Volcanic lakes: the more you know, the less you need

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Volcanic lake research boosted after the 1986 Lake Nyos (Cameroon) lethal gas burst, a limnic rather than a volcanic event. This led to the foundation of the IAVCEI–Commission on Volcanic Lakes, which grew out into a multi–disciplinary scientific community since the 1990s. I here introduce the first data base of volcanic lakes, containing over 300 lakes. In my opinion, this number is surprisingly high, which implies that many of the lakes were mostly unknown, or at least unstudied to date. Some acidic crater lakes topping active magmatic–hydrothermal systems are monitored continuously or discontinuously. Such detailed studies have shown their usefulness in volcanic surveillance (e.g., Ruapehu, Yugama, Poás). Others are Nyos–type lakes, with possible gas accumulation in bottom waters, and thus potentially hazardous. Nyos–type lakes tend to remain stably stratified in tropical and sub-tropical climates (meromictic), leading to long-term build–up of gas, which can be released after a trigger. Many of the unstudied lakes are in the latter situation. In temperate climates, such lakes tend to turn over in winter (monomictic), liberating its gas charge yearly. Acidic crater lakes are easily recognized as active, whereas Nyos–type lakes can only be recognized as potentially hazardous if bottom waters are investigated, a less obvious operation. I will review and line out research strategies for the different types of lakes. A complementary, multi–disciplinary approach (geochemistry, geophysics, limnology, biology, statistics, etc.) will lead to new insights and ideas, which can be the base for future following–up and monitoring. More profound deterministic knowledge (e.g., precursory signals for phreatic eruptions, or lake roll–over events) should not only serve to enhance conceptual models of single lakes, but also as input parameters in probabilistic approaches. After more than 25 years of pioneering studies on rather few lakes ($\sim$20% of all), the scientific community should be challenged to take a step beyond and study the many poorly studied volcanic lakes, in order to better constrain the related hazard. The introduced data base of volcanic lakes should become an interactive, open-access working tool where our community can rely on in the future.

The Nyos Organ Pipes program: Lake Monoun has been completely degassed and Lake Nyos will be safe within five years

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For more than twenty years, a French team of scientists carried out a many-sided project to enhance safety in the surroundings of two gas-laden crater lakes, Monoun and Nyos, in Cameroon. The project included humanitarian, scientific and technical aspects, and was completed by the end of 2011. The degassing technique was first developed during an experimental period from 1990 to 2001. It was then applied on an industrial scale, during which a controlled removal of carbon dioxide from the two lakes was performed at a much higher rate than the natural recharge. The risk of another gas burst from these lakes has thus been eliminated.

Three columns (vertical pipes) were installed in Lake Monoun between 2003 and 2006, and the complete degassing was achieved in late 2009. At Lake Nyos, the first permanent column was installed in 2001 and has worked non-stop since then. Two supplementary columns of a larger diameter were added in 2011. The height of the fountains of water and gas, originally 50 meters, is reduced by now (January 2013) to less than 6 meters.

Due to the safety requirements, the stratification of each lake has to be carefully monitored, because of its definite influence on the stability of the lake water.

In Lake Monoun, the degassing process benefited from ideal circumstances. The salts of iron (iron carbonate, or siderite) were oxidized during the surface discharge and transformed into solid particles of ferric hydroxide, which precipitated down to the depths of the lake. The balance between the loss of the dissolved gas and the precipitation of salts, at a fairly higher temperature than the bottom one, results in a low density for the rejected water, which thus stays at the surface. A steady subsidence of all the layers of the lake is confirmed on the CTD profiles. The layers don't mix, and the stability of the lake is not put at risk.

In Lake Nyos, the dangerous layer, rich in dissolved gas and located between 185 m and 210 m, was removed during the years 2001-2011, due to the functioning of the first column. In the mean time, we observed that the surface layer (0 m - 50 m), originally perfectly differentiated from the underlying layers containing dissolved gas, underwent a de-stratification at the thermocline A mixing zone appeared between 70 m and 90 m. The impact of the de-stratification on the stability of the whole lake has to be monitored, especially because stability is greatly decreased due to the disappearance of the deeper layers, originally charged with dissolved gas.

This presentation describes some of the scientific and technical issues of the overall project and presents data pertaining to the response of certain limnological key parameters of the ongoing degassing process. The patern of the future Lake Nyos internal structure evolution was calculated using the efficiency of the extraction of water as inferred from the evolution of the gas concentration vs. depth distribution.

Chemical structure of Lakes Nyos and Monoun, Cameroon

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The explosive discharge of CO2 gas (limnic eruption) in the mid 1980s at Lakes Nyos and Monoun in Cameroon killed about 1800 people around the lakes. The driving force of the limnic eruptions was the CO2 gas dissolved in the lake water. A good knowledge of lake water chemistry and an elucidation of lake stratification are therefore important ingredients in preventing future limnic eruptions.

Water was collected at Lakes Nyos and Monoun in 2011 and 2012. Dissolved total-CO2 (CO2aq + HCO3-) concentration was determined by volumetric titration. The temperature, pH and dissolved O2 of lakes was measured in situ by use of CTD.

With the temperature and chemistry, Lake Nyos was roughly divided into 3 layers. In the first layer, shallower than -10m, the temperature reaches 25C due to solar radiation, while the temperature of the second layer (-10 to -70m) lies between 21.5 and 22C. In the third layer, deeper than -70m, the temperature increases gradually with depth, reaching 25C close to the bottom (-210m). Except for near surface water, dissolved species (total-CO2, Cl-, Br-, SO4–, Na+, K+ and Mg2+) show depth-concentration profiles that parallel those of temperature, except Fe and Mn, which were low in the first layer, and increased abruptly from -80m. The concentration of dissolved O2 was higher than 2 mg/L in the first and second layers, and less than 0.3 mg/L in the third layer, showing the anoxic environment.

In Lake Monoun, the first layer shallower than -10m was heated to 25C by solar radiation. The temperature of second layer (-10 to -50m) was uniform (19.5 to 20C). In the third layer (-50 to -80m), the temperature increases gradually towards the bottom. In the fourth layer (-80 to -90m) the temperature was uniform (22C). In the fifth layer, deeper than -90m, the temperature increases gradually towards the bottom of the lake at -100m. Like for Lake Nyos, depth-concentration profiles of chemical species in Lake Monoun parallel those of temperature. The dissolved O2 concentration was higher than 1 mg/L in the first layer and less than 0.2 mg/L in the layers deeper than -10m.

The CO3– concentration can be thermochemically estimated based on the total-CO2 and pH. The estimated concentration was multiplied with Fe concentration to make the product, Q (a_Fe*a_ CO3), which was compared with K, the solubility product of FeCO3. The water of Lake Nyos was estimated to be under-saturated in terms of FeCO3 in the first and second layers but oversaturated in the third layer. In Lake Monoun, the water deeper than -30m was oversaturated thoroughly. In Lake Nyos, the deep water has been lifted up to surface by the degassing pipes and Fe(OH)3 precipitate was generated, making the color of lake red after April 2011. The Fe(OH)3 precipitate sinks to third layer then dissolved to be Fe2+ ion due the anoxic condition. The increased Fe2+ ion meets with the high carbonate ion, resulting in the condition of oversaturation in terms of FeCO3

Estimation of vertical profile of dissolved CO2 concentration in Cameroonian volcanic lakes using sound velocity of lake water

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Limnic eruptions in 1984 and 1986 at Lakes Monoun and Nyos in Cameroon were caused by sudden degassing of magmatic CO2 dissolved in the lake water. The disasters killed about 1800 residents around the lakes. To prevent further disasters, monitoring of CO2 in the lake waters is essential. Until today CO2 measurement has been done only once or twice a year because the methods of CO2 measurement require chemical analysis of water samples, and are not suitable for more frequent measurement. For this reason, we are trying to develop a simple and convenient method of CO2 monitoring as part of SATREPS project supported by JICA and JST. In the field of engineering sound velocity (SV) has been proposed to measure salt concentration (Kleis and Sanchez, 1990). We applied the method to dissolved CO2 (CO2(aq)) assuming the following formula

v+ =k1[CO2(aq)]+k2[HCO3-], where v+ is a term additional to SV due to dissolved ions, and k1 and k2 are the empirical coefficients that we should determine by experiments.

Laboratory experiments

To determine k1, a SV profiler (Minos X) with a SV sensor, thermometer, and pressure sensor were placed in a cylindrical stainless vessel filled with pure water. Then, high-pressure CO2 gas was injected into the vessel to produce carbonated water. Additional term v+ was defined as the difference of SV between carbonated water and pure water under the same temperature and pressure. CO2(aq) concentration was calculated using Henry's law. The result indicated that v+ [m/s] was proportional to CO2(aq) concentration [mmol/kg], and the coefficient k1 was found temperature (T) dependent with a regression equation of k1 = 0.033-0.0005*T [m kg/s/mmol].

Field survey

Depth profiles of SV, pressure, T, and electric conductivity of Lakes Nyos and Monoun were measured in March 2012 using the SV profiler. The profiles of total CO2 concentration was determined by the syringe method (Kusakabe et al., 2008). Using these data and the correlation between [HCO3-] and electric conductivity proposed by Kusakabe et al. (2008), k2 was determined to be 0.091 at Lake Nyos and 0.067 at Lake Monoun. Then, CO2(aq) concentration was calculated using the k1, k2, SV, T, and electric conductivity. Comparison of the CO2(aq) profiles between the SV method and the syringe method indicated the accuracy of the SV method was better than +-10 mmol/kg. The accuracy is good enough for practical CO2 monitoring. We confirmed that the SV method is applicable to detect an abrupt change of the CO2(aq) profile that may be caused by sudden CO2 injection to the lakes. Concerning the set of SV, pressure, and T, we measured at 19 points at Lake Nyos and 14 points at Lake Monoun. All the SV profiles at Nyos were almost identical suggesting that lake water was stably stratified. On the other hand, the SV profiles at Monoun can be grouped into two patterns. It suggests that lake water in the west basin contains higher CO2(aq) than water in the east basin.

High CO2 enrichment in surface waters of MCL lake at Taal volcano, Philippines

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The active Taal volcano complex (the volcano island) lies in the middle of a large (15x22 km) prehistoric caldera filled with Lake Taal. The main crater of the volcanic island contains a volcanic lake termed MCL with a volume of 42 million m3 of slightly warm and acidic waters: pH:2.7-3.0, temperature: 30.5 C. About 6,000 people are living on the volcano island.

Echo-sounder surveys were carried in 2011 and 2012 to evaluate the activity of gas vents at the lake floor by measuring the backscattering strength of sound from ascending gas bubbles in lake waters. These surveys revealed an intense CO2 degassing by numerous sub-lacustrine fumaroles with about 60% of the lake's floor degassing. The analyses of the echograms show that a majority of the gas bubbles rising to the surface completely dissolve in the lake waters.

A miniaturized NDIR CO2 gas analyzer used for the first time for volcanic lake monitoring recorded high concentrations of free CO2 dissolved at the surface (10-20 cm depth) of MCL lake with 32-34 vol.% in January 2011 and 13-15 vol.% in January 2013 and shows that the lake surface waters are highly CO2 supersaturated with respect to the atmosphere (above mean values correspond respectively to 428mg/l of dissolved CO2 for 2011 and 181mg/l for 2013). The period of January -June 2011 was characterized by a high seismic activity and elevated CO2 flux of around 3000 T/day much higher than the background values of 650 T/day. The dissolved CO2 concentrations measured by the NDIR sensor are almost constant throughout the lake area (1.2 million m2) varying within a narrow range of values contrary to gas fluxes measured with the floating accumulation chamber.

The large temporal variations observed in CO2 flux and dissolved concentrations suggest that CO2 is a very sensitive indicator of activity at Taal volcano compared to other lake's parameters that remained almost constant during the period 2011-2013 (i.e. temperature, pH, chemistry). Contrary to sulfates and chlorides (and other solutes) which are largely conservative species in the lake waters; dissolved free CO2 has a more dynamic behavior in the lake (much like temperature). Its concentration reflects a steady-state balance between CO2 supplied to the lake by hot springs (in a dissolved form) and by direct degassing and CO2 lost by diffusion at the air-water interface. So, it is surprising that free CO2 is almost never determined in acidic volcanic lakes.

A test experiment of continuous monitoring of dissolved CO2 with the NDIR sensor started in January 2013. This research is made within the framework of a PHIVOLCS-EMSEV cooperation program.

Pinatubo lake chemistry and degassing 1991-2010

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Pinatubo volcano erupted violently in 1991, emitting about 1.7x 10^{10}t SO_2 during its June 15th Plinian eruption of VEI 6, leaving a caldera of approx. 2.5km diameter and 600m depth. Subsequent phreatic events and dome growth continued through 1992. A first small crater lake began to form in 1991. Water samples were collected and in-situ measurements of pH and temperature) made in 1991, 1992, 1994, 1996, 1999, 2000, 2001, and in 2010. We here summarize the data obtained during these surveys, and the current (2010) state of degassing, bathymetry and water chemistry of Lake Pinatubo.

In late 1992, the initial small lake had a significant acid-sulfate component from a possible hydrothermal component during ongoing dome growth, and anhydrite dissolution. Subsequently, this component was "drowned" and quickly overwhelmed by rainfall (2-4 m/y), groundwater draining from the crater walls into the lake, and a few neutral chloride crater wall springs. Prevalent bubbling of a predominantly CO_2 gas phase persists throughout the lakes history, indicating ongoing degassing of a remnant shallow magma related to the 1991 eruption.

Degassing was tracked by sonic bathymetry in 2010 throughout the lake, and appears to occur along linear features, at the 1992 dome, and diffusely along the entire shallow lake margin. Bubble trails in the deep portions of the lake lessen toward the surface, reflecting a process of ongoing dissolution. Dissolved CO_2 was measured in deep water samples taken in situ by two methods, a Niskin sampler, and samples from a hose lowered to depth and pumped from aboard the operators vessel into a closed evacuated vessel. CTD measurements in August 2000 found a strong inverted thermal stratification below 20m depth, reaching over 70°C at 50m depth above the submerged 1992 dome. By January 2001 the lake had homogenized and was much cooler (27°C at all depths), and it was again well-mixed and cool when re-surveyed in 2010. Crater wall fumaroles emit boiling-point hydrothermal gases dominated by water and CO_2.

Surface and ground water chemistry in the vicinity of Lake Nyos

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In the process to achieve overall objective within the SATREPS Cameroon Projects, whose general topic is "Magmatic Fluid Supply into Lakes Nyos and Monoun and Mitigation of Natural Disasters through Capacity Building in Cameroon", an investigation with the assessment of groundwater-surface water system was carried out in the vicinity of Lake Nyos.

On the field, sampling campaign was conducted in January and December 2011. During the survey, 45 water samples were collected from 27 sites. At each sample site, on-site measurements of electrical conductivity (EC), pH, oxidation-reduction potential (ORP), and alkalinity were carried out. The EC value of spring and stream water samples in the watershed other than Nyos Lake were less than 8 mS/m, and some of them are even less than 2 mS/m. Whereas, the stream waters in the watershed of Lake Nyos show high EC values, which were over 10 mS/m. Water sources with low EC values may have no influence from neither the carbonate-rich lake Nyos water nor magmatic carbonate.

The chemical composition of waters in this area is far different from those in other volcanic areas. Bicarbonate is exclusively dominant among anions with very low concentration of chloride < 2 mg/L, and almost no sulfate, which shows only little contribution of air-borne sea-salt and lack of sulfuric sources in this area. For cation and silicon, which are the major rock constituent, the concentration of magnesium is secondary dominant to silicon, and calcium or sodium is relatively low.

Those analytical data set was subjected to multivariate statistical analysis to understand the geochemical potential factors affecting the chemical composition. The variation of major elements was compressed by principal component analysis (PCA) into three principal components. Using thermodynamic calculation, those components were interpreted; the first component was interpreted as silicate dissolution with 50 percent proportionate contribution of all chemical variances. The second component was moderately contributed by Cl and NO3, which was understood as influence of anthropogenic activity or inhabitation of fauna. The third component was understood as iron and magnesium dissolution by carbonic acid under reduced environment. The atmospheric sea-salt influence or hydrothermal contribution was statistically negligible.

The PCA scores of each sample clearly classified the samples into highly carbonate-influenced and non carbonate-influenced waters. The combination between PCA scores and pH-ORP diagram shows that the chemical behavior of dissolved iron and manganese are strongly influenced not only by carbonate concentration but also by pH-ORP conditions. The combination between PCA scores and thermodynamic stoichiometric calculation based on water-rock interaction introduced the theoretical equation "[Si] = 2[Na+] + 1/2 [Mg2+]". This equation fitted well to the analytical data and successfully demonstrated the water chemistry in this area.

Ruapehu Crater Lake: Latest developments of a long temperature record

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Regular temperature records of Ruapehu Crater Lake date back nearly 50 years, but we are still finding new ways to use them to better understand what is happening in the volcano.

The major heat loss from the lake is by evaporation, so the formula used for evaporation is critical for estimating the volcanic heat input to the lake. Recent experiments with a weather buoy have shown that the lake keeps the air above it significantly warmer and wetter, which lowers the evaporative loss. By tracing the history of evaporation equations, it seems that some of the disagreements in this area are due to equations that were formulated from lakes with weather stations on the lake being applied to lakes where the weather information was gathered away from the lake.

The surface temperature of Ruapehu Crater Lake varies between about 20℃ to 60℃, with a tendency to cycle on a 6-12 month basis. It is not surprising that a hot crater lake has sometimes been an eruption precursor, although before telemetered dataloggers were installed the statistics were rather biased by how willing observers were to approach the lake. However, it has also been observed that there is an increased likelihood of an eruption when Ruapehu Crater Lake has a long cold spell. It was assumed that this was because the low heat input was often caused by a blockage in the volcanic vent, but it is only in the last few years that we have had a way of confirming this, by estimating vent temperatures from the ratios of certain gases in lake water samples.

Since a phreatomagmatic eruption in late 2007, water samples have been analysed approximately monthly for their solute gas contents, and it is noteworthy that H_2/Ar and CO/CO_2 ratios have coherently followed lake temperatures over much of this period, with CO/CO_2 equilibrium temperatures ranging between 350 and 700℃. Since mid-2012, however, the curious development of high CO/CO_2 equilibrium temperatures in the absence of any thermal cycling appears to point to the formation of such a blockage. We are waiting to see whether this situation resolves itself by an eruption or not.

Hydrological evolution and chemical structure of a hyper-acidic spring-lake system at White Island, NZ

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White Island has a long and varied history of acid spring discharge and shallow ephemeral lake formation on the Main Crater floor. In the 12 months prior to the 1976-2000 eruptive episode, mass discharge from the spring system increased ca. 10-fold, pointing to a strong coupling of the hydrothermal environment to the evolving magmatic system. However, between 1976-1978, numerous eruption vents to 200 m depth periodically formed in the Western Sub-crater, and these abruptly changed the hydrostatic regime of the volcano, resulting in the reversal of groundwater flow in the massif towards the newly-formed crater(s). This affected not only the style of volcanic activity (leading to phreatic-phreatomagmatic-magmatic eruption cycles), but also led to the demise of the spring system, with total flow from the crater declining by a factor > 100 by 1979. Eruptive activity came to a close soon after moderate Strombolian activity in mid-2000, by which time ephemeral lakes had already started to form in the eruption crater complex.

Since 2003 there have been two complete lake filling and evaporative cycles, reflecting varying heat flow through the conduit system beneath the lake. Over these cycles, lake water concentrations of Cl and SO_4 varied between ca. 35-150 and 5-45 g/l respectively, with pH values ranging between +1.5 and -1. Springs reappeared on the Main Crater floor in 2004, and their discharges have varied with lake level, pointing to the lake seepage being a primary control over the piezometric surface in the crater area. Springs closest to the crater complex show direct evidence of crater lake water infiltration into the crater floor aquifer, whereas distal spring discharges show compositional variations reflecting vertical displacement of the interface between shallow, dilute condensate and an underlying acidic brine fluid. Evidence suggests that this acid brine presently contains a significant component of altered seawater.

Monitoring magmatic-hydrothermal activity with rare earth elements in crater lakes

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A survey of available data from active, crater-lake hosting volcanic-hydrothermal systems worldwide suggests that REE budgets of the lake waters largely depend on the mode of rock dissolution and on the extent of alteration, processes that are directly related to fluid properties. A rough correlation between REE patterns of lake waters and local rocks testifies that lavas and pyroclastics in the volcanic edifice are the principal source of the REE. In general, the correspondence is closest for highly acidic lakes. Observed fractionation systematics among the REE demonstrate that complete, congruent dissolution is rare and only occurs under extreme conditions.

Alteration minerals, formed during water-gas-rock interaction, exert significant controls on REE budgets as well. We infer that alunite often plays a critical role in regulating the signatures of dissolved REE, even though this mineral is commonly not stable in acidic volcanic lakes. Because the saturation state for alunite is inversely correlated with temperature, the REE signatures of a lake reservoir may be inherited from inflow of water that had interacted with this mineral in hotter parts of the hydrothermal system at depth.

Time-series results on REE concentrations in the ultra-acid and highly dynamic crater lake of Poás (Costa Rica) provide evidence for intermittent effects from alunite in the subsurface system. Strong fluctuations in LREE/HREE ratios, observed over decades of monitoring, probably reflect variations in its stability, induced by shifting hydrothermal conditions. Changes in the REE concentrations sometimes coincided with phreatic eruptive events. Given the secondary character of alunite, its presence or absence may affect the porosity and permeability of volcanic rocks and conduits that act as pathways for upward flowing fluids. Evidence from Poás suggests that the formation of alunite may have a sealing effect that reduces the influx of fluid and heat into a lake. Our findings highlight the potential of REE in crater lakes as a versatile monitoring tool for subsurface processes in underlying magmatic-hydrothermal systems.

Thermal and chemical changes in the crater lake of Copahue volcano (Argentina) prior to the December 2012 phreatomagmatic eruption.

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Copahue volcano is part of the Caviahue caldera (Argentina-Chile), located in the Southern Andean Volcanic Zone. During the last 250 years, at least 12 low-magnitude phreatic and phreato-magmatic eruptions occurred and affected the nearby villages. The onset of the last eruptive cycle started on December 22nd 2012. During the hydrothermal activity phase, Copahue volcano hosts a hot acid (30-40℃, pH∼1) crater lake with a diameter ∼200 m. Two acidic hot springs (V1 and V2, pH=1-2) on the eastern flank, located at about 200 m below the crater rim, enter the Upper Rio Agrio (pH∼2) that discharges into the acidified (pH∼3) glacial Lake Caviahue.This study presents the temporal variations of the physical-chemical parameters of the Copahue crater lake along with those of the V1 and V2 thermal springs and the Upper Rio Agrio since 2004, i.e. prior to the phreatomagmatic eruption that occurred at the end of 2012.

In July 2004, ∼80% of the lake surface was frozen probably for the first time, while hot springs displayed the highest temperatures: 81℃ V1 and 69℃ V2. From the lake water the deposition of gypsum, quartz, cristobalite and amorphous silica increased. This process likely produced a mineral cap able to partly isolate the lake from the uprising magmatic fluids, explaining the frozen lake in that period. By the end of 2004 the crater lake surface melted again, and during the following years (2005-2010) it had temperatures between 30 and 40℃, while the outlet temperature of the two hot springs had dropped and remained relatively constant (T_{V1}=60-70 ℃, and T_{V2}=40-50℃). Between 2005 and 2011, the crater lake had no significant changes in temperature, and water level. On the other hand, anions related to the dissolution of magmatic gases progressively increased. Similarly, the discharge rate of fluids from the Copahue summit increased since November-December 2011. In March-July 2012, the crater lake and hot springs were characterized by pH<0, relatively high temperature (65℃) and high concentrations of magmatic-related species (SO_4^{2-}, Cl^-, F^- up to 42000, 18500 and 2000 mg/L, respectively). The level of crater lake water significantly dropped, and before the December 2012 eruption the lake had become very small (∼20 m in diameter). Liquid native sulfur was recognized in the erupted pyroclastic material, suggesting filling of voids beneath the lake or a molten sulfur pool at the lake bottom. As the eruption continued, the crater lake disappeared, the hot springs were covered by a pyroclastic surge and the course of Upper Rio Agrio was modified. Presently, a geochemical monitoring of the acidic springs and Rio Agrio is carried out to forecast the evolution of the volcanic activity at Copahue.

The factors that control the long-term sustainability of a hot crater lake: Insights from a generic numerical model

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Hot crater lakes at volcanoes act as condensers of heat and volatiles released from magma bodies. Monitoring of physical parameters such as water level and lake temperature provides a means of quantifying the amount of heat and mass discharged from volcanoes. Pasternack and Varekamp (1997) showed that most steady-state volcanic lakes are unlikely to maintain a temperature in excess of 45-50 degree C unless the precipitation rate is more than 5,000 mm/yr, as required to achieve a mass balance, whereas the 1st cater at Nakadake in Aso caldera, central Kyushu, Japan, contains a hot crater lake with a water temperature of 60-70 degree C during periods of volcanic calm, in an area with average annual rainfall of 3,000 mm.

To understand the factors that control the long-term sustainability of a hot crater lake, we developed a generic numerical model of such a hot lake based on the conservation of mass and enthalpy. Temporal variations in the characteristics of the lake are investigated by performing numerical simulations of various crater shapes to identify the factors that control the sustainability of the lake.

The results of numerical simulations show that water level and temperature are controlled mainly by the enthalpy of bottom input fluids, the ratio of bottom input mass to lake surface area and crater topography. Suitable factors for the long-term sustainability of the crater lake are found even if the lake temperature exceeds 40-50 degree C. In the case that lake surface area is constant with changing lake level (e.g., a cylindrical crater), the lake is stable against perturbations in water temperature and level. However, in the case that the surface area varies with level (e.g., a conical crater), the mass and energy balances vary with level. Hence, in a conical crater, a decrease in water level results in increasing temperature due to reduced evaporation associated with reduced surface area of the lake, thereby leading to a further decrease in water level. This positive feedback causes shrinkage of the crater lake even in the case that the input of bottom fluid remains constant.

The modeling results explain how the hot crater lake at Aso volcano has been maintained with water temperatures in excess of 70 degree C for over 1,500 years: we consider that stable emissions of volcanic fluid from the crater bottom have continued throughout this period of volcanic calm, which is appropriate size of the crater topography.

Temperature stratification and geothermal heat flux into deep caldera lakes Shikotsu, Kuttara, Tazawa and Towada

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Temperature profiles over the stratification period between July and November 2007 allowed a quantification of the acquired heat geothermal heat fluxes into the deepest waters of four caldera lakes. Because of their enormous depth, heat input from the lake bed was locally separated from heat fluxes from the surface. Hence, geothermal heat input could be measured directly. Two lakes showed a geothermal heat flux of 0.29 or 0.27 W/m2 (Lake Shikotsu and Lake Tazawa), as found in other regions not affected by volcanism, while both other lakes (Lake Kuttara and Lake Towada) showed enhanced heat input of 1 or 18.6 W/m2, respectively. Within our investigated set, all lakes acquired more heat from the underground than the continental heat flux average. Hence, the heat flux into the lakes from the ground was not dominated by the average temperature gradient implied by the inner heat of the Earth. Other effects like the general temperature difference of deep lake water and the groundwater or local sources of heat in the underground deliver more important contributions. Obviously the flow of water in the underground can play a decisive role in the heat transport into the deep waters of lakes.

Biogeochemical processes involving dissolved CO_2 and CH_4 at Albano, Averno, and Monticchio meromictic volcanic lakes (Central-Southern Italy)

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Meromictic lakes hosted in non-active volcanoes may store large amounts of gases, mainly CO2 and CH4, produced by: (i) sub-lacustrine hydrothermal vents or (ii) microbial activity. The occurrence of a gas reservoir in the deep layers favours a clear vertical chemical and isotopic stratification.

This study focuses on the chemical and isotopic features of dissolved CH4 and CO2 in four meromictic lakes hosted in volcanic systems of Central-Southern Italy: Albano (Alban Hills), Averno (Phlegrean Fields) and Monticchio Grande and Piccolo (Mt. Vulture). The δ13C-CH4 and δD-CH4 values of dissolved gases from the maximum depths (from -66.8 to -55.6‰V-PDB and from -279 to -195‰V-SMOW, respectively) suggest that CH4 is mainly produced by microbial activity. The δ13C-CO2 values of Grande, Piccolo and Albano (from -5.8 to -0.4‰V-PDB) indicate a significant CO2 contribution from sub-lacustrine vents originating from (i) mantle degassing and (ii) thermometamorphic reactions involving limestone, i.e. the same CO2 source feeding the regional thermal and cold CO2-rich fluid emissions. In contrast, the relatively low δ13C-CO2 values (from -13.4 to -8.2‰V-PDB) of Averno seem to indicate prevalent organic CO2, although preliminary δ13C values in CO2 discharged from nearby thermal springs (Stufe di Nerone), consistent with those of Averno, support the idea that this restricted area is characterized by an isotopically anomalous carbon source. On the whole, the chemical and isotopic compositions of dissolved CO2 and CH4 at different depths in the four investigated lakes mainly depend on (i) CO2 inputs from external sources, (ii) CO2-CH4 isotopic exchange and (iii) methanogenic and methanotrophic activity. In the epilimnion, vertical water mixing, free oxygen availability and photosynthesis cause the dramatic decrease of both CO2 and CH4 concentrations. In the hypolimnion, where the δ13C-CO2 values progressively increase with depth and the δ13C-CH4 values show an opposite trend, biogenic CO2 production from CH4 tends to counteract the methanogenesis process which is particularly efficient at the water-sediment interface. Theoretical δ13C-TDIC values, calculated on the basis of δ13C-CO2 values, are not consistent with those measured, indicating a lack of equilibrium between CO2 and the main C-bearing ion species (HCO3-) likely due to the fast kinetics of biochemical processes involving both CO2 and CH4.

This research demonstrates that the vertical patterns of (i) CO2/CH4, (ii) δ13C-CO2 and (iii) δ13C-CH4 can be regarded as promising tools to detect perturbations possibly affecting aerobic and anaerobic layers of meromictic volcanic lakes, such as changes in the CO2 input from sub-lacustrine springs.

A physico-chemical study of the Gulf of Kabuno which highlights the risk of a cataclysmic gas explosion

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The gulf of Kabuno, located in the northwest corner of Lake Kivu (DRC), shows a particular configuration that sets its waters apart from those of the main basin. The gulf, 140 m deep, is almost landlocked; it is linked to the main lake by only a narrow passage, the threshold of which is only twenty meters deep. Therefore, the gulf is a lake in its own right, and the physicochemical characteristics of its waters are completely different from those of the waters of Lake Kivu.

Two experimental surveys were carried out in August 2007 and September 2008 to study the physico-chemical stratification of the gulf's waters. The critical part of the experiments consisted in obtaining the concentrations of dissolved gases (carbon dioxide, methane and hydrogen sulphide) as a function of depth, down to 140 m. This study relied on the technique known as "Pan pipes" that we used on the Cameroonian lakes and improved on Lake Kivu. From the concentration profiles of dissolved gases we can deduce the partial pressures of each gas, and finally the total gas pressure. This quantity determines the risk of gas eruption.

The classic CTD profiles (Conductivity, Temperature, Depth) were also performed by adding a partial pressure sensor for methane, which allowed us to deduce the dissolved methane concentration at any depth. When analyzing our results, it clearly appeared that the total gas pressure (the sum of partial pressures) was very close to the hydrostatic pressure at a depth of only 12 m. We are currently faced with a dangerous risk of a limnic eruption; the situation is similar to the one prevailing at lakes Nyos and Monoun in Cameroon before the catastrophic gas releases.

Using a bathymetric map and data giving the concentrations of dissolved CO2 at each depth, we were able to deduce that the total carbon dioxide content in the gulf is 2.92 km3, i.e., almost 10 times the amount of gas in Lake Nyos (0.3 km3).

The Gulf of Kabuno is located in a densely populated area and the city of Goma (one million inhabitants) is only 15 km away. Moreover, the gulf is located on a highly seismic area and threatened by the lava flows from the neighbouring volcano Nyamulagira, of which three flows reached the gulf during the past century. It seems obvious that we must take seriously in consideration the risk of a limnic eruption at Kabuno, which could prove much more deadly than that of Lake Nyos. We therefore proposed to the authorities of the Democratic Republic of Congo a plan aimed at degassing safely the gulf in a controlled way. A project is under discussion with the Ministry of Environment of the DRC.

It turns out that an experimental degassing column, 200 mm diameter and 120 m long, was anchored in the gulf of Kabuno in 2008. The self-siphoning process was easily started by using the "gas-lift" procedure. A water and gas fountain showing a white and sparkling appearance gushed to a height of 80 cm. This demonstration column is still functional today (January 2013).

Acoustic emission of Tarissan boiling Lake, La Soufriere de Guadeloupe

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The Tarissan pit, located at the summit of the andesitic dome (1530 AD eruption) of La Soufriere of Guadeloupe (West Indies), represents a very active thermal zone of the geothermal system, characterized by a deep acid boiling lake. The surface of the lake constitutes a dynamic and complex interface where energy exchanges takes place between the lake and the pit.

In 2011, we recorded simultaneously the acoustic noise inside the boiling lake with two hydrophones, and the ambient seismic noise at the dome summit and slope with seismic sensors, in order to recognize a signature of the lake activity. The frequency signature of this acoustic noise is extremely rich and exhibits several resonant frequencies. We highlight in our analusis energetic frequency bands from noise cross-correlations between the stations. In particular, we show that the frequency centered around 3.2 Hz is measured at each station, and can be attributed to the Tarissan boiling lake. We use the seismic array installed on the dome flank to localize the noise source and we show that it very likely comes from the Tarissan pit, i.e. from the boiling lake.

We present a summary of these different observations and discuss the hypothesis that a model based on collective oscillations of bubbles can explain this source of noise. Remote recording of this noise could thus informs about the activity of the hydrothermal system.

Specific features of the microbiota in the crater lake of east Kamchatka

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Investigation of recovery of centuries-old biota in the basin of the caldera lake and thermal basins of maritime territories is of interest in various aspects (including estimation of time necessary for recovery of trophic chains and description of conditions necessary for the development of volcanogenic-sedimentary formations of ancient calderas using a method of actualism). Over the period of 12 years the author has distinguished two stages of algae successions (Lupikina, 2005, 2008) with dominating allochtonous element and shifted at the 8th year seasonal complexes with dominating Bacillariophyta. Just as in previous years of investigations of biotic variations in Karymskoye Lake, we pay special attention to taxonomical composition and the amount of phytoplankton and periphyton on the south and north shores of the lake. The paper contains the data on standard horizons in winter-spring and summer time collected in Tokareva Crater and the central part of the lake using bathometer and the total amount of cells obtained using a net. In 2010-2011 the samples were collected periodically and hydro-chemical analyses were made with delay. The obtained results allow drawing the following conclusions. In spring time the representatives of Aulacoseira italica i.s. and A. Subarctica (O. Mull) Haworth were dominating in the water layer at S1 station. The amount of them reached 100-4500 cells per liter in bulk samples. Single specimens of valves of Cyclotella tripartite Hakansson and catenulars of Fragilaria pinnata Ehr., F. crotonensis Kitt accompanied them. Rare representatives of Cyanoprokaryota and Chlorophyta were not distinguished to species, but according to the size of single cells (no more than 2.5 mkm in diameter) they should be attributed to autotrophic planktonic forms. Over the period 2010-2011 a distinctive feature of diatoms complexes from the crater lake was a high concentration (from 20 to 62 percent) of teratological forms among Diatoma, Flagilaria and Synedra. We revealed four forms of anomalous formation of shells in several species and considered that they related to proteome and were the indicators. For the first time, transmission electron microscopy allowed us to reveal at ultrastructural level anomalies for single representatives of Aulacoseira and Stephanodiscus from Karymskoye Lake in pre-catastrophic (1976) period. This information is introductory, while detail morphological descriptions are archived. The author is sure that crater microorganisms will be attractive to biologists of different specialities, including geneticists and ecologists, who have interests in cause-and-effect relation.

Evaluating magmatic volatile input in Taal volcano´s Main Crater Lake and Lake Taal, using combined geochemical and hydro-acoustic techniques

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Taal Volcano is a complex volcano 60km south of Manila, capital of the Philippines. The volcano has developed at the centre of a large caldera, filled with Lake Taal (15x22km). It contains a 1.5x1km lake in its largest crater, called the Main Crater Lake (MCL). The MCL is warm (T = 30℃), acidic (pH = 2.7-3) and has a Cl-SO4-Na composition. Gas bubbles are visible at the lake surface. Lake Taal is slightly colder (T = 27℃), alkaline (pH = 8.0) and composed mainly of Cl, HCO3 and Na. It suffers from episodic fish kills for which the cause is currently unknown. Both lakes incorporate seawater from a marine source.

Three field campaigns have been set up in January 2011, September 2012 and January 2013. The chemical composition of the MCL is relatively stable in time, showing variations of less than 10% for most major elements since the early nineties. Its large volume makes the MCL relatively inert to changes in fluid input compared to smaller crater lakes. Temperature, conductivity and pH do not vary with depth, excluding stratification of the MCL.

The concentration of dissolved CO2 in the MCL was measured using three different methods. In situ measurements were performed using a miniature IR sensor, headspace samples were analysed in the lab with an IRMS and a headspace variant has been developed for use in the field with gas detector tubes. Preliminary results show a decrease in dissolved CO2 from 428mg/l in 2011 to 181mg/l in 2012 and 181mg/l in 2013. All concentrations are in strong disequilibrium with the atmosphere. Therefore, residence times are short and the dissolved CO2 concentration can vary quickly in response to changes in in- and output.

The episode of elevated dissolved CO2 in 2011 coincides with a period of elevated seismic activity and high CO2 flux from June 2010 to July 2011, when PHIVOLCS raised the alert status for Taal Volcano twice from 1 to 2 (scale is 0-5). In January 2011, the CO2 flux emitted by the lake surface, measured by a floating accumulation chamber, was 2903T/day, whereas the 672T/day measured in 2012 falls in the range of background values from 500 to 800T/day.

The MCL was surveyed with a single-beam sonar to produce images of sublacustrine fumarolic activity, which were analysed for their volumetric concentration in gas bubbles on the lake floor. Individual profiles were interpolated over the entire lake using kriging to evaluate the spatial distribution of fumaroles. Areas with very low fumarole density can clearly be distinguished from more active zones for both 2011 and 2012. Many fumaroles that were active in 2011 show a decrease in activity or have gone extinct in 2012.

A surface profile of Lake Taal parallel to the shores of the volcanic island points out several areas of decreased pH and elevated temperature and conductivity. These observations demonstrate the input of subaerial or sublacustrine hot springs modifying the chemistry of Lake Taal, on at least a local scale.

An interactive web-based database application for collaborative collection, storage and retrieval of data on volcanic lakes

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Regular or occasional monitoring of volcanic lakes has yielded a growing quantity of data sets on compositions and other parameters that characterize their properties, behavior and potential changes over time. Much progress is made in volcanic lake research, but further steps in more comprehensive and statistical data analysis or data mining would be beneficial to fundamental and applied studies, in particular those focusing on hazard mitigation. Here, we introduce an interactive web-based database application for the collection, storage and retrieval of data on volcanic lakes aimed at serving the scientific community in this field.

The tool is designed for an open web-based environment to allow
(1) fast and robust gathering and storage of new or existing data into a structured, relational database by any researcher with the right of entry using state-of-the-art security and data-safety technology, (2) easy and intuitive data retrieval without access limitations by any user from the volcanological community at large using state-of-the-art web interfaces while providing registered users with additional features, and (3) a time-efficient and easily transferable management routine. Database building is community powered under supervision of (an) expert moderator(s) to secure quality requirements.

The application can handle a wide range of geochemical, physical and other observational data relevant for volcanic lake studies. Features include a comprehensive, intuitive spreadsheet-based interface for both data entry and retrieval. Data can be downloaded in a format suitable for the common spreadsheet programs, if needed, after prior evaluation in tabular form or visualized as a graph on the web page. Flexibility is ensured for the user-defined selection of parameters and their order in output files and for the units preferred for concentration, temperature and other data, to be converted automatically from the original input data.

Currently, the tool is in the late beta-stage of development and virtually ready to use. Potentially interested users are invited to provide suggestions for further refinements of the database and application design and additional features to maximize versatility. We believe that this interactive database application can facilitate progress in our understanding of volcanic lakes and will serve as a resourceful instrument in the collaborative effort to maximally utilize data from past and future field-based research.

Conductivity distribution of the surface layer in the northern Aso Caldera

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Kagiyama and Morita(2008) proposed that volcanism has a wide range of diversity represented by two typical end members controlled by the easiness of magma storage beneath volcano; Eruption dominant (ED) volcanism in difficult condition and Geothermal activity dominant (GD) volcanism in easier condition. In GD volcanoes, magma stagnates beneath volcanoes and maintains geothermal activity. This seems GD volcanoes continue to give much benefit to human society. However, GD volcanoes sometimes have large eruptions after repeated stagnations of magma. This fact suggests it is very important to understand where and why magma stops ascending. Kagiyama and Morita (2008) indicated magma degassing is one of the important factors to control magma ascending. On this aspect, the authors have carried out VLF-MT survey around some active volcanoes in Japan, because electrical conductivity of ground strongly depends on the conductivity of pore water.

Aso Caldera has an acid crater lake in Nakadake, which is one of the post caldera cones, and has many hot springs such as Uchinomaki, Akamizu. Conductivity distribution shows two typical features; caldera floor has almost homogeneous and high conductivity (> 10mS/m), while the post caldera cones show wide range. Most cones such as Kishima-dake and Ohjo-dake have lower conductivity (<3mS/m), except around Naka-dake Craters and western flank of post caldera cones such as Yoshioka and Yunotani (>30mS/m). Kusasenri Volcano, located between Naka-dake and Yoshioka has also rather high conductivity (3-10mS/m). These areas locate along the E-W trend of the major post caldera cones. Most part of the northern flank of the post caldera cones shows low conductivity (<3mS/m). However, higher conductivity was found around Sensuikyo, just north of Naka-dake Craters. This suggests down flow of hydrothermal water from Naka-dake Craters to the caldera floor.

Caldera floor has almost homogeneous conductivity. This feature is explained by the fact that the caldera floor was under the lake until 9 ka and is covered by lake deposit. However, extremely high conductivity was found at three areas (>50mS/m). Two of them correspond hot spring areas; Uchinomaki in the north and Akamizu in the west. The third area is distributed around old post caldera cones, Mietsuka. The age of these cones was estimated around 46 ka, and no hot spring is distributed. High conductive zones, Uchinomaki, Mietsuka and Naka-dake are located along the NNW-SSE line. Hydrothermal water may be supplied along this line.

These results suggest that hydrothermal water is supplied along the E-W trend crack from Naka-dake to Yoshioka, mainly supplied beneath Naka-dake, and expanded to the northern caldera floor. The NNW-SSE trend from Naka-dake to Uchinomaki may suggest a tectonic fault. Aso has wide high conductivity area and degassing in Aso might be large to be GD volcano.

Fluid injections at a crater lake of Aso volcano

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An active crater at Aso volcano, Japan, is typically filled with green colored hot water, which is seen as a crater lake. The water is sometimes dried up and then an eruption occurs. Although these two stages seem to be quite different, both may be same in essential quality. The author applied the cross correlation method of infrasound and seismic signals (Ichihara et al., 2012) to data observed at the small events of gas emissions in 2011, and also the data after the eruption period. As a result, clear patterns of cross correlation functions (CCFs) during the eruptive period, May-June 2011, could be recognized; a stable node of the cross-correlation functions was positioned around Δt=0, and the seismic data had a $\pi/4$ phase delay relative to the infrasound. It suggests that infrasound signals were generated at the gas emissions and they thus induced ground motions at local area around the station, although we could not identify the signals from the original infrasound wave traces. Characteristic patterns of CCFs were also identified several times after the eruptive period, when the crater was perfectly refilled with hot water. The patterns in these post-eruption periods had different features from the ideal ones; the maximum value of the CCFs was seen at the lag time far from the expected $\pi/4$ phase delay of the seismic data, and the position of the node was not same as those during the eruptive period. In some cases, the seismic data had a phase ahead of that of the infrasound. From numerical calculations, it was confirmed that these seemingly-peculiar features are owing to continuous tremors in the background (Takagi et al., 2009). When the patterns of CCFs were observed, whether they were affected by the background continuous tremors or not, the source location of the infrasound signals were determined as the central part of the crater based on analysis of infrasound network data. Therefore, it is interpreted that some kind of events which emit infrasound signals also occurred in the crater after the eruption. One possible candidate of this infrasound source is an ejection of thermal fluids into the crater lake from the bottom, which made the water surface just above the vent swing. If much stronger ejections occur, we will be able to observe them as jets and/or ash plumes through the water surface such as the 2003 and 2004 eruptions (Miyabuchi et al., 2005). In order to clarify this hypothesis, we should carefully monitor the seismic signal relating to the fluid movement as well as the temporal change of the temperature and the water level of the crater lake, and compare them to the results of the cross-correlation analysis. In the presentation, the author also would like to discuss time relation between migration processes of volcanic tremors based on the amplitude ratio analysis of seismic signals (Taisne et al., 2011) and the fluid injections interpreted from patterns of CCFs.

Water flow and circulation in crater lakes of Kusatsu-Shirane volcano, Japan, as studied by using radioactive cesium as a hydrological tracer

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The Kusatsu-Shirane volcano, located in the main island of Japan and about 150 km northwest from Tokyo, is one of the famous active volcanoes in Japan. It has three crater lakes named Yugama, Mizugama and Karagama on its summit. The water chemistries of the three crater lakes have fluctuated according to the volcanic activity of the volcano. The water of Yugama, which is the largest and deepest one of the three, is strongly acidic due to the injection of hydrothermal fluids from the subaqueous fumaroles at the lake bottom. The waters of the other two crater lakes, which are small and shallow, are weakly acidic although there are no visible hydrothermal activities in those craters. The water chemistries of the three crater lakes are expected to be controlled by the hydrothermal system beneath the summit and the water circulation system at the summit area because there are no rivers flowing into and flowing out from the craters.

The Fukushima Dai-ichi Nuclear Power Plant (FDiNPP) suffered serious damage by the huge earthquake and subsequent tsunami on 11 March 2011, and released large amounts of radioactive materials into the environments. The FDiNPP is located in Fukushima prefecture, the northeast Japan, and about 240 km east-northeast from the Kusatsu-Shirane volcano. In this study, we carried out preliminary measurements of the radioactive cesium in surface soils, lake waters and sediments in and around the crater lakes of the Kusatsu-Shirane volcano, and investigated the potential of the radioactive cesium as a tracer of water circulation of the crater lakes and the surrounding environment.

Both Cs-134 and Cs-137 were detected in the majority of the analyzed samples. The detection of Cs-134 reveals that radioactive materials originated from the FDiNPP accident had been transported and deposited on the summit area of the Kusatsu-Shirane volcano. For example, the activities of Cs-134 and Cs-137 in the Yugama water were estimated to be about 50 and 60 mBq/L, respectively at the end of May, 2012. The secular change of the content of radioactive cesium and its content ratio to stable cesium, Cs-133, may be a good indicator of the water circulation in the crater lakes.

The activity of radioactive cesium in the Karagama water was about one-fifth of that in the Yugama water. In addition, non-uniform distribution of radioactive cesium in the surface soils surrounding the lake was observed. The vertical profiles of radioactive cesium in the soils suggest that the cesium from the FDiNPP accident has not penetrated into the soils at this time, staying at the ground surface. Meanwhile, Cs-137 most probably originated from the global fallout before the 1980s has distributed at around 20 cm below the surface. The horizontal and vertical profiles of radioactive cesium in the soils of the craters may give us hints on understanding for water flows in the crater of the Kusatsu-Shirane volcano.

Variation of water isotopes and control mechanisms in lakes of the Cameroon Volcanic Line (CVL), Cameroon (West-Africa)

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The water in most crater lakes is meteoric in origin. Due to their peculiar setting, their water sometimes mixes with volcanic fluids that migrate from depth to the Earth surface. Monitoring the physico-chemical characteristics of these volcanogenic structures provides useful information which can be used to forecast volcano-related hazards. This study is part of an overall objective aimed at setting up a base line geochemical data bank for risk assessment and volcano-related hazard mitigation in Cameroon following the lakes Nyos and Monoun gas explosions that killed about 1800 people in the mid-80s. Lakes Nyos and Monoun are among the about 38 crater lakes located on the CVL. The lakes occupy either maars or depressions dammed by lava flows or pyroclastic materials underlined by alkalic and/or calcic crystalline basement. In the southern coastal region, the lakes experience an annual rainfall up to 11 000 mm while those in the north receive one order of magnitude less precipitation. This write up reports the isotopic composition of 8 crater lakes. The study indicates that, while isotopic variation in rain is marked by negative gradient northwards due to the continental effect, a South-North isotopic enrichment of +0.90 per-mil/100km is instead observed in lake water. Unlike in rainfall where isotopic composition is influenced by the altitude effect, no such effect is discernible to the isotopic signature of lake water. Among the lakes, d18O and dD vary from -1.91 to 14.4 per-mil and from -33.95 to -7.18 per-mil respectively while intra-lake variation is characterized by the presence of an isotopicline that separates heavy isotopically enriched surface water from depleted bottom water. We ascribe this enrichment to the South-North aridity increase characterized by a negative gradient rainfall/evaporation (P/E) ratio.