbon cycle be made only after they have completely returned to their natural status following the disturbance brought about by the gas removal process.

CO_2 flux survey on Lake Rotomahana, New Zealand and preliminary results of CO_2 flux measurements recorded continuously using an innovative floating accumulation chamber technique

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In the period 2010-2011, a CO_2 flux campaign was performed on Lake Rotomahana, New Zealand, using the so-called floating accumulation chamber method. Lake Rotomahana was formed during the 1886 Mt. Tarawera eruption along a 17 km long fracture between Mt Tarawera and Waimangu. Pre-1886, there were two small lakes in the area occupied by present-day Lake Rotomahana. Violent phreatic and phreatomagmatic eruptions deepened and enlarged the two small lakes to form the Rotomahana Crater, now filled to a depth of ~125 m forming a lake five times larger. Today thermal activity occurs mainly along the western shore of the lake with intense bubbling areas occurring in the lake close to these geothermal manifestations. The mean CO_2 flux calculated by sequential Gaussian simulation from the lake was 57 ± 5.7 g/m2/d with total emission of 549 ± 72 t/d. The mapping of the CO_2 flux over the lake and the sub-lacustrine bottom vents detected during the survey highlighted the craters formed during the 1886 eruption. In 2010 the floating accumulation chamber system was modified to record CO_2 flux measurements continuously while moving in a boat. CO_2 concentration was recorded every second, as well as location, atmospheric pressure and temperature. A programme was running in a logger to convert the CO_2 concentration change with time, to a flux, continuously. This improved method has been tested with the floating accumulation chamber method by measuring CO_2 flux at a same site on the lake. The difference in CO_2 flux between the two systems was about 11 %. The advantages of this innovative technique are: (1) we can obtain a more detailed CO_2 flux map and so a more accurate CO_2 output estimation and (2) we can cover a greater area in a shorter time. Although more work needs to be done to validate the method, this preliminary study of this new prototype is promising for future continuous CO_2 flux monitoring on volcanic lakes.

Applications of infrared cameras at Costa Rican volcanoes, crater lakes and thermal features

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Since November 2010, Costa Rican volcanoes, crater lakes and thermal features like hot springs and mud pools, began constant IR imaging by 6 infrared cameras, 4 steady fixed FLIR A320, 1 portable FLIR P660 and 1 portable FLIR T640.

So far the A320's are located on different settings depending on the volcano or research purpose. At Turrialba volcano 2 of the cameras are set permanent at the crater rim, focused on the active crater, mainly on the new vents formed on January 2010 and 2012, from there at ≈300m and ≈500m respectably it is possible to monitor 24/7 the temperature of the gases from the new vents plus the direction and speed of the plumes, that data helps the improve of the use of equipment like Mini-DOAS, MultiGas or FTIR; at Poás volcano the camera is permanent fixed on a bunker structure located at ≈600m from the active hyperacid hot lagoon, from there it is possible to cover the complete crater with the use of a wide angle lens, that way is safely to track phreatic eruptions, observe convective cells from the lagoon, fumaroles activity, as well as temperature, direction and speed of the gas plume, right now we are trying to set up another one on the opposite site of the rim, to get the complete visual perspective of the volcano. Finally the last A320 is set for temporary set up, so far is being used on places like Arenal volcano because on the past they were changing of the pattern of the lava flows and gas plume, now we used at Rincón de la Vieja crater rim because so far is difficult to set up a permanent camera, and finally to do over flights on active volcanoes.

The FLIR P660 and the T640, are had been used to carry out periodic measurements of specific thermal spots, for example at Turrialba and Poás volcanoes, it is possible to get closer views, measuring more precise inaccessible high temperature fumaroles like the new vents at Turrialba (≈800°C) or the ones at Poás dome (≈500°C), places very risky to get gas samples, but that make the job easier with the use of a IR camera, also is being a lot of support to track lagoon convection cells (61°C), fumaroles migration, lagoon phreatic eruptions (130°C), and better characterization of hot springs, small hot lagoons, and mud pools, with temperatures of ≈ 100C that allow the life of extreme organisms to survive.

The use of the thermal cameras at active volcanoes is a valuable tool to detect changes from a secure distance, or to approach risky temperature areas, which can complement the physical and chemical analyses of lakes, fumaroles, gas plumes, etc.

Temporal change of volcanic fluid system beneath Aso volcano, Japan as inferred from seismological observations

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Seismograms recorded around active volcanoes exhibit a wide spectrum of signals from high frequency Volcano Tectonic (VT) to Long Period (LP). In contrast to higher frequency VT events which are attributed to brittle fracture processes, LP events are considered to be generated by the dynamics of magmatic- and hydrothermal-fluid movement. Understanding of the generation mechanisms of LP events is thus of importance for improving insight into the dynamics of fluid-flow and properties of volcanic fluid.
At Aso volcano, Japan, existence of various type of volcanic tremor has been recognized after the pioneering work by Sassa (1935). He installed Wiechert-type seismometers at Aso volcanological laboratory of Kyoto University, and observed volcanic signals during both active and calm periods of the volcano. Among the volcanic tremors observed Sassa, the most remarkable one is the volcanic micro-tremor of the second kind for its extraordinary long period (7.5 s) and its highly repetitive occurrence. After the first detection by Sassa, LP tremors have been continually observed even when the level of the volcanic activities is relatively low, and our observation using modern broadband seismometers revealed the presence of a crack-like conduit just beneath the chain of craters as a source of LP (15 s) tremor (Yamamoto et al., 1999). We also revealed that LP tremor and other short-period tremors are generated by the motion of gas-ash mixture in the conduit based on the numerical modeling of a fluid-filled crack (e.g., Kawakatsu and Yamamoto, 2007).
In this study, to see the temporal evolution of such fluid system, we examine long-term change in LP tremors by analyzing analog and digital seismograms. Since the occurrence of LP tremor is repetitive and the similarity between events is fairly high, we use stacked waveforms to calculate averaged spectra. The observed spectra of LP tremors show gradual temporal change over several years, and the trend of the temporal variation well correlates with a level of surface activity and observed SO_2 emission rate. Based on the fluid-filled crack model, eigen-frequencies of crack oscillation strongly depend on the properties of fluid; in case of a crack filled with gas-ash mixture, resonance periods become shorter as the temperature of the fluid increases and/or gas volume fraction increases. The observed temporal change of LP tremor period thus indicates thermal and compositional change of volcanic fluid in the shallow crack-like conduit.
These results indicate that fluid properties and the state of volcanic fluid systems beneath active volcanoes can be monitored by seismological observation of LP activities. Recently, presence of LP tremors and events has been reported at volcanoes in the world, and some of such LP activities are observed even in calm stage of activities. Monitoring of LP activity thus has a capability to provide quantitative information on shallow volcanic system, and helps our understanding of evolution of volcanic system and volcanic lakes.

Temporal change in CO_2 content of Lake Nyos in recent years

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In 1986, a limnic eruption, a sudden burst of a huge amount of magmatic CO_2 dissolved in Lake Nyos, killed 1,746 people and more than 7,000 cattle around the lake. Since supply of CO_2 was continuing, a degassing pipe was installed in Lake Nyos in 2001, and two additional pipes were installed in December 2010 and February 2011 to avoid the recurrence of the gas burst. The removal rate of gas was extremely accelerated by these pipes. In order to evaluate the effect of gas removal, we have regularly measured the CO_2 concentration in lake water since 2009 using an efficient method designed by Yoshida et al. (2010). The method allowed us to obtain a fine structure of CO_2 distribution and its temporal change in deep water of Lake Nyos as shown in Fig.1. Decrease of CO_2 concentration of water deeper than -150m is obvious, whereas CO_2 profiles of water shallower than -150m remained almost unchanged during the monitoring period (four years). This indicates that water above the intake depth (203~207 m) has simply subsided without any disturbance. We can estimate the decreasing amount of dissolved CO_2 from the change in CO_2 profiles. The total CO_2 amount in the water (-210 ~ -180 m) is calculated to be 2.97 Gmol (2009 Jan.), 2.74 Gmol (2011 Jan.), 2.26 Gmol (2011 Dec.), 2.11 Gmol (2012 Mar.) and 1.88 Gmol (2013 Mar.). The gas removal rate soon after installation of the two additional pipes was enhanced drastically, but it has gradually slowed down as shown in Fig. 2.
This was caused by weakening capability of degassing pipes due to lowered CO_2 concentration in bottom water. Degassing will inevitably cease in near future at Lake Nyos similar to the observation at Lake Monoun. It should be noted that the amount of CO_2 dissolved in Lake Monoun deep water is increasing after cessation of gas self-lifting as shown in Fig. 3. To avoid a re-accumulation of CO_2, we are planning to install a solar energy driven pumping system in Lake Monoun. It will be also necessary to apply this system to Lake Nyos after cessation of gas self-lifting of the degassing pipes in the near future.

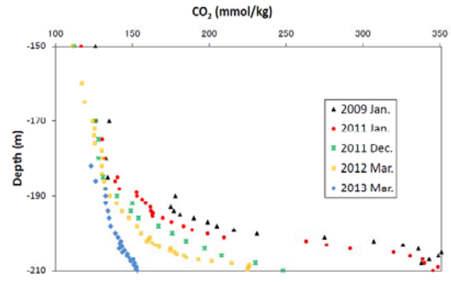

Fig. 1 Temporal change of CO_2 distribution in bottom water of Lake Nyos during 2009-2013

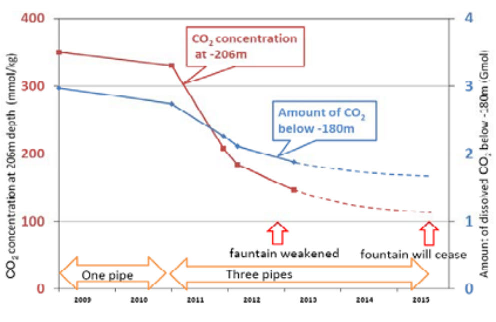

Fig. 2 Temporal change of CO_2 concentration at -206m and of amount of CO_2 below -180m at Lake Nyos during 2009-2013.

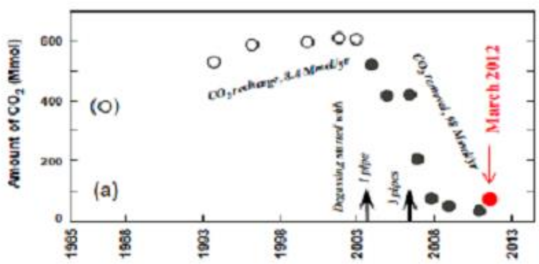

Fig. 3 Evolution of the total CO_2 amount dissolved in Lake Monoun since the limnic eruption in 1984. Note that the increase of CO_2 after cessation of degassing (March 2012).

VOLADA – the first collaborative data base on Volcanic Lakes

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There are more volcanic lakes on Earth than previously thought. The here presented data base is first in its kind and compiles the available information on ~340 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 "IAVCEI-CVL" group, and is controlled and protected by the authors. The lakes are alphabetically compiled by continent-country, and by coordinates-volcano the lake 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, 82 lakes were recognized in Europe (30 in the Azores), 52 in Africa (24 in Cameroon), 45 in North America (20 in Mexico), 57 in Central America (25 in Costa Rica), 21 in South America (13 Chile-Argentina), 58 in Asia (21 in Indonesia e.g.), and 29 in Oceania (18 in New Zealand). In a first step, the lakes will be classified following the classification systems by Pasternack and Varekamp (1997) and Varekamp et al. (2000), for their physical (10 subclasses, from erupting to no-activity lakes) and chemical (rock-dominated or gas-dominated) characteristics, respectively. The "level of study" is indicated 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 focus on tackling these lakes. The data of the last eruptions of the lake or related volcano is indicated. Lake basin characteristic parameters will be 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 in real-time, 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, a pretty novel topic in volcanic lake research.

Multi-disciplinary continuous monitoring of Kawah Ijen volcano, East Java, Indonesia

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Kawah Ijen volcano (East Java, Indonesia) has been equipped since June 2010 with 3 broadband seismometers, temporary and permanent short-period seismometers. While the volcano did not experience any magmatic eruption for more than a century, several types of unrests occurred during the last years. Apart from the seismometers, temperature and leveling divers have been immerged in the extremely acidic volcanic lake (pH ~ 0). While finding instruments capable of resisting in such extreme conditions has been particularly challenging, the coupling of lake monitoring techniques with seismic data improves the understanding and monitoring of the volcanic-hydrothermal system.
To detect small velocity changes, the approach developed by Brenguier et al. (2008) and Clarke et al. (2011) has been implemented to monitor Ijen volcano. We will present the results of this technique compared to other seismic parameters (e.g.: polarization and spectral attributes of the wavefield, seismo volcanic events spectral analysis) and temporal changes in lake temperature, color or lake levels. A special emphasis in the framework of CVL8 workshop will be given to new features of the volcanic lake discovered for the last three years (i.e.: gypsum precipitation inside the lake, shallow stratification of the lake waters,…), the reliability of estimating thermal flux in Ijen environment and finally comparisons with other volcanic lakes recently studied (e.g. Taal volcanic lake, Philippines). The benefits of monitoring Kawah Ijen magmatic/hydrothermal system using those techniques to identify precursors will finally be discussed.

Continuous monitoring of lake and meteorological parameters at Kelud volcano before the 2007 eruption.

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Meteorological and lake temperature data obtained by continuous measurements for nearly a year before the 2007 eruption of Kelud were used to check the validity of heat and mass balance models currently used to evaluate the thermal power released by volcanic lakes. About 10 different parameters have been continuously monitored on an hourly basis. Lake waters temperature and conductivity (at 18 meters depth), air humidity, atmospheric temperature and wind direction and velocity were recorded from a buoy floating in the middle of the volcanic lake. Lake water level, atmospheric pressure, rainfall were monitored from the lake's shore as well as overflow and temperature of the waters discharged through the drainage tunnel. A cross-comparison between several parameters is essential to validate the significance of the measurements. For example, lake level variations are nicely correlated with changes in the conductivity of the lake waters due to the dilution by rain falling in the lake (fig.1). On the other hand, data from the rain gauge (despite the use of a high resolution electronic weighing instrument) give unreliable information most probably because of changes in soil properties affecting the proportions of surface runoff versus infiltration. Numerous transient cooling events of the lake are observed. Most of these events are well correlated with period of elevated wind velocities promoting evaporation of the lake waters. The losses in thermal energy during these periods (up to a maximum of 42 MW) are well correlated with the thermal fluxes obtained from the theoretical model (fig. 2). Only very large rainfall (> 8,000 m3) has a measurable cooling effect.

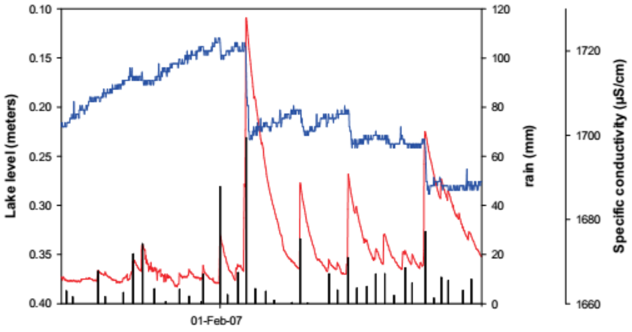

Fig. 1.

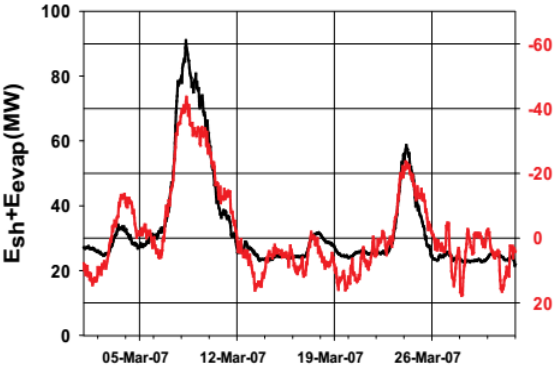

Fig.2.

Science & Arts workshops to increase volcanic risk awareness: Chapultenango, near El Chichón volcano (Chiapas, Mexico)

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This independent and informal study is based on good-will, common sense, working ethics and morality, rather than on a pre-meditated education method or strategy, with the goal to increase the public awareness of volcanic risk in the Zoque indigenous community of Chapultenango, near El Chichón volcano (Chiapas, Mexico). Notwithstanding, the outcomes of this grass roots level approach are afterwards contextualized by methods in social volcanology. With the aim to increase the risk perception in the community, communication means were adapted to each target-group (official authorities, primary and secondary school students, religious leader, and the main population). The effect of the sensitization campaign is evaluated retrospectively, based on existing literature.

Volcanic risk perception drastically decreases after eruptions and during periods of volcanic quiescence. Despite the fact that the adults in Chapultenango lived the 1982 Plinian eruptions, their awareness of present volcanic risk is low. Especially children, adolescents and young adults (born after 1982) should be informed on the activity of El Chichón, as they are most likely to be affected by possible future eruptions. This grass roots level sensitization project uses a novel approach to poll the risk perception and to transmit knowledge on El Chichón volcano among 6- to 11-year old children by combining scientific information sessions with arts workshops. Similar scientific sessions, although without the arts workshops, resulted less efficient for the older age group (Secondary School students). Moreover, the local *Protección Civil* and *Gobierno Municipal* were invited to participate in a basic monitoring of the El Chichón crater lake. A lack in continuity in local political terms resulted the major barrier for an effective and self-sufficient following-up of the volcanic surveillance. The entire population of Chapultenango was involved during informal meetings and semi-scientific projections of "their volcano" on 28 March 2007 (exactly 25 years after), offering an alternative and more scientific view on El Chichón's activity, often referenced in a more mystical-religious frame. It is experienced that the volcanologist is recognized as a highly trusted professional, bridging the gap between the official authorities and society.

Ruapehu the instrument-swallower: A history of temperature and associated measurements in Ruapehu Crater Lake

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It's nearly 50 years since a group of lecturers and students from Victoria University of Wellington dragged a small boat 1000 metre upwards to the summit area of Ruapehu, to take temperature measurements in its crater lake. An early expensive lesson was that the acid lake water dissolved the stainless steel wire suspending a bathythermograph, after it had reached a depth of 297 metres. Also worrying was that when they returned for a final set of measurements, the boat had disappeared in an eruption. Early monitoring of the lake used data loggers recording "in situ" with a considerable likelihood that the most interesting records would never be retrieved. With considerable effort, an armoured cable was installed to a site near Ruapehu Crater Lake, but it did not survive the April 1975 eruption. Also plastic cable insulation had a very short life in the high UV alpine conditions. I became involved about this point, with the idea that comparatively low-frequency radio waves could bend around the mountain, and hence be used to transmit information from the lake. To avoid problems with ice and snow covering the aerial or breaking wires, a telemetry buoy was designed. The transmitted information was very limited, being merely the time between pulses, the interval depending on the lake temperature. About every 10 or 15 minutes, a radio signal modulated with an audio tone was sent, and a receiver with a tuned filter produced a spike on a chart recorder. Most of the eight buoys that were produced did not have a long life, usually either being exploded from the lake, or dragged under, when their anchoring weights sank into the quicksand-like mud under the lake. Some years later a joint project between DSIR Geology & Geophysics (New Zealand) and the Université de Savoie (France) on Ruapehu started to use the then-new Argos satellite system to transmit temperatures from a site by the lake. At this time the satellite radio link was somewhat marginal, and digging out the aerial from snow was necessary to keep the system operating in winter. Then in April 1995 a small phreatic eruption damaged the equipment, followed by a larger eruption on 29 June 1995 in which all the lake edge equipment disappeared, and the sensors and some cable were found near the lake outlet. We had not re-established any temperature recording equipment when the major eruption of September October 1995 commenced, that completely emptied the lake. A further eruption in June 1996 did likewise, and then as volcanic activity decreased, the lake started to refill. Because the natural dam at the outlet was now unstable, being about 7 metres of unconsolidated ash over the previous rock barrier, the main concern became the lake level. As part of the monitoring set up by the Department of Conservation to mitigate the effects of a dam-break, pressure sensors were installed in Crater Lake, telemetering by VHF links to a temporary relay station at Dome Shelter. The early models of these did not last long, but improved sensors were then developed. Another team in GNS Science set up other equipment, including a time-lapse camera, which eventually recorded the dam collapse in the morning of 18 March 2007. Not surprisingly, the collapse occurred during heavy rain, but it did in occur with enough light useful images from the camera. The generally successful operation of the dam-break warning system was a great relief to all concerned. Since 2009, we have again run a telemetering datalogger by Ruapehu Crater lake, recording the lake level and temperature. Improvements to the Argos system now give reliable signal transmission all year. This is now by far the longest data series of quasi-continuous temperature data for Ruapehu Crater Lake, but there is always the risk of Ruapehu swallowing the equipment again.

The Boiling Lake, Dominica, the Lesser Antilles: Factors to be considered

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The monitoring of volcano-hydrothermal surface features, such as crater lakes, is a valuable part of monitoring active volcanoes (*Rowe et al., 1992; Ohba et al., 1994*).
With 21 live volcanoes stretched over 11 volcanically active islands, the Eastern Caribbean remains one of the most volcanically active regions in the world. Whilst the majority of islands contain one active volcano, Dominica is home to 9 volcanic centres. With its complex river system and multiple geothermal systems spread across the island, Dominica yields an assortment of potential hazards, energy sources and sources of revenue. A better understanding of the dynamics controlling the island's geothermal systems and, by extension, those regionally, are therefore needed to assist with hazard mitigation and monitoring. This can also provide additional information in terms of the potential use of geothermal systems for energy production in the Caribbean. One approach is through the monitoring of the geothermal surface features.
A programme of geothermal monitoring was initiated in Dominica in November 2000 by the regional volcanic monitoring agency, the Seismic Research Centre (SRC), and in 2004 - 2005 Dominica's most renowned geothermal feature, the Boiling Lake, experienced sporadic interruptions in geothermal activity. The lake stopped boiling, repeatedly emptied and refilled, and then returned to its long term stable conditions. Descriptions of similar instabilities at the Boiling Lake have only occurred six times during 150 years of its recorded history. In response to the 2004-2005 event, the SRC in collaboration with the GFZ German Research Centre for Geosciences, Potsdam, Germany installed atmospheric and lake monitoring sensors at the lake. Meteorological information together with the temperature, pressure and level data recorded were collated.
The author gives an overview of conditions at the lake, presents data collection limitations, and suggests possible explanations for the Lake's long term stability and periods of instability. Relationships between heavy rains, lake temperature and lake level were observed, and the influence of seasonal effects and regional seismic events considered.

Theme 2. Geophysical study of crater lakes

Yellowstone Lake Seiche Waves Produce Surface Deformation Influenced by Upper Crustal Magma

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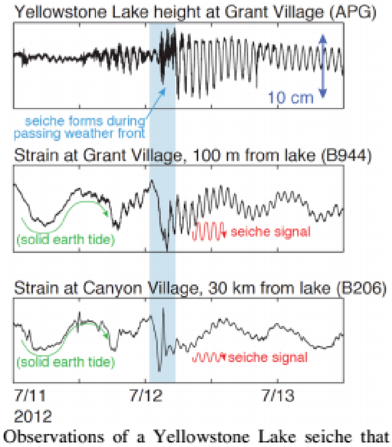
Following the installation of Plate Boundary Observatory (PBO) borehole strainmeters in Yellowstone, one of the more surprising signals observed has been the solid earth deformation resulting from seiche waves in Yellowstone Lake. These resonant standing water waves have amplitudes up to 10 cm and characteristic periods up to 78-minutes. Strainmeter B944, ~100 m from the lake, records strains from these seiches that are comparable in amplitude to the solid earth tide, up to 20 – 50 nanostrain (ns). More surprisingly, strainmeter B206, ~30 km from the lake, records strains about one order of magnitude less, up to 1 – 5 ns, which are observed at the same time (with little or no delay) as the strains at B944 and the seiche in Yellowstone Lake. Similar seiche signals have also been observed at two other ~30 km distant strainmeters (B205 and B207) and one other ~1 km distant station (B208). Models of deformation expected from a lake seiche via the mechanisms of pore pressure diffusion or loading of a homogeneous elastic crust predict strains at distant stations that are either subject to a significant delay (~days predicted) or whose amplitudes are significantly smaller than those observed (~0.01 – 0.1 ns predicted). Deformation predicted from a two layer model representing an upper elastic crust overlying a viscoelastic partially molten layer can successfully recreate the observed strainfield. These models indicate this more viscous material is present up to 3 – 6 km below the surface, with a Maxwell viscosity less than 1011Pa s (corresponding to ~35% melt), though these observations do not constrain the total volume of the material. These estimates of the location and material properties of partial melt in Yellowstone are consistent with those from other geophysical and geochemical observations. The particular sensitivity of the seiche strain observations to the shallowest crustal structure make it a valuable complimentary source of information relevant to potential future volcanic unrest. Monitoring of such strain signals continues at Yellowstone and other volcanic centers.



Observations of a Yellowstone Lake seiche that began on 12 July 2012, apparently initiated by a passing weather front. Seiche is directly observed by an Absolute Pressure Gauge (APG) in Yellowstone Lake (top), and resulting crustal deformation is observed on Borehole Strainmeters 100 m from lake (B944, middle) and 30 km from lake (B206, bottom).

Theme 3: Geochemical study of crater lakes

Specchio di Venere Lake alkaline lake (Sicily, Italy): geochemical investigations based on gas and water compositions.

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The word "volcanic lake" is instinctively linked to a hot and acidic water body although alkaline lakes being not too rare. The abundant geogenic CO_2 also contributes to weathering reactions within cold or thermal aquifers that release alkali and bicarbonate to groundwater. Such waters emerging at the surface, together with the right climatic and hydrologic conditions, can possibly lead to the formation of alkaline lakes (Pecoraino and D'Alessandro, in press).
Lago di Venere is a small (1.5 km^2) alkaline lake located in an endorheic basin on the northern side of Pantelleria Island (South Italy), a Pleistocene stratovolcano located in the NW-SE trending continental rift developed between North Africa and Sicily. With the aim to discriminate the different contributions (geothermal, meteoric, bubbling gases) to lake waters we have collected free and dissolved gases, major and trace elements in the lake and in the springs and shallow wells on its shores. Three main water components can be inferred from chemical data: a) meteoric water; b) sea water; c) local geothermal water. Mixing between meteoric and local geothermal waters is the most evident process. Lake water shows high Cl^- and alkali contents, high electrical conductivity (up to 40 mS/cm^2) and pH values up to 9.3. Depletion in Mg^{2+} and the high concentrations in alkali, mainly Na^+, are the result of notable interactions between waters and Na-rich peralkaline rhyolite (Pantellerite). This process is enhanced by large amounts of dissolved CO_2 of deep mantle origin. Due to the small volume of water, changes in hydrological and meteorological/rainfall inputs strongly control the composition of lake water which is strongly influenced by evaporation and precipitation of solid phases (mainly carbonates). Thermal spring and well waters have also $Cl\text{-}SO_4$ alkaline composition but are characterized by higher temperatures (24-65°C), acidic pH and lower EC values respect the lake. Most of sampled waters show a partial equilibrium with rocks at temperature estimated around 170 °C. Dissolved gases in thermal waters are influenced by hydrothermal/magmatic contribution, CO_2 being the predominant species. Finally the trace element content of the lake and the feeding springs is also strongly controlled by the same process that influences the overall chemical composition (mixing of different end-members, evaporation and precipitation of solid phases).

Geochemistry of Accesa sinkhole (Southern Tuscany, Central Italy): an analogue of a volcanic lake

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Lake Accesa (42°59'17"N, 10°53'44"E, 157 m a.s.l.) is located in southern Tuscany (Italy), 10 km west of the Tyrrhenian Sea, at the southern border of the "Colline Metallifere", an area characterized by presence of S-bearing mineralization associated with magmatic ore bodies. The lake is hosted within a funnel-shaped cavity originated by karst phenomena (sinkhole) and located at the intersection of two orthogonal fault systems oriented NNW-SSE and ENE-WSW, respectively. Lake has a subcircular shape (~400 m of diameter), with a maximum depth of 38.5 m, a surface area of 16 × 10^4 m^2 and an estimated volume of 2.5 × 10^6 m^3. The lacustrine basin is characterized by a general absence of a true littoral platform, except for the south-western zone where a carbonate bench develops between 0 and 5 m water depth, and by steep walls followed by a gentle slope that reaches the sub-horizontal bottom of the lake. Thermal sub-aquatic springs were recognized during scuba diving surveys, whereas the main effluent consists of the Bruna River. These morphological and hydrological features resemble those typically shown by lakes hosted in active and quiescent volcanic systems.
On the basis of water and dissolved gas samples collected during two surveys on May 2012 and March 2013, this study focus on investigating *i)* the chemical-physical processes controlling the chemistry of the lake, and *ii)* the possible occurrence of extra-atmospheric gases along the vertical water column. Lake Accesa has low content of dissolved gas (0.80-0.84 mmol/L), and can be classified as holomictic, although at the lake bottom a slight decrease of dissolved O_2, as well as dissolved CO_2 and CH_4 increases, were measured. The $\delta^{13}C$-CO_2 values (from -11.8 to -9.2 ‰ V-PDB) indicate a contribution of deep-originated inorganic CO_2. Lake water chemistry shows relatively high TDS values (3 g/L) and a Ca(Mg)-SO_4 composition with high contents of reduced sulphur compounds (ΣS^{2-} species up to 160 mg/L), B (up to 1.6 mg/L) and Sr (up to 7.2 mg/L). Temperature varies from 21°C at the surface (May 2012) to 8.5 °C at the bottom. A similar $\delta^{13}C$-CO_2 and $^{34}S/^{32}S$ isotopic signatures and water chemistry was found on the thermal spring of Aronna (23 °C), which is located a few hundred of meter north of Lake Accesa and related to the same N-S verging tectonic element of the sub-lacustrine springs. The chemical features of Lake Accesa are uncommon for non-volcanic lakes, since its main source consists of thermal water from the regional hydrological deep circuit, so far constituting a unique case of sedimentary lake that simulates the characteristics of a volcanic lake.

The acid crater lake of Taal Volcano, Philippines: evidence of gas–water interaction from isotopic, chemical and dissolved gas composition

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Taal volcano is one of the most active volcanoes in the Philippines and has produced some of its most powerful historical eruptions. Located on the southwestern part of Luzon Island in the Philippines Archipelago, the volcano consists of a 15-22-km prehistoric caldera, occupied by Lake Taal, the active vent complex of the volcano Island and the Crater Lake, 1.9 km in diameter. Six of 24 known eruptions at Taal since 1572 have caused many fatalities, and several million people live within a 20-km radius of Taal's caldera rim, making the volcano the largest threat to the Philippine population. Typical precursory signals of Taal eruptions are increase in frequency of quakes with occasional felt events accompanied by rumbling sounds, increase in temperature and level of Taal Crater Lake, development of new thermal areas and/or reactivation of old ones and ground swells or inflation. An alarming increase in seismicity, gas emission, deformation and temperature of the Taal Crater Lake, from March 2011 has been interpreted as the result of a new magma intrusion beneath Taal Crater Lake. These signs of growing instability prompted PHIVOLCS to place Alert Level 2 in April. Since 2008, ITER in collaboration with PHIVOLCS and with the support of the Minister of Science and Education of Spain and the Spanish Aid International Agency (ACECID), has been performing regular CO_2 efflux surveys at the surface of Taal Crater Lake as well as sampling of fumaroles discharges and waters from the Crater Lake.

Measurements have been performed following the accumulation chamber method to determine the scale of total CO_2 emissions at the Taal Crater Lake and to evaluate their temporal and spatial variations in relation with the volcanic-seismic activity at Taal. At the same sites of these measurements, water temperature, pH and conductivity have also been undertaken. Moreover, in March and June 2011, vertical profiles of temperature, pH and conductivity water together with sampling at every 10m were performed to analyze the isotopic, chemical and dissolved gas composition of the water. A bathymetry and an echosounder survey were used to investigate the morphology of the bottom of the lake and the activity of gas vents at the lake floor by measuring the backscattering intensity.

Preliminary results of vertical profiles show a vertical trend in pH even when the lake is well stirred by many CO_2 plumes and bubble trains. Both conductivity and pH suggest that the surface waters have higher dissolved contents, presumably more dissolved carbonate. Other magmatic gas components as SO_2 might dissolve during bubble rise and contribute to the observed low pH values. An oversaturation in the aqueous CO_2 (predominant dissolved gas specie at the observed pH~2.7) was observed at all the depths, ranging between 750 and 960 cc/L. Dissolved helium exceeded between 9 and 15 times those of ASW and its isotopic composition also showed a steady value of $^3He/^4He$ around 7.4 R/R_A along the vertical profile. No significant vertical gradients in He, $^3He/^4He$ and CO_2 were observed, suggesting an extensive interaction between rising magmatic volatiles and waters at Taal Crater Lake.

The increase of stress in the rocks surrounding the reservoir due the movement of magma and inflation of the volcano might explain the recorded seismicity at Taal. These geochemical and geophysical observations support unrest of the volcanic system indicating anomalous gas release from the magma at depth, as is also suggested by other geophysical/geodetical observations such as water temperature increase from 30.1°C to 31.8°C, water level recede at Taal Crater Lake from 0.36 m to 0.33 m, and a slightly inflation recorded at the Taal Volcano Island by a ground deformation survey (precise levelling; PHIVOLCS).

Geochemical evolution of the ultra-acid crater lake of Poás volcano, Costa Rica, 1978 until present

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Poás volcanic complex hosts an ultra-acid lake that is among the very few lakes of its kind worldwide with a long term monitoring record. A geochemical dataset of the lake covering four decades of activity, demonstrates that Poás is one of the most dynamic magmatic-hydrothermal systems known, as is reflected by drastic fluctuations in lake chemistry and eruptive activity. Two major processes control the chemistry of the lake: (1) Input and dissolution-hydrolysis of magmatic volatiles in a sub-surface reservoir forming extremely acidic brines, and (2) Partial or wholesale dissolution of rock, enriching the waters in rock-forming elements. This combined uptake of magmatic volatiles and water-rock interaction makes the Poás hydrothermal system among the chemically most extreme aqueous environments on Earth.

Based on long-term geochemical records, the evolution of the lake since the late 1970s has been divided into five alternating active and quiescent stages, which appear to have a periodicity on the order of 6-10 years. These successive stages of peak activity and quiescence are characterized by gas-phase (during peak activity stages) or liquid-phase (during quiescent periods) dominance in the hydrothermal domain between a cooling magma body and the crater area. In Stage II (Sept. 1980-April 1986) and Stage V (March 2005-Present), Poás volcano showed peak-activity status and gas-phase dominance when fumarolic discharges around the composite pyroclastic cone registered high volatile fluxes and near magmatic temperatures up to 1020°C in 1981 (Stage II) and up to 890°C in 2009 (Stage V)-. Eu anomalies [Eu/Eu*,where Eu* is defined as 2EuN/(SmN+GdN)] indicates that in 1987 (Stage II) and 2006 (Stage V) Eu/Eu* values were closest to those of Poás unaltered lavas pointing to a new interaction of fluids with relatively pristine rocks, either from freshly intruded magma or through the opening of new fissures and cracks (Martínez, 2008). Resurging input of heat and mass leading to high T fumarolic outgassing further suggests intrusion of two small batches of fresh magma into shallow levels in stages II and V. Enhanced energy output and volatile release could however also be triggered by hydro-fracturing of the brittle chilled margin around a cooling body, or by rupturing of an impermeable seal. Microgravity changes monitored at Poás volcano between 1985 and 2009 seem to support the magmatic intrusion hypothesis (Rymer and Brown, 1989; Rymer et al., 2000; 2009).

This work supports calls for long-term geochemical monitoring of crater lakes as part of studies on gas-water-rock interaction processes in magmatic-hydrothermal systems and volcano hazard assessment efforts.

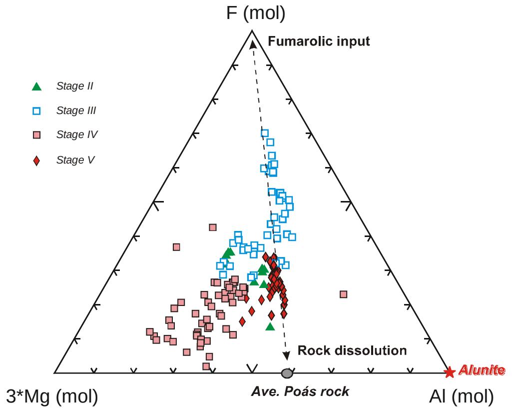

Figure 1. *Ternary diagram illustrating variations in the relative molar abundances of major volatiles and rock forming elements (F-Al-Mg) in the lake waters for the stages of activity distinguished and comparison to average composition of Poás lavas and alteration minerals. In stages III and V the solutes in the lake are largely derived from a combination of (near-)congruent rock dissolution (cations) and volatile input (anions).*

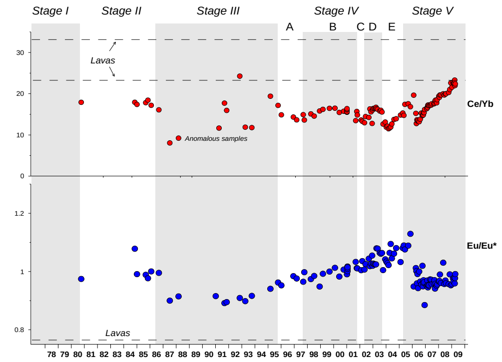

Figure 2. *Time series of Ce/Yb and Eu anomalies [Eu/Eu*, where Eu* is defined as $2Eu_N/(Sm_N+Gd_N)$] for Poás lake compared to reference lavas. Subscript N refers to chondrite-normalised values (Sun and McDonough, 1989). Sudden drops in the Eu ratios suggest a major reorganization of the gas-water-rock interaction regimen around the onset of phreatic activity in Stages III and V.*

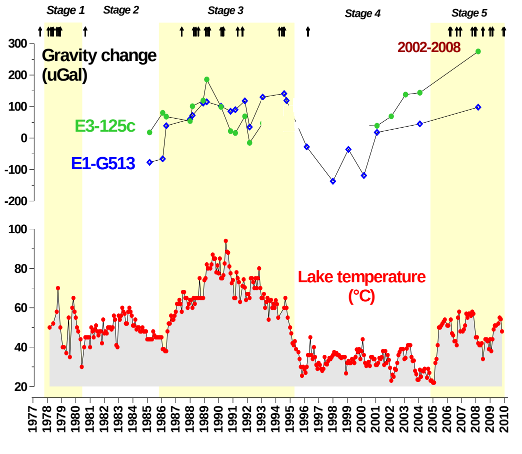

Figure 3. *Time series of temperature monitored at the acid lake of Poás and microgravity data at the bottom of the crater (Rymer et al., 2005, 2008; 2010). Arrows on top of the plot indicate phreatic eruptions.*

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Geochemical evidence of magma intrusion at Taal Volcano in 2010-2011 inferred from diffuse CO_2 emissions from the Main Crater Lake and fumarole chemistry

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Taal Main Crater Lake is a 1.2 km wide ~80m deep acidic lake (pH<3) within the Main Crater of Taal Volcano. Monitoring of CO_2 emissions from the Main Crater Lake and soils within the Main Crater started in 2008, through a collaborative project between ITER and PHIVOLCS. Results show changes in CO_2 emissions from the lake and soil as well as fumarole plume chemistry before and during a volcano-seismic unrest from 2010-2011. In August, 2010 the total diffuse CO_2 emission from the Taal Main Crater Lake increased almost three times from a previously measured baseline emission value ~1000 t d^{-1} to 2,716 ± 54 t d^{-1}. The highest CO_2 emission value in the crater lake was measured in March, 2011 at 4,670 ± 159 t d^{-1} two months before the highest earthquakes (high frequency volcanic quakes) count (115) recorded (PHIVOLCS Volcano Bulletin, 2011) in the unrest period. Average lake water temperatures during the unrest period ranged from 29 to 34ºC, and are similar to slightly lower than average ambient air temperature. At the same time ground temperatures within the fumarolic areas on the north shore of the lake remained below 100ºC. However, significant changes in the CO_2/SO_2, CO_2/H_2O and SO_2/H_2S ratios in the fumarole gases were observed. We present here variations in total CO_2 output from the Main Crater Lake and fumarolic areas from April 2008 to July 2012 and yearly measurements of fumarole chemistry. We interpret these changes as the result of magmatic activity.

Preliminary geochemical investigation of Tupungatito and Planchón-Peteroa (Argentina-Chile) hyperacidic crater lakes

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Central Chile volcanism (CCV; 33-36°S) is controlled by dehydration of Nazca plate and subsequent partial melting of the mantle wedge (Hildreth and Moorbath 1984). Among the thirteen volcanoes of the CCV, whose location is structurally controlled by Cenozoic east-verging margin-parallel folds and thrusts, six of them experienced historical eruptions (Tupungatito, San José, Maipo, Tinguiririca, Planchón-Peteroa, Quizapu). Tupungatito (33.4°S-69.8°W; 5600 m.a.s.l.) and Planchón-Peteroa (35.5°S-70.2°W; 4,107 m a.s.l.) are the most active volcanoes of central Chile since up to nineteen historical eruptions were recognized (González-Ferrán 1995). These volcanic systems are characterized by a permanent fumarolic activity and they host two crater lakes at their summits. This study presents and discusses the preliminary water geochemistry data collected at the lake surface from these hyperacidic crater lakes during three campaigns carried out in 2010-2012.

Tupungatito lake water has a temperature, pH and TDS ranging from 32.2 to 35.2 °C, 0.34 to 0.6 and 38.9 to 45.1 g/L respectively. SO_4 and Cl are the mains anions (up to 13.69 and 12.50 g/L respectively), however important concentrations of F are found (up to 0.31 g/L). Ca correspond to the main cation (up to 1.48 g/L), followed by Na, K and Mg (up to 0.8, 0.49 and 0.47 g/L respectively). On the other hand, Planchón-Peteroa lake waters has a pH, temperature and TDS ranging from 1.49 to 2.91, 7.4 to 43.2°C, and 4,58-7,50 g/L respectively. SO_4, Cl and Ca are also the mains ions (3.28, 0.66 and 1.47 g/L respectively) followed by Na, K and Mg (806, 492 and 470 mg/L respectively).

The SO_4- and Cl-dominated composition of Tupungatito and Planchón crater lakes are typical of volcanic lakes affected by strong inputs of magmatic gases such as those shown by the lake hosted in the summit crater of Copahue volcano (Varekamp et al. 2003), which is part of a volcanic complex at the border between Argentina and Chile, few hundreds of kilometers south of Planchón-Peteroa. These lakes, generally classified as hyperacidic brines, typically act as condensers and calorimeters for magmatic fluids and heat, thus they are able to record changes of the magmatic-hydrothermal activity of the hosting volcanic system (Varekamp et al. 2000). Information about hyperacidic lakes is a powerful tool for developing monitoring programs aimed to the geochemical surveillance in areas, such as those of the Andean volcanoes, where the access is limited during winter season due to adverse weather conditions (Agusto 2011; Velez 2012).

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Decoupling of CO_2 and He in deep water of Lake Nyos, Cameroon: implications for spontaneous gas exsolution and the sub-lacustrine CO_2-recharge system

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A model of spontaneous gas exsolution is proposed for the cause of the 1986 limnic eruption at Lake Nyos. This idea is based on the observed temporal variation of CO_2 profiles at Lake Monoun between 1986 and 2003 before artificial degassing started. During the period the deep CO_2-rich layer thickened while its CO_2 concentration remained constant, i.e., the CO_2 profile evolved steadily. A similar phenomenon was observed at Lake Nyos just before the degassing operation that started in 2001. The deep CO_2-rich layer thickened with the constant CO_2 concentration of about 350 mmol/kg. These observations imply that the recharge fluid coming from beneath the lake bottom and it pushed the deepest water upward, resulting in CO_2 saturation at the top of the CO_2-rich layer as schematically presented in Fig. 1. This mechanism, which does not require any external trigger, might have induced the 1984 and 1986 limnic eruptions.

At Lake Nyos, pre-degassing deep water at depths between 160 and 188 m had low $CO_2/^3He$ ratios of ~0.5 $\times 10^{10}$, whereas the deepest water at depths greater than 190 m was characterized by higher $CO_2/^3He$ ratios of ~1.7 $\times 10^{10}$ in 2001 (Fig. 2). This suggests that the behavior of CO_2 and He in the lake was decoupled. If the deepest water represents the recharge fluid that was added to the lake during 1986 and 2001 (pre-degassing period), it turns that the $CO_2/^3He$ ratio changed with time. Noble gas signatures indicate that the pre-degassing recharge fluid was characterized by high CO_2 and He concentrations and high $^3He/^4He$, $^{40}Ar/^{36}Ar$, $^{20}Ne/^{22}Ne$ and $^{21}Ne/^{22}Ne$ ratios. The noble gas isotopic ratios indicate significant contribution of gases from the CVL mantle. The recharge fluid mixed with groundwater carrying air isotopic signatures in a sub-lacustrine fluid reservoir. The later recharge fluid contained lower He concentration.

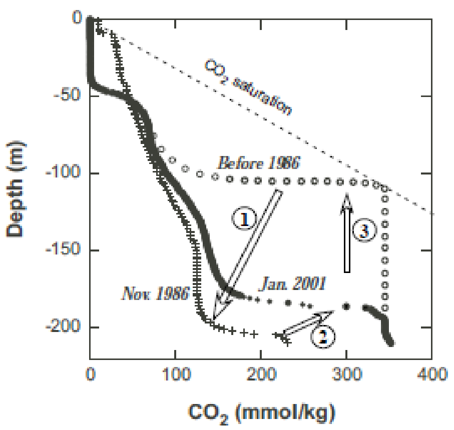

Fig.1. A model of spontaneous limnic eruption at Lake Nyos. An assumed pre-eruption CO_2 profile is shown by small open circles as "Before 1986". After the eruption the CO_2 profile turned to the post-eruption profile shown as "Nov. 1986" (process 1). It evolved to the January 2001 profile in 15 years (process 2). If natural recharge continues, the January 2001 profile may "recover" the pre-eruption situation (process 3).

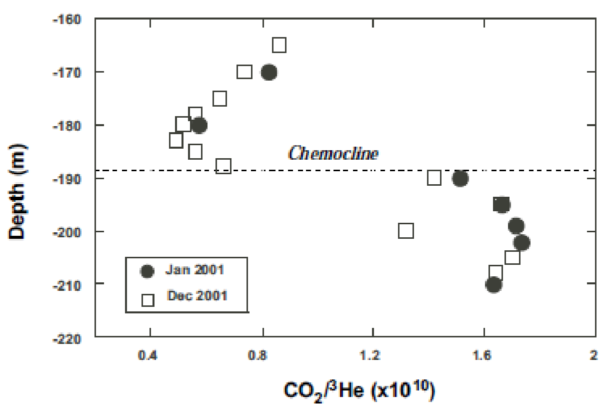

Fig.2. $CO_2/^3He$ ratios observed in the depth range of 160-210 m at Lake Nyos in January 2001 (solid circles) and December 2001 (open squares). There is a clear difference in the ratio above and below the deep chemocline, showing "decoupling" of CO_2 and ^3He.

Degassing activity of a volcanic crater lake: Volcanic plume measurements at the Yudamari crater lake, Aso volcano, Japan

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Compositions of the lake gases and the fumarolic gases are quantified by plume measurements with Multi-GAS and alkaline-filter techniques. Compositions of both gases show large temporal variations and have distinct features; the fumarolic gases have larger CO_2/SO_2 ratios and smaller SO_2/HCl and SO_2/H_2S ratios than those of the lake gases. The HCl/H_2O ratio of the lake gas is close to that of a vapor phase in vaporation equilibrium with the lake water, implying that the lake gas and the lake water are differentiated by vapor-liquid equilibrium at lake surface conditions. Solubility of lake gas species indicates negligible gas contents in the lake water under the equilibrium conditions. Although dissolved gas contents are quite low, reactions of the gas species in the lake also control the lake gas and the lake water compositions. The large SO_2/H_2S ratios of the lake gases are attributed to S_e formation at lake temperature. A disproportionation reaction of SO_2 is the source of sulphate and S_e in the lake and likely controls distribution of S species in the crater lake system.

Compositions of hydrothermal fluids supplied to the lake are estimated based on the compositions of the lake gases and the lake waters, and water discharge rates by lake gas evaporation and lake water seepage. The hydrothermal fluid compositions are also estimated considering formation of S_e, which contributes about 50% of the total S in the lake fluids. The estimated hydrothermal fluids compositions have H_2O/S and H_2O/Cl ratios similar to the fumarolic gases but have slightly smaller S/Cl ratios and significantly larger CO_2/S ratios. The composition contrast between the fumarolic gases and the hydrothermal fluids and their occurrences suggest that these fluids are derived from vapor and liquid phases formed under hydrothermal conditions. Direct contribution of magmatic gases to these fluids is also suggested based on the high-temperature features of the fumarolic gases and gas-rich compositions of the lake gases. The large temporal variation in the lake gas and the fumarolic gas compositions is likely the results of changes in the mixing ratios of the magmatic gases and conditions of the hydrothermal phase separation.

Factors controlling REE concentrations in waters of El Chichón crater lake

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REE were determined in waters of the El Chichón Crater Lake, in hot springs (40-100°C) and shallow waters that drain fresh pyroclastic deposits of the volcano (Table 1). The total REE concentrations in El Chichón waters vary from 0.1 to hundreds of ppb and depend mainly on pH. The secondary factors are ionic strength and degree of the host rock alteration. The crater lake of El Chichón is fed by rain waters, Cl-free steam-heated thermal springs and a group of boiling neutral Na-Ca-Cl springs (SP – Soap Pool springs) with a variable discharge rate. These springs are the main source of chloride in the lake water (Taran and Rouwet D, 2008). When the flow rate of SP springs is ceased, the Cl content in the lake water rapidly (in two-three months) decreases almost to zero. The total REE concentration in SP springs is not higher than 0.3 ppb and does not depend on the Cl concentration. However, the concentration of REE in the lake water apparently linearly depends on the Cl concentration reaching ~ 100 ppb at 3000 ppm of Cl (Fig.1). The lake water pH during the last two decades was in a narrow range of 2.2 – 2.5. We suggest that contribution of REE to waters occurs at shallow depths. The REE patterns of all El Chichón ground waters are similar to those of the erupted volcanic rocks. Interaction with altered rocks results in the slight depletion in the LREE. Europium anomalies are controlled by the redox potential (Eh) in a given spring vent.

	AC	AS1	AS2	L	SP	AR
t° C	71	51	78	34	100	26
pH	6,4	2,3	7,5	2.4	7,1	3,7
Major ions, mg/L						
Na	816	2124	4711	1233	1775	16
K	109	233	446	191	277	13
Ca	623	488	1173	545	591	277
Mg	51	19	2	98	93	16
Cl	2230	4162	10051	2795	4118	4
SO4	451	389	65	755	206	710
HCO3	191	0	142	0	60	0
REE μg/L						
La	0.075	6.32	0.019	20,9	0.059	198
Ce	0.152	15.5	0.023	44,1	0.053	324
Pr	0.012	2.0	0.009	5,1	0.009	16.3
Nd	0.034	7.0	0.015	13,9	0.028	59
Sm	0.009	1.8	0.016	4,0	0.019	11
Eu	0.003	0.41	0.022	1,69	0.018	2.95
Gd	0.010	0.53	0.022	4,1	0.015	11
Tb	0.0011	0.23	0.003	0,6	0.002	1.44
Dy	0.017	1.25	0.017	2,99	0.015	7.34
Ho	0.004	0.25	0.005	0, 6	0.005	1.5
Er	0.016	0.63	0.023	1.23	0.016	3.63
Tm	0.002	0.08	0.004	0.13	0.001	0.46
Yb	0.015	0.56	0.026	1.17	0.18	2.56
Lu	0.0012	0.09	0.004	0.13	0.001	0.36
ΣREE	0.351	38	0.208	101	0.260	639

Table 1. A set of representative REE analyses of El Chichón thermal waters.
AC – Agua Caliente springs, southern slope; AS1, AS2 – Agua Salada springs, western slope. L – crater lake; SP – Soap Pool spring in the volcano crater; AR – Agua Roja, cold springs draining the anhydrite-rich pyroclastic deposits

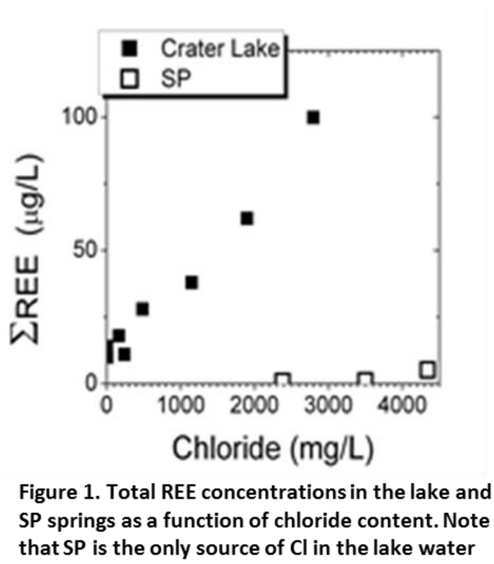

Figure 1. Total REE concentrations in the lake and SP springs as a function of chloride content. Note that SP is the only source of Cl in the lake water

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Regional extent of magmatic CO_2 in crater lakes of the Oku Volcanic Group: Constrains from petrogenesis and relation with tectonic events

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The Cenozoic volcanism of the Cameroon Volcanic Line (CVL) dominantly produced alkaline basaltic magma. This magma differentiates by fractional crystallization to transitional and more evolved felsic lavas with a minor role of crustal contamination. The Nyos maar located in the Oku Volcanic Group (OKVG) is the only maar along the CVL with the existence of both tholeiitic and alkaline basalts. After the sudden release of about 0.6 km^3 of CO_2 gas in 1986 killing about 1,750 people and over 3,000 cattle, most studies have focused on the origin and accumulation of CO_2 gas in lakes along the CVL. These studies have concluded that CVL crater lakes are rich in magmatic CO_2 gas. This raises the main question as to why the Nyos maar is relatively richer in CO_2 gas than other crater lakes. In addition, the regional extent of this enrichment within the OKVG has not been investigated. Nevertheless, limited data in geochemistry and volcanology exist in this area. This study seeks to address these issues by comparing geochemical characteristics of both alkaline and tholeiitic basalts from Lake Nyos and neighbouring crater lakes (Lakes Wum, Elum and Oku) in the OKVG. The relationship between petrogenetic and tectonic processes could provide valuable information on the high CO_2 beneath Lake Nyos. This can enhance the understanding and mitigation of potential hazards along the CVL.

Twenty mafic rock samples from the Nyos maar and neighbouring crater lakes were analyzed using XRF, ICPMS and TIMS. Preliminary results classify these samples as basanite, basalt and tholeiitic basalts with SiO_2 less than 55 wt.%, MgO > 4 wt.% and $K_2O/Na_2O < 1$. All samples show a marked LREE enrichment and a strong fractionation between LREE and HREE. Similarities in trace elements abundances in alkaline basalts suggested similar mantle source and petrogenetic processes beneath the 4 lakes. However, the tholeiitic basalts found only around Lake Nyos have lower trace element abundances, Ce/Pb and La/Yb ratios when compared to alkaline basalts. This indicated melting at different depths, which in turn relates to tectonic activity. Tholeiitic basalts were probably formed during the initial rifting of the CVL, resulting to partial melting at shallow depth while alkaline basalts were later generated at greater depth. The occurrence of fragments of tholeiitic basalts in Nyos surge deposits is consistent with the fact that it existed prior to the phreatomagmatic explosion. The occurrence of fragments of tholeiitic basalts in Nyos surge deposits is consistent with the fact that it was formed prior to the phreatomagmatic explosion that deposited the surge. During this event, the Nyos "hard substrate" (diatreme) would have been highly fractured. Then considering the OKVG as a system, a probable inter-connectivity between the Nyos diatreme and neighbouring lakes via fractures could favour the migration, accumulation and subsequent leakage of CO_2 from the system below Lake Nyos.

Theme 4: Volcanology of crater lakes

The history of Laguna Caliente, Poás volcano, Costa Rica: 185 years of observations at an acidic crater lake

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Poás volcano is a complex stratovolcano with an altitude of 2,708 m asl, located in the Cordillera Volcánica Central of Costa Rica. Its summit hosts an acidic lake (Laguna Caliente) which has been the object of numerous descriptions and measurements during the past 185 years. The most important three historical eruptions occurred on 7 February 1834, between January and May 1910 and during the period 1953-1955. We here present an overview of 185 years of describing Poás' acivity and its reflections on its crater lake.

The acidic nature of the lake was described for the first time in 1828 by notes of Miguel Alfaro: vapor columns launched rocks into the air, blue flames originating from sulfur deposits, conical pure sulfur masses of 1.5 m high, and an extremely acidic, hot and active lake generating rumbles.

In 1859, von Frantzius managed to descend to the lake after three years of failed intents, being able to measure the temperature of Laguna Caliente water for the first time (39.1°C). Moreover, he noticed how his clothing changed color due to the gases coming off the lake. Pittier (1889), described black jets and columns coming out of and falling back into the lake, generating rumbles. Lake water temperature was 64.4°C.

Leiva (1904), reported a lake water temperature of 42 ºC, besides phreatic eruptions. Rudín (1905) also described the occurrence of multiple phreatic eruptions from the lake. He estimated a diameter of Laguna Caliente of 500 m. Leiva ascended again in 1906 and observed that the Laguna Caliente lake level descended. He reported constant phreatic eruptions; moreover, prior to his visit to the volcano, some people living near Poás reported sulfur combustion. Afterwards, Sapper (1913) described his climb to Poás volcano on 6 March 1899: a steaming, white, small and dynamic lake, throwing columns of mud to altitudes of 5 to 7 m above the lake surface, and a lake water temperature of 52°C.

The 1910 euption expulsed material with an estimated volume of 1.6 x 10^7 m^3 (Mora-Amador, 2010). Deposits are composed of hydrothermalized fragments, with sporadic juvenile fragments (vesicular lapilli). The eruption was classified as vulcanian, and the deposits evidence pyroclastic fall out and surges, close to the crater area. The VEI was estimated to be 2.

Between 1934 and 1950, Hantke (1951 and 1953) reported low fumarolic activity in the main crater. He reports a relatively low lake level for Laguna Caliente on 4 February 1947.

The 1953-1955 eruption led to significant changes in the form of the lake, due to the extrusion of a 40 m-high dome in and a related lava flow the center of the crater, in the southern end of Laguna Caliente. To the east of the current Laguna Caliente, relicts of a lava pool with a maximum thickness of 8.5 m are observed. During this entire eruptive period, the acidic lake disappeared. The eruption was classified as mixed-type: Strombolian, phreatomagmatic, vulcanian with related dome extrusion. A total volume of 2.1 x 10^7 m^3) of ejecta and a VEI 3 were estimated.

Dóndoli (1965) mentioned that during 1956 the volcano continued its fumarolic activity, with ejection of ash. During periods of intense rainfall, the lake re-appeared for short periods, alternating with periods of strong evaporation leading to lake disappearance and vigorous mud expulsion. This feature was repeated several times during the period 1956-1965. We deduce that for an entire decade, Laguna Caliente formed and disappeared dynamically, a behavior related to periods of intense rainfall and variations in volcanic activity.

During the 1970s Laguna Caliente reached high levels, despite the phreatic eruptions described by Bennett and Raccichini (1978). Lake water temperature was 50 °C. Afterwards, the lake dried again in April 1989, revealing "sulfur volcanism" described in detail by Oppenheimer (1992): sulfur pools, flows and small volcanoes. Once again, Laguna Caliente reformed -yet "classically"- accompanied by small phreatic eruptions. The last time the lake dried out completely was in April 1994.

The lake recovered once more, and reached its maximum lake level in January-February 2005, after a decade of relative quiescence, lower lake water temperatures and thus minor evaporation. During this occasion, the lake overflowed its main basin and flooded many of the fumarolic fields, reaching its estimated maximum depth of more than 50 m.

Since March 2005, the lake has started to return to its stable basin, noted by a decrease in the lake diameter, and accompanied by an increase in fumarolic activity and dispersion in the inner east wall of the main crater. This culminated into a spectacular sulfur flow from the "Naranja" fumarole of more than 80 m, flowing towards and almost reaching Laguna Caliente.

In March 2006, the volcano resumed its phreatic activity; an eruptive cycle which is still ongoing. Currently (May 2013), the lake level is very low with an approximate depth of 10 m and lake water temperature is near 50°C.

Does the August 2012 overturn of Lake Barombi Mbo a precursor to another potential deathly explosion along the Cameroon Volcanic Line?

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Because of their capability of accumulation of lethal gas (CO_2, CH_4, …) at their bottom, and that can be released and cause many causalities, crater lakes and especially those filling maar-diatreme volcanoes represent one of the hazardous volcanic lakes on the Earth. Lakes Nyos and Monoun (Cameroon) and Albano Lake maar (Italy) are some cases. Maar lakes can also experience frequent overturn due either to climatic effect or to volcanic origin.

In August 2012, after a dramatic overturn of Lake Barombi Mbo, the population of Kumba (700,000 inhabitants), southwest Cameroon, became frightened and mostly bothered by thoughts from memories of lakes Monoun and Nyos deathly gas outburst events. Lake Barombi Mbo is a 2.5km wide and 111m deep crater lake filling a maar of the same name, located 200Km SW of the Nyos Maar. According to the chief of the community of Barombi Mbo (a small village in the scar of an old maar west of Barombi Mbo Maar), lake-overturn events at this maar occur every 5-10 years. Generally, the event caused negligible disturbance of waters that got clear few days after. During the recent event, water became muddy-like, and took seven months to recover it clarity, depriving the population of clean water.

This phenomenon has been attributed to a climatic effect, but a volcanic force cannot be ignoring since the lake is of volcanic origin. Understanding the context in which this lake was formed, might provide insights on the volcanic force and in its potentiality in being hazardous. To this end, a comprehensive study of pyroclastic deposits of the Barombi Mbo Maar was carried out. Lithofacies were recorded, and pyroclasts were collected for granulometric analysis and physical properties. Samples were sieved and counted for particle size distribution and componentry, whereas juvenile clasts were SEM- and microscopically examined. Preliminary results reveal that phreatic, phreatomagmatic and magmatic activities prevailed during its formation, suggesting a polycyclic polymagmatic monogenetic volcano.

Microscopic examination confirmed existence of fluid and melt inclusions bearing minerals of rock samples. Though this is still in studying progress, it suggests the possibility of a gas rich-magma chamber beneath this volcano. A magmatic gas leakage could be therefore one of the causes of the overturn. The fact that the lake water was muddy-like during the last August 2012 overturn events similarly to that of 1950s, could indicate that the gas discharge would have been responsible to the upwelling of sediment at the bottom of the lake, causing the high dirty aspect of water during the seven months.

However, because the last activity occurred about 1Ma ago, it must be consider as an “extinct” volcano. Thus, a volcanic source is not plausible. According to J.M. Bardintzeff, the definition of an extinct volcano is not so strict, and if the Barombi Mbo maar is set to be a polymagmatic or polygenetic volcano that usually presents long live, the lake-overturn might be quite a precursor to further volcanic eruption at this maar.

Pre-eruptive diffuse acid steaming from a crater lake: the case of the Copahue volcano (Neuquen, Argentina)

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Copahue volcano, at the border between Chile and Argentina, hosts a crater lake continuously fed by melting of an ice cap covering the western side of the crater rim. As reported by Agusto et al. (present workshop) in the period 2003-2012 the crater lake water has displayed a significant temperature variability: from frozen (July 2004) up to 65° C (March-July 2012), though still remaining extremely acid (pH < 1). In 2011 despite the lack of significant temperature increases (30-40°C) the lake surface showed a diffuse steaming. Although no direct measurements were carried out, witnesses testified that steaming was clearly accompanied by the presence of very acid compounds, possibly HCl and HF.
Steaming steadily increased in March 2012 when temperature of the lake water reached 60° C. In this period steaming was so intense to conceal the lake surface. Clouds standing or moving over the crater rim strongly charged of acids to make breathing extremely difficult as the crater summit was approached. In July 2012 steaming was accompanied by a severe drop (some meters) of the crater lake, which was further reduced in December 2012 to a strongly degassing pool less than 20 m in diameter, just before the eruption that started on Saturday the 22nd. In one single day, the eruption evolved from an early phreatic stage, over a phreatomagmatic stage into Strombolian activity. In January 2013 the crater rim and its flanks were completely covered by still cooling scoria deposits, while three small actively degassing craters were occupying the inner portion of the crater floor.
In conclusion, phenomena like pre-eruptive diffuse acid steaming clearly suggest that scrubbing of even very acid, water soluble species passing through crater lake waters can be reduced or completely cancelled when it reaches hyper-acid conditions, leading to real plume degassing from a crater lake.

Evolution of the Copahue crater lake (Argentina) during the 2012 phreatic and phreatomagmatic eruption cycle.

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Copahue volcano (37º45'S-71º10'W, 2977 m a.s.l.) is part of Copahue-Caviahue Volcanic Complex (Argentina-Chile), located at the Southern Andean Volcanic Zone. The summit of this stratovolcano, consists of nine NE-oriented craters. Eruptive activity during the last 250 years, occurring from the easternmost crater that hosts a hot acidic lake (30-40°C, pH~1) with a diameter of~200 m, was characterized by at least 13 low-magnitude phreatic and phreato-magmatic events, affecting the nearby villages. Eruptive cycles took place from this crater in August 1992, September 1995 and from July to October 2000; and the last eruptive cycle began in 2012 and is still ongoing. Dimensions and chemistry of the crater lake was significantly affected by such frequent eruptions, Copahue Lake is a typical example of hyperacidic lake whose water composition data served as memory of the eruptive activity of a volcanic system in which geochemical monitoring is very difficult due to the absence of summit fumaroles and the occurrence of a well developed hydrothermal aquifer where magmatic gases are almost completely dissolved, masking any signal of deep magmatic inputs at the surface. In this study the chemical and physical variations of the Copahue crater lake in 2011-2012 are presented.

In 2012 phreatic and phreatomagmatic eruptions occurred after 12 years of solfataric state. In November-December 2011, a column of vapour and acidic gases some 200-300 meters above the crater was observed, testifying an increase of the fluid discharge rate from the volcano summit. By March 2012, the waters from hot springs and crater lake showed (1) the highest acidity (pH<0), (2) highest temperature (~65°C), (3) highest contents of magmatic species (SO_4^{2-}, Cl^-, F^-) since the 2000 eruption, and (4) a significant decrease on the crater water level due to enhanced evaporation. On July 17 a phreatic eruption occurred, manifested as vertical jets 10 meters above the crater lake level. On July 19, a phreato-(magmatic?) eruption occurred with the expulsion of pyroclastic material. During the following months fumarolic activity and intense bubbling continued, crater lake parameters showed high values of temperatures (~60°), high acidity (pH<0), and extremely high electrical conductivity. The lake water level continued to decrease until becoming a boiling pool only ~20 m in diameter before the December 2012 eruption. On the 22nd of December a new phreatomagmatic eruption occurred. This eruption caused the disappearance of lake water and the occurrence of several high temperature fumaroles (maximum measured temperature = 420 °C) and liquid sulfur ponds formed at the lake bottom. Two months later the crater lake began to be restored. In March-April 2013, the formation of two incipient water pools with intense gas bubbling was observed.

A geochemical monitoring of these newly formed lakes and that of the fumaroles discharging from their surroundings took place to provide information of on the on-going evolution of this volcanic system.

Variations in physico-chemical features and seismicity related to phreatic activity for the two active crater lakes in Costa Rica: Poás and Rincón de le Vieja volcanoes

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Poás volcano hosts Laguna Caliente, which after 12 years of quiescence resumed a cycle of phreatic eruptions in March 2006. Between 2006 and 2013, the lake dropped its level by ~35 meters, and showed variations in color (from emerald to gray), temperature (from 22 to 60°C), SO_4/Cl molar ratio (from 0.66 to 1.67) and a pH always near 0.
On 8 January 2009, the Mw=6.2 Cinchona earthquake occurred with the epicenter at 6 km from Poás. This earthquake was preceded by a slight SO_4/Cl increase (from 0.99 to 1.11) and was followed by a phreatic eruption on 12 January 2009. Sulfur combustion from the main dome fumaroles was observed in August 2009, and preceded the first major phreatic eruptions (500 m above the lake surface) of the 2006-ongoing eruption cycle on 17 September and 25 December 2009. In 2010, more than 1,000 phreatic eruptions occurred; eruption height varied from 5 to 500 m. In August 2011, incandecence was observed at the dome (the 1953-1955 dome, see Mora-Amador et al. Poster), consistent with measured temperatures as high as ~900°C, and accompanied by phreatic eruptions from the lake. On 13 April 2012, a major phreatic eruption (~300 m above the lake surface) generated base surges on and around Laguna Caliente. On 5 September 2012 a major tectonic earthquake occurred at 150 km from the volcano (Sámara, Mw=7.6), followed by phreatic eruptions from Poás that same day and a major phreatic eruption in October 2012. Since March 2013, a decrease in the lake water temperature (from 47 to 43°C), but an increase in the temperature of dome fumaroles (from 150 to 240°C), was registered. On 1 and 2 May 2013, a series of phreatic eruptions occurred, which were preceded by a clear increase in seismicity since 29 April (>200 LP events, above a background seismicity of 50 LP events/day). Moreover, lake water temperature increased again to 46°C, the temperature of the strongly degassing dome increased significantly (from 240 to 550°C), and a "subaquatic sulfur plume" showed a high temperature of 55°C (FLIR measurements)
The large distance from San José and the difficult access to the active crater (9 hours hiking back-and-forth) leads to less frequent visits to Rincón de la Vieja volcano. Moreover, the inner walls of the active crater, hosting the acidic lake, are nearly vertical with a crater rim 100 m above the lake surface. That is why sampling of the lake water is only possible by throwing a rope+recipient down the crater, leading to the collection of only a few cl of water at each throw.
Since September 2011, Rincón de la Vieja entered a new phase of phreatic eruptions, the first eruptions since 2001. These eruptions partly threw out the lake, causing hot lahars in the northern sector of the volcano, and fish kill in the surrounding rivers downslope. In April 2012, during a visit to the crater area, we observed four minor phreatic eruptions with an eruption height of ~10 m above the lake surface. The lake water temperature was 38°C, and the pH 1.5. The eruptions continued the next weeks, which led to the closure of the crater area for tourists.
As well for Rincón de la Vieja, after the Sámara earthquake (5 September 2012, 130 km from the volcano) volcanic seismicity increased (mainly tremor), which eased to recognize phreatic eruptions (without visit).

During a visit two weeks after the earthquake, we observed (1) a descend of the lake level by 0.5 m, (2) an increase in the lake water temperature (48.7°C), (3) a drop in pH (to 1), and (4) convective cells in the center of the lake. Due to this apparently increased dynamics (activity?) of Rincón de la Vieja, sampling and measurement campaigns were intensified in 2013. In February 2013, (1) the lake water temperature decreased (38°C), (2) the pH remained near 1, (3) the fumarole temperature (near the lake, so remotely sensed by FLIR) increased from 115°C (September 2012) to 180°C, above the melting point of S, and thus manifesting small sulfur flows, (4) an additional lake level drop of ~2 m, and (5) floating sulfur spherules on the lake surface. In April 2013, we observed (1) an additional temperature drop of the lake water (32°C), (2) a pH drop to ~0.5, (3) a further lake level descend by 0.5 m, (4) still the presence of sulfur spherules, and (5) an increase in volcanic tremor. These observations might be consistent with the emplacement of a molten sulfur pool at the lake bottom, which could eventually lead to vent sealing, and thus more violent phreatic activity, and related lahar risk at the north flank of Rincón de la Vieja. To increase volcanic surveillance, during this last visit in April 2013, a continuous T-gauge was left in order to register lake water temperature, every 5 minutes for the following six months.

Theme 5. Biological studies of crater lakes

Biogeochemical processes in Hule and Río Cuarto lakes (Costa Rica): preliminary results of a multidisciplinary approach

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The 7th Workshop of the IAVCEI Commission of Volcanic Lakes (CVL7) held in Costa Rica from 10th to 19th March 2010 was attended by an international group of scientists, including volcanologists, geochemists, limnologists and microbial ecologists with the main focus on developing effective multidisciplinary strategies for understanding and monitoring these natural systems where geosphere and biosphere are strictly related.

Costa Rica is a land of volcanoes, where hyperacidic volcanic lakes, i.e those hosted in the active craters of Rincon de la Vieja and Poás volcanoes, and Nyos-type lakes, e.g. Laguna Hule and Laguna Río Cuarto, occur.

Hule and Río Cuarto maars are located on the Caribbean side of the Central Volcanic Range of Costa Rica, and lie along a N–S trending, ~ 27 km-long volcanic fracture crossing the Poás volcano. Laguna Hule is hosted in a wide caldera (the Bosque Alegre caldera), formed about 3,000 years ago. This volcanic lake has a maximum depth of 21 m and a water volume of 6.9 × 106 m3, and shows a well-developed hypolimnion. Río Cuarto has a maximum depth of about 70 m, a water volume of 15 × 106 m3, and a morphology characterized by steep side walls and flat bottom. It has a thermocline at depth varying between -20 and -25 m and an anoxic hypolimnion characterized by a strong enrichment in nutrients. In both lakes, significant concentrations of CH4 and CO2 were recognized at depth > 10 m. Sporadic episodes of fish deaths were observed by the local population in recent years, likely related to rollover phenomena during which oxygen-poor deep waters were brought to the surface.

This study presents and discusses geochemical and microbiological data of water and dissolved gas samples, collected during the CVL7 meeting from Hule and Río Cuarto lakes at various depths along the vertical water columns. The main goals are i) to produce a complete bio-geochemical characterization of these two lakes, and ii) to investigate the biogeochemical processes at different redox and temperature conditions along the vertical profiles, and their implications for surveillance related to the limnic eruption hazard.

Bacterial community composition in the Nyos (Cameroon) watershed: Preliminary results

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Lake Nyos is a meromictic Lake located in the Nyos village in Cameroon. All together, the lake and the surrounding springs and rivers constitute the hydrological network of the area. The lake is permanently stratified and its water column is 210 meters deep with strong vertical increasing CO_2 concentration gradients to an anoxic environment at the bottom. In 1986 it suddenly released a cloud of carbon dioxide into the atmosphere, killing about 1,700 people and 3,500 livestock in nearby towns and villages. Early after the disaster, several studies on the geochemical aspect were conducted on Lake Nyos and the surrounding springs and rivers. However, research has been scant in relation to the biological aspect. Such a knowledge on the bacteria community composition (BCC) present in these environments (the surrounding rivers and spring as well as of the Lake water column) may lead to a better understanding of the hydraulic connections in the watershed, the biogeochemical interactions (between the BCC and their environment) and the suitability of the resource for various purposes for people that are resettling the area after the catastrophe. Considering the previously cited reasons, investigations of the BCC in this area raise a lot of interest and constitute the aim of this study.

Water samples were collected during March-April 2013 (dry season). We used the PCR-DGGE (Polymerase Chain Reaction-Gradient Denaturing Gel Electrophoresis) approach for the16S rRNA gene-based community analysis. The fingerprinting of bacterial communities indicates a diverse community. Bacteria communities were stratified by depth in the lake water column and varied between ground water samples. Obtained sequences were matched to known taxon-specific biogeochemical functions and found correspondence between environment and bacterial function. Species close to potential pathogenic and biotechnology interesting bacteria were also detected. These results suggest a rich microbial diversity and potential functional composition in the Nyos area. Season-related community shifts is also to be tested.

Keywords: Nyos, CO_2, meromictic Lake, groundwater, bacterial community composition, 16S rRNA, PCR-DGGE, Bacterial diversity, fingerprinting.

Theme 6: Limnology

Variations and characteristics in changes of the crater lake level of Irazú Volcano (1965-2012), Costa Rica

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The small and ephemeral crater lake of the Irazú has presented noticeable changes in its coloring, temperature, pH, and depth from 1965 until 2012. The level has varied from 31 m in 1995 and 2001 to stay completely dry in 1977, 1979, 1982-83, 1987 and 1990. These levels are not always directly related to the amount of rainfall. It seems that at times the waterproofed base of the lake was cracked allowing the lake to drain relatively quickly, leaving the base visible for several months or years, and after a time, formed again. The variation of the color (green, turquoise-blue, yellow, rare whitish and reddish), temperature (16º-35ºC), and pH (2.85-5.85) seems to be related to the depth, underwater fumarolic activity, algae activity and ferruginous sediments produced by the constant landslides of the walls.

Theme 7. Hydrology of crater lakes

Physico-chemical and isotopic composition of some lakes and springs in the Bamenda Highlands, North West Cameroon

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The Bamenda Highlands (6°12'N, 10 °24'E), Northwest Cameroon, is located mid-way along a chain of volcanoes (ca. 1600 km long) cutting diagonally across Cameroon called the Cameroon Volcanic Line (CVL). The area is characterized by volcanic lakes and springs. Information on the chemical composition and recharge of these lakes and springs is necessary given the lethal incidence from some of the Lakes along the CVL like Lakes Monoun (1984) and Nyos (1986). In this study, we present the physico-chemical and stable isotope compositions of Lakes Oku, Bambili and Ber and some springs discharging from the flanks of the volcanoes on which these lakes are located. The objectives are to determine the source of mineralization and recharge mechanism.

Hydrogeochemical analysis of Laguna Botos water and its importance in the water use of the facilities of the Parque Nacional Volcán Poás, Costa Rica

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Poás volcano (Costa Rica) is a complex stratovolcano hosting two crater lakes. The most active one, known as Laguna Caliente, is hot and hyperacidic. The second lake, Laguna Botos, shows low activity (TDS 12-15 mg/l), and is cold (T = 13-16°C) and slightly acidic (pH 4.7-5.2). The water of this lake has mainly a meteoric origin (δD = -42±10‰ vs V-SMOW and $\delta^{18}O$ = -6.7±1.6‰ vs V-SMOW) and its acidity is due to (i) the direct input of acidic rain due to plume degassing from Laguna Caliente, and (ii) continuous CO_2 degassing (0.85 t/d), manifested as bubbling degassing in the southern sector of Laguna Botos. This is thought to be the remnant effect of past activity some 50 ka BP. This CO_2 degassing sometimes causes death of birds.

Laguna Botos has natural effluents by lake overflow (Río Angel, Q = 17 l/s), so confining the maximum lake level, as well as an artificial drainage to provide water for the sanitary facilities of the Parque Nacional Volcán Poás (Q = 0.1 l/s). This acidic water from Laguna Botos is used by tourists and park rangers.

We applied a box model approach to estimate the water mass balance of Laguna Botos (ΔV-Botos = Δinput – Δoutput), together with a hydrological balance based on the method by Schonsinsky (2006). We measured the bathimetry of the lake in the field with an ultrasonar (fish finder) in order to better estimate the lake volume.

We sampled the lake twice and at different depths and the chemical analyses were compared to the Guidelines for Drinking–water Quality of the World Health Organization (WHO). The outcome was that the acidic water from Laguna Botos is not recommended for human consumption. That is why we stress that measures should be taken: (1) waters should be treated before use in the sanitary facilities, or (2) artificial drainage from Laguna Botos should be abandoned and water should be provided from elsewhere.

Hydrogeochemistry and groundwater quality in Nyos area about three decade after the CO_2 gas burst (North-western Cameroon)

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Groundwater of Nyos catchment situated at the Wum volcanic district in the Western part of the Cameroon Volcanic Line (CVL), have been extensively monitored in summer January 2013 to assess its genetic relationship with lake waters and to identify the main factor controlling its mineralization about thirty years after the CO_2 gas burst which killed about thousand peoples and cattle. Field measurements of physical parameters were preceded by chemical analyses of the samples for major ions. Electrical conductivity and total dissolved expressed by large variation between minimum and maximum values and high standard deviation suggests that water chemistry influenced by local variation in point sources in the study area is heterogeneous. Water type alters from Na-HCO_3 and Ca-Mg-HCO_3. The combined use of stoichiometric relations between major elements, saturation index and conventional graphical plots such as Gibbs plot, scatter diagrams point out that dissolution of carbonate minerals, weathering of silicate minerals and ion exchange process predominantly regulate the major ion chemistry. Interpretation of hydrochemical data allows identifying four distinct groups of groundwater with no mark of lethal (CO_2-rich) deep lake discharge. In general, total hardness (TH) values show overwhelmingly soft water types and the chemical budget of shallow groundwater were below the WHO guidelines for drinking water. Various determinants such as Sodium Absorption Ratio (SAR), Percent Sodium (Na%), Residual Sodium Carbonate (RSC) and Kelley's ratio revealed that studied samples are suitable for irrigation and consequently, CO_2-rich lake water which has low diffusivity with surrounding aquifer do not affect the quality of groundwater within the basin.

Keywords 2: Hydrogeochemistry, groundwater quality, CO_2 gaz burst, Nyos, North-western Cameroon.

Theme 8. Modeling, simulations and innovative studies on crater lakes

Numerical simulations of CO_2 air dispersion from gas driven lake eruptions: examples from Lake Nyos (Cameroon) and Lake Albano (Italy)

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Lake Nyos, Cameroon, on 21 August 1986 suddenly degassed as consequence of a limnic overturn producing the most tragic event of gas driven lake eruption. During this event a dense cloud of CO_2 suffocated more than 1700 people and an uncounted number of animals in one night affecting areas up to about ten kms from the lake. The event stimulated a series of studies aimed to understand gas origins, gas release mechanisms and strategies for gas hazard mitigation. Only recently few studies have been carried out for describing the transport of dense CO_2 clouds in the atmosphere.
In order to simulate dispersion of a heavy gas and assess the related hazard we used a model based on a shallow layer approach (TWODEE2). This approach uses depth-averaged variables to describe the flow behavior of dense gas over complex topography. The model was applied also to simulate CO_2 dispersion from natural gas emissions in Central Italy, showing how the dispersion pattern is strongly affected by the intensity of gas release, the topography and the ambient wind speed.
Here we applied TWODEE2 code to simulate the dispersion of the large CO_2 clouds released by limnic eruptions. A first case study is focused on August 1986 lake Nyos event. In this case main difficulties for the simulations are related to the lack of pivotal quantitative information such as gas fluxes, meteorological conditions, and accurate digital elevation models. Different scenarios were taken into account in order to reproduce the qualitative observations available for this episode. Simulation results are in good agreement with available semi-qualitative observations.
A second application deals with a hypothetical gas release from Lake Albano (Italy), a volcanic lake that probably degassed in the past as reported in historical chronicles by the Roman historian Titus Livius. Nowadays the lake is far from saturation conditions and the occurrence of such an event is very unlikely. However a recent re-interpretation of literature data clearly shows the presence of anomalous CO_2 enrichment of the lake waters during the last seismic crisis which affected the area in the eighties. Considering an assessment of the probability of occurrence of conditions that can lead to an increase in gas fluxes input into the lake we performed a series of simulations to evaluate the impact of a future limnic eruption in this densely populated area located 20 km south-east from the center of Rome.

Reactive Transport Models of Chemical Processes Operating in Sub-volcanic Lake Environments

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Chemical processes operating beneath crater lakes are particularly difficult to unravel, as we often have only the lake water to study, and this typically shows integrated signals from several different reaction environments beneath the lakes. Recently we have added the analysis of solute gases into our routine monitoring activities on Ruapehu, and these results have raised at least as many questions as they have answered, and point to rather complicated processes operating at depth of which we were not previously aware. We have undertaken a reactive transport modelling approach using X1t to examine some of the likely reaction relationships operating in these environments.
Lake water circulation through the vent of Ruapehu has previously been proposed to account for both heat and mass budget characteristics of the lake system. We therefore use lake water to simulate reaction at 50 ^{0}C with primary minerals along a 10 m long column of permeable substrate having 35 % porosity, and thereby allow it to form a suite of alteration minerals. Into this we inject a 300 ^{0}C magmatic condensate proxy consisting of 0.5 molal H_2S and SO_2, and 1 molal each of HCl and CO_2 with a head pressure of 0.2 kPa for a period of 1 day.

Heat rapidly decouples from the advancing chemical front, owing to heat loss to the enclosing rock mass. Three chemical equilibrium buffer zones migrate downstream from the inlet, with each having a significant effect on system Eh and pH. The first zone is characterised by the presence of elemental S, alunite, pyrite and quartz, with an Eh of ca. +0.4 V and pH of ca. 0.8.
The formation of elemental S eventually depletes S species from solution, leading to the formation of the second, more oxidised zone characterised by the mineral assemblage quartz, anhydrite , alunite, hematite and jarosite and a system Eh of +0.8 V, and a pH of 0.2. Further downstream of this zone reside the remnants of the original alteration assemblage, including a number of Al-silicates and carbonate minerals with near-neutral pH, and rather more reducing conditions (Eh ca. -0.2 V). Significant permeability reduction is associated with the precipitation of elemental S proximal to the inlet, and carbonate minerals further downstream, making the processes consistent with seal formation models at Ruapehu and Raoul Island, respectively.

Qualitative insights (Cl, δD) into evaporative degassing from active crater lakes: theoretical background and practical tools

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This work provides the theoretical background and necessary practical tools to study one of the most spectacular natural features: vigorous evaporation from active crater lakes. We will give qualitative insights (lake water chemical –Cl content, and isotopical composition) rather than quantify evaporation fluxes from lakes. A major problem is that, with the current methods, we are only able to sample the lake water, while the input fluid rising into the lake (sublacustrine) and evaporation plume coming off the lake remain "untouchable". This means that the lake behaves as a "black box", being the result of in- and outgoing fluids of unknown chemical and isotopic composition. As visually demonstrated at many active crater lakes, evaporation is a major process. Strong evaporation from the lake surface will affect the isotopic composition of the remnant lake water, and the "steam devils" (evaporation plume) swirling over the lake. It is found that the kinetic (diffusion) isotope fractionation overwhelms the equilibrium isotope fractionation effect, as it is intuitively hard to imagine a dynamic crater lake as an equilibrated system. Besides a hot water mass in evaporation, water of active crater lakes are generally hyper-saline (total salinity >100,000 mg l-1) and hyper-acidic brines (pH as low as -1). Although "small scale" equilibrium fractionation effects, the "isotope salt effect" and "isotope acid effect" lead to isotopically heavier evaporation plumes, with respect to vapor coming off pure neutral water. Besides isotope fractionation of the water itself under such extreme lake conditions, HCl_{gas} (and HF) will partition between the liquid and vapor phase. HCl degassing is enhanced when pH is continuously lowered by the input of acidic gases (SO_2, HCl, HF), lake temperature is higher, and evaporation is physically favored by wind or lake convection. It is empirically deduced that HCl partitioning into the vapor phase is chemically controlled by the lake water temperature and density, rather than the Cl content or pH. A better quantification of the chemical and isotopic composition of evaporative gas plumes from active crater lakes will be of importance for volcano monitoring when we aim to deduce the flux and composition of the "hot magmatic end member", through chemical and isotope budget analyses.
A major challenge for the future is to develop field methods to enable to sample the evaporation plume coming off lake surfaces, so we can directly determine its chemical and isotopic composition and compare them with the theoretical approach of this review.
We should elaborate experiments, mimicking the natural situation of a crater lake, with controllable factors to better understand how evaporation and HCl degassing occurs at crater lakes, and how they relate to the underlying processes of magmatic input and fluid recycling. The here reviewed literature of similar experiments provide the theoretical base for such future work. Evaporating real lake samples under various conditions is probably most suitable, as crater lake brines are extremely complex solutions very hard to copy in the laboratory.

A probabilistic framework to quantify hazard related to volcanic lakes

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The presence of a volcanic lake increases the probability of certain types of volcanic hazard. So far, this topic has only been approached in a purely deterministic way, e.g.: phreatic-phreatomagmatic eruption behavior, dynamics of Nyos-type gas bursts and gas accumulation and dispersion, models on lahars and their triggers, dispersion of acidic brines upon lake seepage, gas hazard from degassing lakes, etc. BET_UNREST, the Bayesian Event Tree structure to better assess the state of volcanic unrest, is an advanced code based on the previous BET_EF, the Bayesian Event Tree for Eruption Forecasting. BET_UNREST 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. The BET_UNREST structure permits to introduce such "non-magmatic lake scenarios", given an appropriate selection of "monitoring parameters" at each node of the event tree. Exactly these non-magmatic scenarios are those helpful to track volcanic unrest for volcanoes hosting active magmatic-hydrothermal systems and volcanic lakes. 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.

At Node 1, we need to evaluate the probability of a "lake system" being in state of unrest or not; at Node 2, given unrest, if it is in a state of magmatic unrest or not; at Node 3 both the magmatic unrest and non-magmatic unrest scenario can lead to an eruption or not; at Node 4 the hazardous feature should be specified to better assess the hazard, as also non-magmatic and non-eruption unrest can pose volcanic hazard.

Scanning some lake situations: (1) Nyos-type lakes are possibly hazardous without renewal of magmatic input; monitoring parameters should reflect CO_2 input fluxes, thresholds and eventually the rate of artificial degassing, and cloud dispersion models (e.g., Lake Nyos and Monoun, Albano Lake, Lake Kivu), (2) phreatic eruptions at highly active crater lakes (e.g., Poás, Yugama, Aso, White Island) are often anticipated by long-term heating and sometimes by short-term cooling episodes, by floating sulphur spherules or by changes in the evaporative regime, (3) phreatic eruption activity itself can become precursory for later phreatomagmatic eruptions, due to pressure drop in the system (e.g., Ruapehu), (4) prolonged seepage of acidic lake brines and hydrothermal alteration can mechanically weaken the volcano flank, eventually leading the flank collapses (e.g., Rincón de la Vieja, Irazú), (5) lake throw out or overflow, or simply anomalous rain events can trigger lahars on the (weakened) volcano flank (e.g., Ruapehu), (6) persistent evaporative degassing from a lake can harm crops, cattle and human activity on surrounding (farm) lands, and can become more intense when the lake eventually disappears (e.g., Poás, Aso, Copahue), (7) dispersion of acidic brines originating from lakes into the hydrologic network can threaten the health of surrounding populations (e.g., Kawah Ijen).

This deterministic knowledge should now be translated properly into adequate monitoring parameters with specific thresholds at the various Nodes within the BET_UNREST structure, in order to provide probability density functions (PDFs) for specific hazardous events, for each specific lake. The numerical outcome of the application of BET_UNREST will provide (1) a guideline for future deterministic research in search for 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), 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 method to quantify probabilities of possible occurrences of lake-related hazards, useful in volcanic surveillance.

Numerical simulations (TOUGH2) to quantify crater lake seepage: a case study for Laguna Caliente, Poás Volcano (Costa Rica)

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Volcanic lakes are different from the common reservoirs of meteoric origin because of the interaction with the hydrothermal system of the volcano. The hot fluids (gas + liquid) of volcanic origin rise through the bottom of the lake resulting in strong acidic water and a variable temperature usually tens of degrees above the ambient. Contrariwise, the water of the lake infiltrates through the soil and changes the thermodynamics and the path of hydrothermal circulation. The balance established in this complex system is very delicate: the survival of the lake depends on the particular combination of meteoric recharge, runoff, water loss by infiltration within the volcanic edifice (seepage) and evaporation from the lake surface. The water level of the lake and its temperature are closely linked to the activity of the deep magmatic source and surveillance of the lake can provide important information for the monitoring of the volcano. Not all of the factors influencing the evolution of the lake are directly measurable, as several authors have addressed. In particular the seepage is unmeasurable, as it is sublacustrine. These unknown fluid fluxes can only be estimated from the calculation of the mass and energy balances of the lake. Numerical simulations can help to study the temporal evolution of the lake and to understand the physical dynamics behind seepage. Our simulations are based on the model of Poás volcanic system (National Park in Costa Rica), hosting Laguna Caliente. This volcano is well known, and long-term monitoring has shown that the crater lake is particularly active, and well represents the main features of volcanic lakes, in general.

The simulations were obtained with a multiphase, multicomponent integral finite differences simulator, TOUGH2. We focused mainly on the effects of the different thermodynamic conditions of the hydrothermal source and on the permeability of the rocks that make up the volcanic cone and surround the lake. Due to the geometry of the conical summit of the volcano, the simulations are carried out on a two dimensional domain representing the axial section of the system. The computational domain assigned to the simulation of the lake extends to 125 m from the axis of symmetry to a depth of 50 m, while the whole domain is 1 km wide and 250 m deep, for a total of 2288 elements. The base of the domain communicates with a source of fluid (water and steam) that is hot and pressurized. In this way we simulate the ascent of deep fluids of the hydrothermal system of Poás. A first set of simulations is run considering a stationary lake, whose temperature and water level are fixed in time. This is useful to investigate how the presence of the lake affects the hydrothermal circulation of the volcano. The volcanic lake, however, is an important boundary condition that changes through time as a function of its interaction with the volcano itself. To describe this effect, we included the lake in the computational domain in a second group of simulations. In these simulations the same porous media flow model is used to approximate the dynamics of the lake, assuming a very high permeability and a porosity of 1. In this way, the model describes the changes in water level and temperature as a result of the interaction between meteoric water and hydrothermal system. Even if this is an elementary representation, it shows the development of convective cells in the simulated lake. The calculation of the Rayleigh number shows that the real lake is definitely in convection, hence, to achieve a realistic simulation this efficient heating mechanism cannot be overlooked. In a third group of simulations we introduced the contribution of the rain. The meteoric recharge, in fact, strongly affects both temperature and water level of the lake. In this way it is possible to simulate the birth of Laguna Caliente, moreover, this contribution can hardly be neglected for a realistic description of the lake evolution. For each group we performed multiple simulations with different permeability along the bottom of the lake to simulate a greater or lesser “waterproofing”, mainly due to the presence of chemical compounds dissolved in water (in particular molten sulphur pools). Other simulations have been made instead to study the changes of the volcano and Laguna Caliente in function of the temperature and pressure of the hydrothermal source. Therefore, we simulated the injection of fluids, hottest and most pressurized corresponding to a higher activity of the volcano, and the injection of fluids with lower temperature and pressure to simulate periods of lower activity. The results show that the mutual interaction between the hydrothermal system and the lake is very narrow. Changes in characteristics and thermodynamic conditions in depth are recorded by the volcanic lake and they involve a different evolution over time.

Flow Dynamic of Apoyo Lake Using Isotopic and Geochemical Data.

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Lake Apoyo is one of the 10 crater lakes in Nicaragua. Its form describes a circular shape of 6Km in diameter and 175m depth. The drainage area defined by steep caldera walls is about 38km^2. The watershed is endorheic, with some crickets running in the walls and discharging into the lake. Average precipitation is 1454 mm/year. Lake levels have shown a decrease of about 10 m over the last 30 years. Lake Apoyo represents an important tourist destiny and an economical source for the small town developed within its influence area. The decrease in lake level is a big issue that needs to be understood in order to establish a management focused on maintaining water levels.

This research aims to establish a conceptual model that determines flow dynamic of Lake Apoyo and its watershed, using geochemical and isotopic tools. A series of chemical and physical water parameter records from 2003 to 2009 have been used in this analysis. A chemical-isotopic survey was carried out in 2006-2007. Data for ^{18}O and D were monitored for the lake, springs, surface and groundwater sources and precipitation.

A regional hydrogeological study shows that the lake receives groundwater from NW and SW in a tiny band of flow, due to a low permeable geological formation. Isotopic composition and salinity shows young water in wells and a relation between groundwater and lake waters ($\delta^{18}O$ = -5.28‰ δD=-29.26‰ for precipitation, $\delta^{18}O$ = -7.33‰, and δD=-46‰ for groundwater and $\delta^{18}O$ =2.25‰ and δD= 9.98‰ for water lake). Evaporation plays an important role in the water balance, as was shown by isotopic concentrations, with enrichment of heavy isotopes.

As for chemical content, there are three groups of water: 1) recent infiltrated water in wells located SW and W of the lake (HCO_3-Ca-Mg y HCO_3-Ca-Na, HCO_3-Na-Ca type) which indicates groundwater domain;2) saline water (Cl-Na y Cl-Na-$SO4^{-2}$) that indicates evaporated water from the lake and thermal springs and 3) mixed water (HCO_3-Cl-Na) in some wells near lake Apoyo and a well a far distance from the lake, but presumed to be connected through a geological fault.

Arsenic concentrations of X to X, high salinity and thermal influence makes it necessary to extend chemical and isotopic characterization to better define the aquifer zones and connection between aquifer, thermal springs, lake and geological structures.

Detecting magmatic CO_2 input in a volcanic lake using a CTD probe, an example of the Laacher See, Germany

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The Laacher See is a volcanic lake in the East Eifel volcanic district in Germany that has had its last eruption around 12,900 years BP. Active degassing of essentially mantle CO_2 can be observed both in the lake and on the shore (Aeschbach-Hertig et al., 1996). Along the eastern shoreline, several zones, called "mofettes", are known where gas bubbles make their way from the lake bottom to the surface. Water samples were taken in 2012 and 2013 for chemical analysis. pH and alkalinity were measured in situ. Gas-tight vials were filled completely with lake water for subsequent headspace analysis by IRMS. A miniature IRGA sensor was used to measure dissolved CO_2 in situ. Whereas the lake waters have a near neutral pH between 7.94 and 8.6, the mofettes are slightly acidic with pH descending down to 5.9, consistent with the dissolution of gaseous CO_2 and the dissociation of carbonic acid. Major element concentration varies little since 2007 (Gal et al., 2011). Alkalinity is very constant throughout the lake, varying between 383-397 mg/l HCO_3 -in the mofettes to 406 mg/l in more quiet zones, measured by titration. Therefore, the dissolved CO_2 in equilibrium with these values, as calculated with the PHREEQC program, can be directly calculated from measured pH. The pH in the mofettes varies on a very local scale and calculated CO_2 is around 200-450 mg/l with extremes up to 980 mg/l, and background values in non-active zones of around 4 mg/l. The Total Dissolved Inorganic Carbon (TDIC = CO_2aq + HCO^{3-}+ CO_3^{2-}) calculated using PHREEQC was compared to laboratory headspace analysis after acidification. For the mofettes, measured values of 11-18 mmol/l correspond well with calculated values of 12-29 mmol/l. Background values are 7 (measured) and 6 (calculated) mmol/l. IRGA in situ analyses yield a slightly lower CO_2 aq for the mofettes, ranging from 79 to 280 mg/l. The differences in pH and TDIC between zones with intense degassing and no apparent activity represent a chemical halo that is present around the mofettes. These halos can be detected with a detailed chemical survey, using a CTD (conductivity-temperature-depth) equipped with a pH probe. The probe is dragged behind a moving rowing boat and can detect minor changes in chemical parameters (Figure 1).

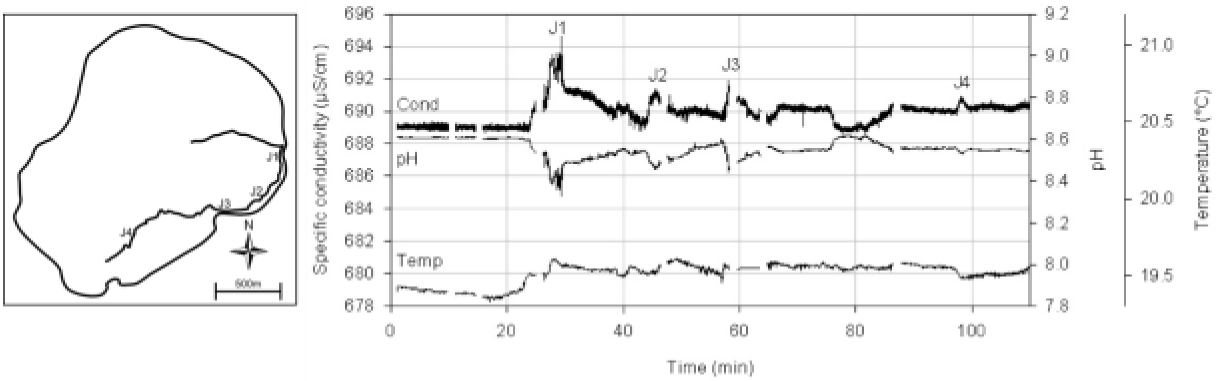

Figure 1: Conductivity, Temperature and pH profile of Laacher See in July 2012
Along the eastern shore, peaks of high conductivity and low pH coincide with visible mofettes. Some of these peaks coincide with a sudden increase in temperature but this relationship is less evident. Furthermore, similar types of chemical halos can be seen on the west and south side of the lake, in places where mofettes have not been reported up to present. Preliminary results demonstrate the potential of this technique to detect gas vents, also at relatively low fluxes where gas bubbles are not always visible. A more detailed survey will give a better insight into the geometry of sub-lacustrine fumaroles and might reveal fracture patterns that up to now have been hidden.

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Flash draining of a Boiling Lake? Insights from analogue experiments.

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Sudden episodes of lake draining and filling have been documented on some hot temperature lakes or ponds, e.g. at Dominica Boiling Lake (Fournier et al., 2009) where emptying and filling cycle can last a few days. We conducted analogue measurements in order to understand the physical processes at the source of this behavior. We used a one-meter-high and 70 mm diameter steel column, filled with water, and heated at its base with a hot plate. At the water surface level in the column, we inserted a metal grid in order to generate pressure drop. A hollow cooling plate made of brass was set-up at several centimeters above this grid, with its temperature maintained constant at 20°C by circulating water. Our aim is to simulate the behavior of a deep reservoir of water at boiling conditions connected with an upper layer of water in liquid phase (lake), through a constricted medium (soil). When the water reaches its boiling conditions inside the column, its thermal expansion and the steam formation push the water through the grid in the cooled upper part. At this time, a colder and denser liquid layer overlies a boiling water layer, thanks to capillarity effects and frictional forces inside the constricted grid and to the formation of a bubbly layer just below the grid. Such configuration is unstable, and we observed that in some cases, after several minutes the upper layer drains rapidly, and cools the upper part of the water column. As the water is continuously heated at the bottom of the column, the layer above the grid restarts to fill-in, followed after several minutes by a flash draining. The existence and the period of the draining-filling cycle depend on the pressure drop in the constricted medium and on the distance between the constricted medium and the water surface. In natural systems, like a boiling lake, flash draining could be triggered by sudden cooling of the upper layer, e.g. by the input of cold rainwater, or by permeability changes in the fractured medium beneath the lake.

Theme 9: Physical studies on crater lakes

Calculating (potential) density of limnic waters of unusual chemical composition

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Small density differences in lakes control vertical circulation, and hence the refreshment with atmospheric oxygen as well as the distribution of solutes. If the vertical circulation is incomplete, layers of special chemical milieus can form, which allow reactions that would not take place in a circulated lake. As a consequence, highly accurate density calculations are required. However, this can be a difficult task in volcanic areas. As the composition of solutes varies between lakes, a general formula can only be of limited accuracy. Lake specific adjustment can solve part of the problem, but still vertical gradients in the composition as well as temporal changed can be found, especially in volcanic lakes.

We present empirical approaches, how lake specific density formulas can be evaluated. A temperature compensation for the electrical conductivity must be implemented, before it can be used for calculating density by quantifying dissolved substances with the bulk measurement of its electrical conductivity. High accuracy measurements of density are used to produce a correlation of density against temperature and electrical conductivity (Boehrer et al. 2009).

A second approach uses partial molal volumes. This approach is based on the knowledge of the composition of the solutes. Hence for each solute its specific contribution to both mass and volume of the solution can be added. Recently a comprehensive list of coefficients of limnic solutes has been published and the accuracy of this approach was assessed (Boehrer et al. 2010). This equation is also made available on the internet www.ufz.de/webax. If chemical reactions can impact on the density structure, they can eventually control the circulation pattern, e.g. geochemically meromictic lakes. If a numerical simulation of the stratification (and circulation) of these lakes is attempted, a density calculation based on the actual chemical composition of the solutes can be implemented. The feasibility of this approach has been demonstrated (Moreira et al. 2011).

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(Invited)

Electromagnetic evidence of movement of hydrothermal water around Naka-dake Craters, Aso Volcanic Group, Japan

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Aso Volcanic Group has an intense geothermal activity in the 1st crater of Naka-dake, one of the post caldera cones. This crater shows a characteristic cycle of activity that consists of the formation of hot lake, drying-up of the lake water, and finally Strombolian eruptions. Recent observations indicate an increase in eruptive activity including a decrease in the level of the lake water, mud eruptions, and red hot glows on the crater wall. These changes associate the change of the activity of Long Period Tremor (15 sec) about 1km beneath the craters, Short Period Tremor (1-2Hz) and thermal demagnetization just beneath the 1st crater.

Energetics of the crater lake: Terada et al. (2012) carried out precise and continuous observations of the level and temperature of the lake water, and developed a numerical model of a hot crater lake. The numerical model revealed seasonal changes in mass flux and enthalpy for the fluid supplied to the lake. The relation between the enthalpy and mass flux indicates that the bottom input fluid is a mixture of low- and high temperature fluids; rainfall groundwater and the high-temperature volcanic gas from magma, respectively. The estimated flux of high temperature fluid shows close relation with the amplitude of volcanic tremor, suggesting that heating of the hydrothermal system drives the tremor.

Electrical conductivity structure around the crater lake: Measurement of the subsurface electrical conductivity is a promising method in investigating the shallow structure of the volcanic edifices, where energy from various sources accumulates, and in investigating the behaviors of magma and volcanic fluids. Kanda et al. (2008) conducted AMT surveys around the craters of Naka-dake, and identified highly conductive zone at shallow levels beneath the crater. The storage of thermal energy inferred from temporal variations in the geomagnetic field detected by Tanaka (1993), corresponds the upper part of this conductor, and the hypocenters of volcanic earthquakes are located immediately beneath the conductor. The results of seismic studies and self-potential anomaly suggest that volcanic gases are supplied from deep-level magma toward the active crater, generating volcanic earthquakes and various kinds of tremors along the pathway. Volcanic explosions act to release the energy transferred from magma or volcanic fluids.

Diffusion of hydrothermal water around the crater: Kagiyama and Morita (2008) indicated magma degassing is one of the important factors to control magma ascending, and to characterize the failed eruptions in Aso. On this aspect, the authors have carried out VLF-MT survey within Aso Caldera, especially around Naka-dake. Conductivity profile across the 1st crater shows high conductive zone just near from the crater and steep decrease in conductivity according to the distance from the crater. This evidence suggests degassing from the crater. Distribution of conductivity in Aso Caldera shows another feature. Most post caldera cones show low conductivity (<30μS/cm), except around Naka-dake craters and geothermal area on the western flank of post caldera cones such as Yunotani and Yoshioka(>300μS/cm). High conductivity zone expands to the north of Naka-dake and the caldera floor. These results suggest that hydrothermal water is supplied beneath Naka-dake, and move to the northern caldera floor. Aso has wide high conductivity area and it means degassing from magma might be large to suppress explosive eruptions in Aso.

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Session Program

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CVL8-O15	Hydrogeochemistry and groundwater quality in Nyos area about three decade after the CO2 gas burst (North-western Cameroon)	Tchakam KB, Fantong WY, Tiodjio ER, Anazawa K, Wirmvem MJ, Ueda A, Mvondo OJ Kusakabe M, Tanyileke G, Ohba T, and Hell JV	Tchakam B.	16:51 - 16 :54		
CVL8-P6	Flow Dynamic of Apoyo Lake Using Isotopic and Geochemical Data	Flores Y, Calderón H., Aravena R.	Flores Y.	16:54- 16: 57		
CVL8-P2	Numerical simulations (TOUGH2) to quantify crater lake seepage: a case study for Laguna Caliente, Poás Volcano (Costa Rica)	Nespoli M., Todesco M., Rouwet D., Bonefede M., Mora-Amador R.	Rouwet D.	16:57 - 17: 00		
CVL8-P3	Numerical simulations of CO2 air dispersion from gas driven lake eruptions: examples from lake Nyos (Cameroon) and lake Albano (Italy)	Chiodini G., Costa A., Rouwet D., Tassi F.	Rouwet D.	17:00 - 17: 03		
CVL8-P10	Qualitative insights (Cl, D) into evaporative degassing from active crater lakes: theoretical background and practical tools	Rouwet D., and Ohba T.	Rouwet D.	17:03 - 17:06		
CVL8-P8	Science & Arts workshops to increase volcanic risk awareness: Chapultenango, near El Chichón volcano (Chiapas, Mexico)	Rouwet D, Iorio M, Polgovsky D	Rouwet D	17:06- 17:09		
CVL8-O1	Diffuse CO2 emission from certain crater lakes located on the Cameroon Volcanic Line (CVL): A contribution to global carbon cycle budget and CO2-related hazard assessment in Cameroon	Issa, Ohba T., Aka F. T., Fantong W., Gbetnkom MA, Yoshida Y., Kusakabe M., Chako T. B., Sighomnoun D., Sigha Nkamdjou, Tanyileke G., Hell J. V., Nnange, J. M.	Issa	17:09 - 17:12		
CVL8-P9	The Boiling Lake, Dominica, the Lesser Antilles: Factors to be considered	Robertson D., Joseph E., Fournier N, Woith N.	Robertson D.	17:12 - 17:15		
CVL8-O17	Hydrogeochemical analysis of Laguna Botos water and its importance in the water use of the facilities of the Parque Nacional Volcán Poás, Costa Rica	González G., Ramírez C., Mora-Amador R., Rouwet D., Alpizar Y.	González G.	17:15 - 17:18		
Poster core time				**17:20 - 18:20**		

Session 1: July 28th				9:00 - 10:30	Session Chair	time keeper
					Dr Dmitri Rouwet	**Ms Yuka Sasaki**
CVL8-O23	Pre-eruptive diffuse acid steaming from a crater lake: the case of the Copahue volcano (Neuquen, Argentina)	Agusto M., Tassi F., Caselli A.T., Vaselli O., Rouwet D., Capaccioni B., Chiodini G.	Capaccioni B.	9:00 - 9:15		
CVL8-O30	Geochemical evolution of the ultra-acid crater lake of Poás volcano, Costa Rica, 1978 until present	Martínez M, Van Bergen MJ, De Moor JM, Avard G, Fernández E	Martínez M	9:15 - 9:30		
CVL8-O06	A probabilistic framework to quantify hazard related to volcanic lakes	Rouwet D., Sandri L., Mora-Amador R.	Rouwet D.	9:30 - 9:45		
CVL8-31	New findings at Lake Monoun in 2013 by the cooperative research project between Japan and Cameroon under "SATREPS†" program	T Ohba, Y Sasaki, M Kusakabe, Y Yoshida, A Ueda, K Anazawa, K Saiki, K Kaneko, Y Miyabuchi, Issa, F Aka, W Fantong, G Tanyileke, L N Sigha, J V Hell	Ohba T.	9:45 -10:00		
CVL8-O2	Temporal change in CO2 content of Lake Nyos in recent years	Yoshida Y., Issa, Kusakabe M., Ohba T., Tanyileke G., Hell J.V.	Yoshida Y.	10:00 - 10:15		
CVL8-O20	Decoupling of CO2 and He in deep water of Lake Nyos, Cameroon: implications for spontaneous gas exsolution and the sub-lacustrine CO2-recharge system	Kusakabe M., Nagao K., Matsuo T., Ohba T., Yoshida Y., Issa, Tanyileke G., and Hell J.V.	Kusakabe M.	10:15 - 10:30		
CVL8-O10	Physico-chemical and isotopic composition of some lakes and springs in the Bamenda Highlands, Northwest Cameroon	Wirmvem M.J., Ohba T., Fantong W.Y., Ayonghe S.N., Suila J.Y., Asaah A.N.E., Asai K., Tanyileke G., Hell J.V.	Wirmvem M.J.	10:30 - 10:45		
CVL8-O14	Regional extent of magmatic CO2 in crater lakes of the Oku Volcanic Group: Constrains from petrogenesis and relation with tectonic events	Asaah A.N.E., Yokoyama T., Aka F.T., Usui T., Wirmvem M.J., Chako T. B., Ohba T., Tanyileke G., and Hell J.V.,	Asaah A.N.E.	10:45 - 11:00		
Coffee break 11:00 - 11:15						
Adress session 11:15 - 12:15					**Dr Dmitri Rouwet**	
	Advertisement of CVL9 candidacy					
	CVL9 - Nyos	Cameroon	Greg Tanyileke	11:15 - 11:30		
	CVL9 - Taal - Pinatubo	Philippines		11:30 - 11:45		
	CVL9 - Kivu	Democratic Republic of Congo		11:45 - 12:00		
	Closing remarks		Prof Takeshi Ohba	12:00 - 12:10		
	General photo			12:15		

ACTIVITY REPORT OF THE IAVCEI COMMISSION ON VOLCANIC LAKES

The **first book on Volcanic Lakes** (Springer-Heidelberg, guest editors: *Dmitri Rouwet, Bruce Christenson, Franco Tassi and Jean Vandemeulebrouck*) is soon to be submitted to Springer and will probably become the first book of the IAVCEI Advances in Volcanology series by Springer (series editor: K. Németh). The book will contain about 25 chapters on various themes of Volcanic Lake research, from fluid, rock and isotope geochemistry, geophysics, limnology, isotope geochemistry, sedimentology, petrology, volcanology and hazards, numerical modeling, biology, etc…

"Fluid geochemistry of volcanic and geothermal systems" is the first **course** organized last March (11-15) 2013 by *Universidad Nacional de Río Negro* and *Asociación Volcanológica Argentina*, and supported by the IAVCEI Commission on Volcanic Lakes, in Caviahue (Argentina). The course was a success and aims to become a reference for at least Latin America during the next years. In 2014 the course is planned to be repeated.
The **scientific community** working on volcanic lakes and lake hosting volcanoes has been **extremely productive** the last couple of years. Scientific productivity is demonstrated by the number of publications in peer-reviewed journals; in 2011-13 publications, in 2012-20 publications, in the first half of 2013-7 publications.

Some of the volcanic lake bearing volcanoes kept many of us extremely busy:
Copahue volcano (Argentina) entered a new eruptive phase in December 2012. Caviahue has been recently evacuated, after the crater lake disappeared giving place to phreatic-phreatomagmatic and Strombolian activity. Dome extrusion is suspected.
White Island (New Zealand) has shown anomalous activity, raising concern at GNS. Sulfur volcanism (boiling sulfur pools near the crater lake), higher SO_2 fluxes and increased fumarole T are monitored.
Poás volcano (Costa Rica) continuous its phreatic eruption cycle, resumed in 2006. Recently (May 2013) phreatic eruptions from the dome occurred just S of Laguna Caliente crater lake.
Rincón de la Vieja volcano (Costa Rica) resumed phreatic activity after a decade of quiescence. For both Poás and Rincón, a possible relation exists between eruptive activity and the occurrence of recent tectonic earthquakes (three >Mw 7 earthquakes in Central America in August-November 2012).
Two additional degassing pipes were installed in 2011 and 2012 at **Lake Nyos**. The degassing process is monitored and Lake Nyos bottom waters are expected to be CO_2-free within the next years.

Dmitri Rouwet is taking steps to lobby proposals for the **next CVL9-2016 workshop**. So far, three candidates have come up with a concrete proposal: CVL9-Nyos (30 years after the 1986 gas burst), CVL9-Philippines (Taal and Pinatubo, 25 years after the Pinatubo eruption), CVL9-Kivu. Let's say that the future of CVL is assured.
VOLADA. Dmitri Rouwet, with the help of Veronica Chiarini, took steps to create the first collaborative data base on volcanic lakes. Surprisingly, 475 volcanic lakes were recognized globally… a lot more than previously thought. Most of those lakes are poorly known and mostly unstudied. With the Lake Nyos disaster in mind, surface waters of lakes cannot show if CO_2 is stored in the bottom waters. So, there's a still lot of work to do! The VOLADA data base will be available for the scientific community through the **VHub page (CVL group)**, and hopes to become an interactive and open-access tool for many users. VOLADA will be presented during CVL8.

The **Facebook page of the Commission on Volcanic Lakes** has become an important billboard, especially for students in Latin America (Costa Rica e.g., 443 followers). Activities and links are continuously posted on this forum.

Dr Dmitri Rouwet,
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We hope to see you all at the next CVL9!

The future of CVL depends on your hard work

CONTACTS

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IAVCEI-VHUB -CVL-Group:	https://vhub.org/groups/iavceicvl
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