

Temporal geochemical variation in Ethiopian Lakes Shala, Arenguade, Awasa, and Beseka: possible environmental impacts from underwater and borehole detonations

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ABSTRACT

We present chemical analyses of 25 major, minor, and trace elements in 59 water samples from four lakes and five streams in central Ethiopia. Our major-element data extend to 2003 the intermittent series of measurements that reach back 40 to 65 years for Lakes Shala, Arenguade, Awasa, and Beseka within or adjacent to the Main Ethiopian Rift. Our minor-element and trace-element data help establish baselines for future monitoring of these four lakes.

Water chemistry was analyzed using samples taken in Lake Arenguade and Lake Shala both before and after detonation of submerged explosive charges as part of an active-source seismic survey of the Main Ethiopian Rift. Our data demonstrate no clear impact on the chemistry of Lake Shala from a 900-kg detonation suspended in the water column, whether from dispersal of the explosive charge in the body of water, or from mixing of the lake, or from stirring up of bottom mud into the lake water. In contrast, some changes in the chemistry of Lake Arenguade, most notably a decrease in Na and K concentration of 15 – 20% occurring between 1 and 11 days after detonation of a 1200-kg charge placed on the lake bottom, may possibly be ascribed to reaction between lake water and sediment stirred up by the detonation. However, these chemical changes that are potentially caused by our seismic detonation are significantly smaller than the natural variations in lake chemistry documented by long-term records.

Additionally, we found no change in water chemistry of samples taken from Lakes Awasa and Beseka and from several streams both before and after nearby borehole detonations of 50 to 1775 kg.

Detonating explosive charges underwater greatly enhances seismic data quality. Bottom charges stir lake-bottom sediments into the water column, perhaps resulting in temporary changes in lake chemistry. Our borehole and suspended lake charges had no measurable chemical or lasting environmental effects. These ‘negative’ results – the lack of alteration of lake habitats consequent on seismic detonations – are a positive outcome.

INTRODUCTION

Need for, and consequences of, underwater seismic detonations

Seismic survey design favors underwater detonations as being both cost-effective and energy-efficient (Kohler & Fuis, 1992; Jacob et al., 1994) because source coupling is an order of magnitude greater in water than in rock. The incompressibility of water allows for very efficient energy transfer from underwater shots compared to detonations in boreholes, which use much of their energy in fracturing rock. It is also cost-effective to shoot in lakes whenever possible because much of the cost of a field experiment is attributable to shot-hole drilling (Kohler & Fuis, 1992). This cost-efficiency is particularly significant for the very largest seismic controlled sources, which may therefore only be logistically feasible in lakes, e.g. a 5-tonne shot detonated in the Dead Sea, Israel (Gitterman & Shapira, 2001) and 18-tonne shots in Siling Tso (lake), Tibet (Huang et al., 1991).

Underwater shots should be detonated at the “optimum depth”, sufficiently deep that energy is not lost from a large plume of water at the surface, but not so deep that the surface ghost (the reflection of the upgoing energy from the water surface) is substantially delayed from the initial pulse. Shots that are too shallow also tend to produce high-frequency energy that is relatively rapidly absorbed during propagation, as opposed to lower-frequency energy that can more readily propagate the several-hundred kilometers necessary for observing seismic waves that penetrate deep into the crust or upper mantle. In practice these considerations mean that

shots of the order of 1 tonne (the size typically used in crustal refraction experiments) require water depths of some tens of meters (Burkhardt & Veas, 1975). Detonations in much shallower lakes or rivers may not provide substantially more far-field radiated energy than detonations in boreholes.

Although more energy-efficient and cost-efficient, lake shots may potentially cause biological and chemical damage to the lake and the surrounding area. Chemical changes from underwater detonations could result from introducing chemicals into the lake waters from the explosive and its packaging, from mixing stratified lake waters, or from incorporation of bottom mud into the lake water by the detonation. Possible biological consequences include direct mortality due to the shock wave, or indirect mortality due to chemical changes consequent on a detonation.

Previous experiments have studied the biological impacts of lake shots throughout the United States. Detonations for seismic studies have been permitted in lakes of special scenic, scientific, and biological value, such as Yellowstone National Park (Braile et al., 1982; Smith et al., 1982) and Mono Lake (Hill et al., 1985) with no noted biological impact. Detailed environmental studies have documented minor fish kills due to detonations; one such study by the U.S. Geological Survey analyzed a group of 22 shots totaling 45 tons and found that the average mortality was 55 game fish, with a total weight of approximately 8 kg per ton of high explosive (Stuart, 1962). A careful study by members of the Kenya Department of Fisheries and Wildlife in Lake Baringo, Kenya, found only two dead fish following a one-tonne lake shot in Lake Baringo during the Kenya Rift International Seismic Program in 1985 (Prodehl et al., 1994; M. Aftab Khan, pers. comm., 2002).

Although the biological impacts of underwater detonations have been studied prior to our experiment, to the best of our knowledge no detailed study of the chemical response to underwater detonations has been published. A general assessment of environmental consequences of 25 lake detonations in Alaska (U.S. Geological Survey, 1988; G. Fuis, pers. comm., 2002) noted no significant changes in alkalinity, hardness, conductivity or pH. However, there was a temporary decrease in dissolved oxygen in the upper few feet, and a temporary

increase in suspended solids by an order of magnitude or more, with a rapid decline towards the original values over the following two days. Clearly, there remains a dearth of data and documentation regarding chemical effects from the detonation of underwater lake shots.

The Ethiopia-Afar Geoscientific Lithospheric Experiment (EAGLE) (Maguire et al., 2003; Maguire et al., 2006) was a controlled-source wide-angle reflection/refraction experiment in Ethiopia conducted in January 2003, using a total of 18 borehole shots and two lake shots (Figure 1). At the request of the Ethiopian Environmental Protection Agency we made an in-depth examination of the two lakes in which large underwater shots were fired (Shala and Arenguade), and we also examined the water chemistry of two lakes (Awasa and Beseka) and five streams beside which borehole shots of various sizes were detonated. A previous seismic experiment in 1971 had utilized submerged shots in Lake Arenguade and the Awasa River (Burkhardt and Vees, 1975). Measurements of water chemistry were not made in association with the 1971 experiment.

Scope of study

Our study compares the results of chemical analyses from samples taken before and after seismic detonations. The precision of modern analytical methods is such that there are inevitably apparent differences in chemistry of nominally identical samples. An uncritical comparison of results from samples taken at different times or depths may suggest systematic time- or depth-dependent chemical changes when or where none exist. Most of the changes before and after our seismic detonations do not exceed the accuracy of our analytical methods. In order to assess the significance of the few apparent changes that exceed expected analytic uncertainty, we present a comprehensive listing of all prior measurements of chemical composition of the studied lakes (Loffredo & Maldura, 1941 *cit.* Talling & Talling, 1965; Talling & Talling, 1965; Prosser et al., 1968; Baumann et al., 1975; Chernet, 1982; Von Damm & Edmond, 1984; Kifle, 1985 *cit.* Zinabu et al., 2002a; Wood and Talling, 1988; Kebede et al., 1994; Zinabu, 1994; Gizaw, 1996; Reimann et al., 2002; Zinabu, 2002a; Zinabu & Pearce, 2003) (Table 1). By demonstrating that the magnitude of all apparent changes lie within previously established natural chemical variability of the lakes, we establish that, for the most part, there are no discernible chemical consequences of our seismic experiment (Tables 1, 2, and 3; Figures 2 and 3). Some measured

changes in the chemistry of Lake Arenguade, although less than the long-term variability within that lake, may nonetheless represent effects of our seismic detonation (Table 3; Figure 3)

Thus this paper serves twin purposes: we gather together all available chemical data on Lakes Shala, Arenguade, Awasa and Beseka; and we document the minimal environmental impact of seismic detonations on these lakes as a case study intended to facilitate permitting of future seismic experiments in any lakes. In addition our study provides limited new data on water chemistry in central Ethiopia, a region plagued by water scarcity and poor water quality (e.g. Gizaw, 1996; Reimann et al., 2002). Our minor- and trace-element data help to establish baselines against which to monitor future changes in the health of the lakes (e.g. Zinabu, 2002b). Our major-element data lengthen existing time series of chemical analyses of the lakes that may demonstrate both anthropogenic and climatic effects on ecosystem chemistry and productivity (e.g. O'Reilly et al., 2003). Finally, although over a dozen prior papers have previously reported chemical data from the Ethiopian lakes that we studied, many of these papers have published analyses of single water samples. By presenting analyses of as many as a dozen samples taken from a single lake on the same day, we help determine the extent to which the different results of previous authors represent true environmental change as opposed to analytic uncertainty or natural sample variability due to incomplete mixing.

Limnology of studied lakes

Tudorancea et al. (1999) present a comprehensive review of Ethiopian limnology. Lakes Shala (in older literature called O'a), Awasa and Beseka (also called Metahara) (Figure 1) are all located within the Main Ethiopian Rift of the East African Rift system. Lake Arenguade (sometimes called Hora Hado or Green Lake) is a crater lake on the western margin of the Rift (Figure 1). General lake morphology and chemistry of these four lakes have recently been reviewed by Baxter (2002): all currently function as closed basins or terminal drainages in a region of rainfall deficit (evapotranspiration exceeds precipitation) in which a wet season approximately from March to September alternates with a dry season from October to February. All four lakes are alkaline (8.5 to 10 pH units, Table 1) and saline (Shala: 17 – 22 g/l, Awasa: 0.8 – 1 g/l; Beseka: ~50 g/l in 1961, ~ 5 g/l in 1091; Arenguade: 5 – 6 g/l: Wood & Talling, 1988; Kebede et al., 1994), due in large part to evaporative concentration. In all four lakes the

concentration of major cations is, in decreasing order, $\text{Na} > \text{K} > \text{Ca} > \text{Mg}$ in contrast to most lakes in temperate regions in which $\text{Ca} > \text{Mg} > \text{Na} > \text{K}$ (Tudorancea et al., 1999). The unusual abundance of alkali elements is presumably related to their high concentrations in the trachytic and rhyolitic volcanic rocks that blanket the flanks and floor of the Main Ethiopian Rift: the Late Miocene-to-Pliocene Nazret peralkaline pantelleritic ignimbrites and their correlatives are several hundred meters thick at or near the surface across the entire area of interest (Abebe et al., 2005). The high volcanic CO_2 flux throughout the Main Ethiopian Rift leaches Na and K from these rocks, and also causes precipitation of calcium carbonate, further increasing the Na/Ca ratio (Gizaw, 1996). Previous studies in Shala, Awasa and Arenguade suggest that a superficial (chiefly 0 to 3 m) thermal and chemical stratification generated daily by solar heating in calm weather is most likely diurnal, breaking down overnight and reforming over the course of the day (Baxter et al., 1965; Prosser et al., 1968; Wood et al., 1984). Aquatic micro-flora and fauna of the lakes are discussed in detail in Tudorancea et al. (1989) and Tudorancea & Taylor (2002).

Lake Shala, the deepest of the Ethiopian Rift lakes, has an average depth of 87 m (maximum 266 m) (Baxter, 2002) and has filled the 13 x 25 km O'a caldera since its formation c. 240,000 years b.p. (Mohr et al., 1980). Ongoing hot-spring and fumarolic activity on all sides of the lake presumably shares the same underlying cause as the minor Holocene pumice and basalt outcrops around the lake (Mohr et al., 1980). Lake level was >100 m higher 5000 years ago than at present, and separation of the modern Lake Shala from Lakes Abijata and Langano immediately north and west only occurred in the last 2000 yrs (Benvenuti et al., 2002). At present Lake Shala receives its water from the Adabat River from the southeast and the Gidu River from the west, with additional contributions from nearby hot springs (Baumann et al., 1975; Baxter, 2002). Baumann et al. (1975) argue that the relative ionic content of the hot springs around Shala matches that of the lake, so that Lake Shala can be regarded as a mix of freshwater and hot-spring water. In addition to a superficial (0 – 3 m) diurnal stratification, Baxter et al. (1965) intermittently found a moderate discontinuity in temperature and dissolved oxygen above 20 m depth, but inferred that at least some mixing extended to their maximum sample depth, 90 m. Baumann et al. (1975) inferred stratification from different ion concentrations at the surface and at depth, and from a thermocline at 50 to 70 m water depth. The sparse algal flora is dominated by diatoms (Kebede, 2002). Fish are rare (there is not even

subsistence fishing in this lake) but we collected a small-sized fish (probably *Aplocheilichthys* sp) during our study (Mengistou, 2004); this and *Oreochromis niloticus* are the only two species yet described from Lake Shala (Golubtsov et al., 2002). The Shala-Abijata “Rift Valley Lakes” National Park was established to protect the feeding and breeding ground for over 350 migratory and resident species of birds.

Lake Arenguade, an alkaline soda lake with a diameter of approximately 800 m and average depth of 19 m (maximum 32 m), is one of the shallower Bishoftu lakes located in and around the town of Debre Zeit, about 50 km southeast of Addis Ababa (Prosser et al. 1968; Baxter et al., 2002). The maars (volcanic explosion craters) hosting the Bishoftu lakes probably formed within the last 250,000 years (upper Pleistocene to Holocene) (Mazzarini et al., 1999), possibly about 7000 years ago (Mohr, 1961, cit. Tudorancea et al., 1989). Lake Arenguade’s crater rim, rising up 200 m above the lake, shelters it from winds and probably helps it maintain superficial (~ 0 – 3 m) thermal stratification for much of the year (Talling et al. 1973; Baxter et al., 2002). Baxter et al. (1965) found no deeper chemical or thermal gradients of note in Lake Arenguade. Lake Arenguade is named (Arenguade = green in the Oromigna language) for the dense production of the filamentous blue-green alga (cyanobacterium) *Spirulina platensis* (*Arthrospira fusiformis*) (Kebede, 2002), which in some years sustains a large breeding population of lesser flamingos (Mengistou et al., 2003). Local people use the lake for laundry and ablutions, water their cattle at the freshwater springs feeding the lake (Mengistou et al., 2003), and even encourage the cattle to drink the lake water believing that the *Spirulina* water has therapeutic effects and compensates for some lack in the diet of their cows (Kebede, 1997).

Lakes Awasa and Beseka, by contrast, fill shallow depressions of little tectonic or volcanic significance (though Beseka is bounded by a lava dam: Kebede et al., 1994), and have average (and maximum) depths of 14 m (23 m) and 6 m (11 m) respectively (Ayenew, 2004). Both are less saline than Shala and Arenguade, Awasa significantly so, to the extent that it supports a small commercial fishery (Golubtsov et al., 2002). Both lakes have grown in recent decades. Awasa increased its lake level by c. 2.5 m from 1976 to 1999 (and now threatens the town of Awasa), with a volume increase of c. 20% due to land-use changes resulting in increased runoff in its catchment (Ayenew, 2004). This volume increase is reflected in the 15 to 25%

increase in conductivity and decrease in ionic concentrations from the 1960s to the 1990s (Zinabu et al., 2002) (Table 1). The case of Lake Beseka (smaller in volume by a factor of c. 6) is more dramatic. Lake level has increased by >3 m from 1976 to 1997, and continues to rise at c. 15 cm/yr, requiring Ethiopia's main highway and only railroad to the Gulf of Aden to be raised on an embankment. From inception of the Metahara irrigation project south of the lake in 1964 to 1998, the lake area increased 13-fold, and lake volume 130-fold (Ayenew, 2004). The volume increase may be caused either by increased recharge from irrigation runoff and the higher levels of the River Awash maintained in recent years by Koka Dam (Ayenew, 2004), or by a combination of increase in recharge from submerged hot springs and decreased discharge due to an increase in groundwater level resulting from excessive irrigation downstream (Zemedagegnehu et al., 1999). The only chemical analysis of a hot spring close to Lake Beseka that we have found in the literature (United Nations, 1973 *cit.* Gizaw, 1996) is significantly more dilute (by a factor of c. 3) than even present-day Lake Beseka, implying that such hot springs could be a cause of the growth of Lake Beseka. The volume increase of the lake led to a 10-fold decrease in ionic concentration from 1961 to 1991 and concomitant shift in phytoplankton community (Kebede et al., 1994).

METHODS

Seismic methodology

Lakes Shala and Arenguade were identified as candidates for submerged detonations because of their geographic location with respect to the subsurface geological targets of the EAGLE program, their >20 m depth (desirable because it provides low-frequency seismic energy (Burkhardt & Veas, 1975) that propagates long distances), and their restricted or absent macrofauna. Lakes Awasa and Beseka were also favorably geographically located, but were known to support fish or larger vertebrates, so instead charges were placed in 50 m-deep boreholes within 200 m of their lake shores to take advantage of the shallow water table without risk of the shock wave causing significant mortality within the aquatic community.

Chemical explosives (an ammonium nitrate/fuel oil (ANFO) emulsion, sold as Powergel-C+ by ICI) were detonated in Lakes Shala and Arenguade, in boreholes adjacent to Lakes Awasa

and Beseka, and close to surface streams (Fig. 1). The detailed chemical analysis is proprietary, but the materials safety data sheets for the explosive states that ammonium nitrate makes up more than 60% of the explosive. “Cellulose starch, oils and other oxygen-negative materials”, stabilizer and “other inorganic oxidizers” each comprise 1-9% of the total weight. “Miscellaneous metal powder” and sodium perchlorate each account for less than 1%. Specific gravity is 1.1 to 1.35, and solubility in water is stated to be “negligible”. In an ANFO detonation under optimal conditions, a mixture of 94% ammonium nitrate (NH_4NO_3) reacts with 6% long-chain hydrocarbons ($\text{C}_n\text{H}_{2n+2}$) to form only the gases N_2 , CO_2 and H_2O . This 94% NH_4NO_3 – 6% $\text{C}_n\text{H}_{2n+2}$ mixture is the likely approximate composition of Powergel C+. In practice, such blasts also produce modest amounts of the gases CO , H_2S and nitrogen oxides (NO_x); but the vast majority of all products are vented from the lake or borehole as gases. The seismic shots also destroyed, fragmented, or dispersed the plastic sacks containing the Powergel-C+, the electrical caps, the detonating cord, the seismic boosters used to ignite the detonation, and the ropes used to suspend the explosive from the plastic buoys at the surface of the lake, all potentially leading to chemical contamination. All floating debris was collected for disposal following the detonation.

In Lake Shala, 1000 kg of explosives were suspended at a depth of 84 m (the optimum depth for generation of seismic energy for a 1 tonne charge: Jacob, 1984) in an area where the lake is approximately 100 m deep. The 1000 kg were split into ten 100-kg subcharges along a 210 m line. 900 kg of the ammonium nitrate explosive successfully detonated. Due to a break in the detonating cord the remaining 100 kg is presumed not to have detonated, but rather to have been dispersed in the lake due to detonation of the adjacent sub-charges. No waterspout was observed after the detonation, nor was any surface discoloration noted from disturbed bottom sediments. In Lake Arenguade, a 1200-kg dispersed charge was placed on the lake floor at a water depth of 31 m; the charge was split into four subcharges, all of which were completely detonated. A brief water-spout was noted, and muddy bottom waters rose to the surface and discolored the lake (Figure 4), but within 18 hours the original green color had been restored. In both lakes, the charges were placed in the lake less than 6 hours prior to the detonation.

The seven borehole shots within 200 m of lakes and streams had an average shot weight of 700 kg. They were placed in boreholes approximately 50 m deep, typically within about three days prior to detonation. Details of typical loading and firing procedures for borehole shots are given by Brocher (2003).

Water sampling

Water samples were collected in January 2003 in the hours preceding and following the detonation from the two lakes in which underwater detonations took place. Samples from “1 m” depth were taken at arm’s length beneath the surface; deeper samples were collected with a Van Dorn sampler. As a precaution, and despite no expectation that chemicals from explosive could contaminate nearby waters, we also monitored stream, irrigation-ditch and lake chemistry before and after each borehole shot, wherever surface waters were present within c. 200 m of a shot. A fifth stream was sampled adjacent to a small borehole shot in December 2002. All samples were filtered at the point of collection (with the exception, noted below, of the Lake Shala samples collected 24 hours prior to detonation) using a 0.45 μm Nalgene filter to remove any biological material and all but the very finest clay particles. Samples were stored in factory-new plastic Nalgene bottles, filled to overflowing to avoid any trapped air-spaces, for transport back to the United States.

Water sampling was carried out by eight separate teams whose highest priority was the safe preparation and detonation of the seismic charges on a precisely timed schedule. Some intended samples were not acquired because of lack of time before a scheduled detonation, and, due to misunderstandings, one sampling protocol (onsite filtering) was omitted for the set of samples collected from Lake Shala 24 hours prior to shot detonation. The samples collected from Lake Shala 24 hours prior to shot detonation (“T-24” in Table 2 and Figure 2) were hand-carried to Addis Ababa where, after one day, they were refrigerated for one week prior to filtering. It is possible that continued biological activity may have modified some elemental concentrations in these Lake Shala T-24hr samples. These T-24hr samples from Shala were collected before the explosives were placed in the lake; in contrast, the T-1hr Shala data and the T-3hr Arenguade data were collected after the explosives had been placed in the lake (before detonation), though by design the explosives should be substantially stable in water for at least

24 hours. In addition, samples from Lakes Shala and Arenguade were taken immediately after the shot and 10 days later; samples were collected at depths of 1 m, 10 m, 20 m, and 30 m below the surface (for Shala, also at 60 m and 90 m). Because logistical problems had prevented us from conducting significant sampling of Lake Shala before the detonation of that lake shot, we also sampled at a location 1 km from the shot location following the detonation, expecting that if the detonation had affected the lake chemistry, these distant samples would still be representative of the “before shot” chemistry. Even if the 1 tonne of explosive had been comprised exclusively of a single element, after dispersal out to 1 km radius in the 100-m deep lake it would raise the concentration of that element by only 0.003 ppm. Because analysis of our full dataset (Table 2) showed no spatial changes in chemistry between these distant samples and those at the detonation site, in all subsequent discussion we only consider chemical changes with time and combine these spatially separated samples accordingly into a single group “up to 24 hours after shot” (Tables 1 & 2; Figure 2).

Chemical Analyses

Samples were air-freighted from Ethiopia to the USA, and analyzed approximately 5 months after collection. All samples were acidified at Stanford using trace-metal–clean nitric acid, and allowed to equilibrate overnight to permit re-dissolution of any precipitates or materials adsorbed to the Nalgene bottles. A Thermo Jarrell Ash IRIS inductively coupled plasma optical emission spectrophotometer (ICP-OES) equipped with an autosampler was used to determine the concentrations of 23 elements (As, B, Ba, Be, Ca, Cd, Co, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Sr, Ti, U, V, Zn). A Dionex Ion Chromatograph (IC) with conductivity detection was used to determine the concentrations of Cl and SO₄. Basic principles of ICP-OES and IC analysis are given by Sparks et al. (1996) and Soil and Plant Analysis Council (2000). pH was measured, also 5 months after sample collection, using a Cole-Parmer pHTestr-3 digital pH meter.

We analyzed a total of 70 samples on the ICP-OES. A standard sample (Table 5) was analyzed for quality control after every fifth field sample to assess variability in the ICP-OES system. As standards we used NIST 1643c provided by the National Institute of Standards and Technology; and two solutions (“Salt Solution” in Table 5) that we prepared to include Ba, Fe, K, Mg, Na, PO₄, Rb, SO₄, SiO₂, Sr, Ti, and U NIST standards diluted to concentrations

approximate to those anticipated for our samples. The standards were alternated so each one was run as every twelfth sample. As estimates of our analytical uncertainties, Table 5 gives the mean and standard deviation for each solution on which we made multiple measurements.

The listed elements were analyzed to determine possible changes in lake chemistry. The major elements (e.g. Na and Cl) control the salinity, which together with temperature determines the water density, and so is a proxy for lake stratification. Trace elements were included in our survey due to their potential for large change by contamination from the shot materials. Because our initial concern, and hypothesis to test, was that we might contaminate water sources with trace metals from the explosive, we focused on obtaining accurate measurements of trace elements, and so did not dilute our samples prior to analysis. Our alternate concern and hypothesis, that any lake stratification might be disturbed by our seismic detonations, would normally be tested by absolute differences in major ion concentration. However, Na concentrations in Lakes Shala, Arenguade and Beseka, and Cl in Lake Shala, all exceed 1000 ppm, which is beyond the linear range of our chosen analytical methods. Unfortunately we did not collect a sufficient volume of sample for repeat analyses at greater dilutions to bring Na and Cl within the linear instrumental range. Although we calibrated the non-linear range of the ICP-OES and IC by analyzing reference solutions prepared with similar and even higher concentrations (up to 7000 ppm Na and 3000 ppm Cl), there remain significant uncertainties (at least $\pm 10\%$) in our reported absolute values of Na concentration in Lakes Shala, Arenguade and Beseka, and Cl in Lake Shala. Nonetheless, relative changes between different samples from the same lake still have diagnostic value, and allow us to demonstrate the lack of stratification with depth in Lakes Shala and Arenguade (the two lakes for which depth profiles were obtained). The lack of sufficient sample also precluded later measurements of other chemical species. For example, we initially chose not to measure nitrogen concentrations, because although N is the major element in the explosive, successful detonation should lead to complete conversion to N_2 and its rapid loss from the surface of the lake as gas bubbles; and we now lack any remaining sample to carry out this analysis.

RESULTS AND DISCUSSION

Concentrations of the analyzed elements for all samples are listed in Tables 2 and 3 for Lakes Shala and Arenguade, respectively, and in Table 4 for water bodies (including Lakes Awasa and Beseka) adjacent to our seven borehole shots. Selected results from Tables 2, 3 and 4 are plotted in Figures 2, 3 and 5 respectively. We found no systematic chemical change within analytical error with distance from a shotpoint or with depth in the lakes (no lateral variations in the lake and no obvious chemical stratification). We found possible evidence of systematic change in major element concentrations in the days following one of our detonations, SP31 in Lake Arenguade (Table 3, Figure 3), and this possible effect is discussed in detail below.

Inevitably there are differences in the chemical analyses between the different water samples taken at different times in the same place, or different places in the same lake at similar times. It is commonly hard to assess the significance of such changes, and whether they represent methodological differences and analytical uncertainty, or natural sample variability due to lack of mixing, or true changes in lake chemistry. True chemical changes might represent long-term environmental change whether natural or anthropogenic, or short-term changes due to our underwater and borehole detonations. In the absence of *a priori* knowledge of natural sample variability, the range of previously published values provides a range within which any variation in our 2003 dataset (from “before shot” to “after shot”) may still represent natural sample variability. Even if variations in our 2003 dataset are due to our seismic charges, because the ionic abundances remain within the previously measured range we are at least assured that we have not shifted the lake ecosystem beyond the natural range of environmental conditions.

Absence of stratification in Lakes Shala and Arenguade

Aside from seemingly random fluctuations, our results suggest a homogeneous depth distribution of major elements, and hence a lack of significant chemical stratification in both Lakes Shala and Arenguade for all sample times (Figures 2d & 3d; also Tables 2 & 3), in agreement with earlier results of Baxter et al. (1965), Prosser et al. (1968), Wood et al. (1984) and Baxter (2002). In contrast, Baumann et al. (1975) inferred water stratification from differing major-element concentrations at the surface and at depth (Table 1); however Baumann’s results lie within the range reported by other authors (Table 1), and have an internal variability no more

than the seemingly random variation we found between different samples (Table 2). Precise geographic location is also a potential factor in water chemistry, e.g. distance from the hot springs on the shore of Lake Shala or below the surface in Lake Beseka. Baxter et al. (1965) demonstrated lateral variations in temperature and dissolved oxygen in Lakes Shala and Awasa; and Zemedagegnehu et al. (1999) noted the existence of spatial isotopic gradients in Lake Beseka due to incomplete mixing. However, our vertical profiles in two locations in both Lakes Shala and Arenguade show no obvious differences.

Although in our dataset some major-element concentrations, e.g. K and Ca (Tables 2 & 3) show considerable unexpected variation between different samples, we found no systematic trends in composition associated with depth (Figures 2d & 3d) or location (Figures 2b & 3b) of sampling. The observed variability between different samples in our study (all collected within a two-week period) captures a significant fraction of the apparent long-term variability in some ionic species (Table 1) and so suggests caution in directly interpreting these previously published measurements as evidence of seasonal or long-term change in these lakes.

Apparent long-term variability of lake waters

The available major-element time series for Lakes Shala, Arenguade, Awasa and Beseka, including our new data, range from determinations on 16 separate occasions over a 65-year interval for Lake Shala, to just three determinations over 40 years for Lake Arenguade (Table 1, Figures 2a and 3a). The data show large variations between individual analyses from the same lake. We speculate that some of the changes may be more apparent than real, and may relate to variable sampling protocols, analytical methods or sample locations (commonly not documented in older publications), or simply natural variation (incomplete mixing) - see previous section. Significant seasonal effects cannot be ruled out, but have not yet been clearly documented: although Zinabu (2002a) suggested slightly higher Ca and slightly lower K and SO₄ concentrations in the dry season than in the wet season, almost ubiquitously his range of “dry season” concentrations overlaps with his “wet season” measurements (Table 1).

Our major element results (Table 1) confirm some previously recognized trends. As Lake Beseka grows in volume it continues to be diluted in Cl, though at a far lower rate than the factor

of ten over 30 years documented by Kebede et al. (1994). Mg and Ca appear stable. In contrast the c. 20% volume increase of Lake Awasa since 1976 (Ayenew, 2004) is not reflected in a clear trend in any of the major elements (Table 1). Lake Awasa is the only Ethiopian water body for which there are now three sets of heavy metal and trace element data (Table 4: Zinabu & Pearce, 2003; Reimann et al., 2002; this paper); but for only one (Sr) of 14 elements for which three observations are available over eight years is there a consistent decreasing or increasing trend, so we prefer to consider the existing data sets as expressing natural variability, or possibly analytical uncertainty, rather than long-term environmental change.

For Lake Shala, almost all our measured abundances match well the range of 16 previous measurements of major elements (Table 1) and the one previous suite of analyses of minor and trace elements (Table 2; Reimann et al., 2002). The notable exception is Cl, about one-third of previous reported results (Figure 2a). Because of the size of Lake Shala (36.7 km³: Baxter, 2002), it is hard to imagine changes to the entire water body sufficient to alter the lake chemistry by this amount; and because Cl is typically a highly conservative element, changes in its concentration should lead to corresponding changes in many other elemental abundances. We have no explanation for this discrepancy. However, our 23 sample results are internally very consistent, so that whether the cause of the discrepancy is true variation or our analytic or computational error, our data does not support chemical change due to our seismic detonation.

In Lake Arenguade we provide only the second repeat measurements of major elements in four decades, as well as the first ever analyses of minor and trace elements. Zinabu (1994) stated that “changes in the major ions of Lake Arenguade were minimal” despite reporting changes from April 1963 to April 1992 (i.e. ignoring the intervening 1964 measurements) in Na, K and Ca of -12%, +42% and +19%, respectively (as well as no change in Cl concentration). The statement that such seemingly large changes are “minimal” in part reflects the much larger, presumed anthropogenic, changes observed by Zinabu (1994) in some of the Bishoftu crater lakes closer to the town of Debre Zeit; he attributed the relative preservation of Lake Arenguade to the lack of human habitation within the drainage and the very steep crater walls that limit access. Our 2003 observations show relative stability of Na, a steep decline in Cl, and a reversal of the 1963-1992 trend in K, Mg and Ca (Figure 3a). K, Ca and Cl have all decreased by one-

third or more from their 1963-1964 values; Mg has remained approximately constant; and pH has decreased by c. 0.5 pH units (Table 1). We suspect that these ionic decreases are real, because all 20 of our analyses for K, Ca and Cl, comprising eight samples taken before and 12 samples taken after our seismic detonation, are well below the two independent sets of results available for samples measured in the 1960s (Prosser et al., 1968; Wood & Talling, 1988), and the third independent set from 1992 (Zinabu, 1994).

It is conceivable that a volume increase due to increased rainfall, lowered evaporation, or spring recharge has taken place to dilute Lake Arenguade in the 1990s, following a drying trend from the 1960s to 1980s. Lake Hora (or Biete Mengest), a crater lake of similar size to Arenguade and only c. 8 km north for which Zinabu (1994) found equivalent or larger changes in Na, K and Ca from 1962 to 1992, increased its depth by as much as 3 m from the late 1980s to the late 1990s (Lamb et al., 2002), possibly following a decrease in depth by a similar amount over the preceding 25 years. Based on the bathymetry presented by Prosser et al. (1968), a 3 m increase in water level at Lake Arenguade would increase the lake volume sufficiently to dilute a fixed quantity of solute by as much as 20%. A further possible example of climate change is the appearance, in 1968, of Lake Chelekleka in the vicinity of the Bishoftu crater lakes as a permanent water body for the first time in at least the preceding ten years (Teferra, 1980); and its persistence to the present (Kebede et al., 2002). Our very crude bathymetric observations in Lake Arenguade (point measurements at four locations during water sampling) did not detect any water depths greater than the 32 m maximum depth given by the 1963 soundings of Prosser et al. (1968) so are consistent with cyclic changes in lake depth and volume. Hence we can neither confidently reject nor definitively accept lake-volume changes as a cause of chemical changes between 1964, 1992 and 2003. Even if volume changes occurred, the different behaviors of different species are not easily explicable: a volume increase could explain the dilution of Cl, K and Ca (Figure 3a), but not the relative constancy of Na and increase in Mg. Rippey and Wood (1985) suggested that, in the Bishoftu crater lakes, Mg should be non-conservative due to authigenic aluminosilicate formation even while Ca and Na remain conservative (change concentration proportionally during evaporation). Though the Rippey and Wood (1985) model implies different behavior for different species, we still lack a satisfactory model to explain the differential changes among all the elements studied.

Chemical impact of underwater detonations in Lakes Shala and Arenguade

In order to assess whether our seismic detonations caused any effect on lake chemistry, we tested whether there were larger changes between samples taken at different times (before and after the detonations) or between samples taken at the same time (intra-sample variability). We looked for changes between the mean and range of concentrations sampled at three different times: before the detonations, in the succeeding 24 hours (“one day later”), and 11 to 13 days later. We focus on chemical species for which the mean concentration at one time was >1.5 standard deviations (σ) different from the mean at another time. However, for some trace elements the very low absolute abundance causes the standard deviation to be correspondingly small, in some cases below the repeatability of different measurements of our standard solutions (Table 5). For example, As in Lake Arenguade appears to drop by 1.5σ from before the detonation to 11 days after (Table 3), but the difference in mean concentration is <9 ppb, little more than the detection limit of 7 ppb or the 5 ppb deviation of our six repeat measurements on the standard solution. In addition, the relative standard deviation of some groups of samples (we only collected four or five samples before each detonation, and only four samples 11 to 13 days later) is smaller than the percentage uncertainty in concentration we estimate from repeat measurements of our standard solutions. For example, Cl in Lake Shala appears to increase by 1.8σ from before the detonation to 13 days after (Table 2), but the difference in mean concentration is only 4%, less than the 9% uncertainty in repeat determinations of our standard solution. Hence as additional tests of the significance of apparent changes in chemistry we also compare apparent differences to the absolute uncertainty in measurements, examine whether there is any overlap between the different groups of samples, carry out a t-test to distinguish whether sample populations are statistically different at or above the 95% level, and finally compare the apparent short-term variations to differences in the long-term published record.

For Lake Shala no systematic changes were observed either one day or two weeks after the shot (Figure 2b & c; Table 2). Elemental concentrations remained uniform within 1σ or better except for Mo and Zn ($+1.1\sigma$ and -1.3σ from before the detonation up to 24 hours after) and Ba, Cl and SO_4 ($+1.4\sigma$, $+1.8\sigma$ and $+1.8\sigma$ from before the detonation to 13 days after). For Mo and Zn these changes are not statistically significant; for Ba these changes are significant at

the 95% level. For all three metals, Ba, Mo and Zn, inter-sample variability is high and the range of measurements before the detonation overlaps with those afterwards, so we suspect this apparent variation is not the result of our seismic detonation. In contrast, none of the measurements of Cl and SO₄ on the five “before shot” samples are as large as any of the four measurements on the four samples collected 13 days after the detonation, and the changes between these two groups are very highly significant at the 99.9% level (Table 2). However, we suspect these changes in Cl and SO₄ concentration, though statistically significant, are not due to our seismic detonation as they are less than changes in Cl and SO₄ concentration found by other authors in the absence of detonations. Baumann et al. (1971) found larger percentage (and significantly larger absolute) variations in 11 samples collected in a single month (Table 1). Zinabu (2002a), in six samples collected over a decade (but presumably in the same location and with similar sampling and analytic methods), found >50% variability in Cl and five-fold changes in SO₄ (Table 1). Since we see no other corroborating chemical changes, and lack any model to explain why Cl and SO₄ concentration should increase while all other measured species remain statistically unchanged, we conclude that we detected no chemical effects in Lake Shala due to detonation of a 900-kg charge suspended in the water column c. 20 m above the lake bed.

For Lake Arenguade, most elemental concentrations also remained statistically constant from immediately before to immediately after the seismic shot (Figure 3b & c; Table 3). Elemental concentrations remained uniform within 1 σ or better from before the detonation up to 24 hours after except for Cd and Mo (+1.1 σ and -1.2 σ), of which only the change in Mo is statistically significant at the 95% level. We discount both apparent changes, because Cd concentrations are around 1 ppb, at the detection limit of the ICP-OES, and the apparent change only 0.2 ppb; and the change in Mo is only 1% (1 ppb), no greater than the repeatability of our standard solution (Table 5). We conclude that we detected no chemical effects in Lake Arenguade due to contamination by 1 tonne of Powergel-C+ and its packaging or due to mixing of any pre-existing chemical stratification, resulting from detonation of a 1200-kg charge placed on the lake bed.

In contrast to samples collected less than one day after the detonation, if we compare those samples collected from Lake Arenguade 11 days after the detonation with those collected

before the detonation, there are more numerous and larger variations in concentration, with As, B, Be, Cd, Cl, Li, Mg, Mo, Na, P, Pb, Sr, Ti, and V all changing by $>1\sigma$ (Table 3). The samples collected 11 days after the shot were collected by a different team of scientists on our behalf and could conceivably represent sampling artifacts, but we are not aware of any change in the collection procedure that would affect specifically these elements (the samples collected by the same team on our behalf from Lake Shala 13 days after the shot do not show comparable anomalies for these elements). Of this list of elements, B, Cl, Li, Mg, Mo, Na, and Ti have mean values 11 days after the seismic detonation that are statistically lower than the mean values before the detonation with high significance, at the 99% level or above, and have absolute differences in abundances greater than the repeatability of multiple measurements of our standards. All these elements decreased in abundance by $>20\%$ (except Cl, only 14%). Because some other elements (including Ca and Ba) increased in concentration, albeit by smaller amounts, we can probably rule out an unrecorded dilution of these samples. These "anomalies" do not follow any plausible patterns related to contamination, mixing of stratified waters, or changing biological productivity. However, the explosive charge was placed on the lake bottom, and large quantities of mud were visibly stirred into the entire lake (Figure 4). Two effects are possible: elements could be leached by lake waters from bottom mud which would increase elemental concentrations; or reaction of sediment particles with lake water could remove elements and decrease their concentration.

Yuretich & Cerling (1983) have shown that in Lake Turkana (an alkaline, slightly saline Rift Valley lake extending from Ethiopia into Kenya, pH 9.2) sodium is removed as an exchangeable cation on smectite, and magnesium may be incorporated into poorly-crystalline smectite. If smectite is present in the bottom muds of Lake Arenguade, stirring up large quantities of sediment into the water column should allow these exchange reactions to proceed, thereby depleting Mg and Na throughout the lake. The clays in Lake Turkana absorb sodium in a rapid Na-Ca ion exchange reaction while the sediments are in suspension, suggesting there should be a consequent increase in Ca; Lake Arenguade (Table 3, Figure 3b) does show a slight, but not statistically significant, increase in Ca between the levels before the shot and 11 days after the shot. In Lake Turkana illite may take up potassium (Yuretich & Cerling, 1983); Lake Arenguade (Table 3, Figure 3b) shows a large (20%) but not statistically significant decline in

mean K concentration from before the detonation to 11 days after the detonation. These “reverse-weathering” reactions have also been implicated by Von Damm & Edmond (1984) in the chemical balance of Lake Shala, in the sediments of which abundant smectite and illite have been found (Baumann et al., 1975). We see no significant changes in abundance of the trace elements for which Yuretich (1986) found a strong correlation with smectite and illite (Co and Ni); unfortunately we lack data on any association of B, Li and Mo (for which we do see post-detonation concentration decreases) with these clay phases. We also lack a good explanation for the very highly significant 14% decline in Cl from before the shot to 11 days after. Yuretich & Cerling (1983) believe that entrapment of evaporatively-concentrated water (in preference to dilute inflowing river water) by deposition of highly undercompacted sediments may be the significant Cl removal process in Lake Turkana, but this does not seem relevant to Lake Arenguade.

The very highly significant change in Na that we detected is consistent with interaction between lake water and bottom sediments mixed into the water by the detonation (Figure 4). The causative suspended particles would be the clay fraction $> 0.45 \mu\text{m}$, the size of the filter used during sample collection. The water samples collected 11 days after the detonation remained in reactive contact with this clay fraction on average 20 times longer than the samples collected < 1 day after the detonation. Although we lack data on the grain size and composition of bottom sediment in Lake Arenguade, in Lake Shala the mean grain size is $1 \mu\text{m}$ and the dominant clay type is smectite (Baumann et al., 1975). A simple mass balance based on a cation exchange capability of smectite of 1 meq/g (Yuretich & Cerling, 1983) shows that a 10 cm layer of smectite covering the bottom of Lake Arenguade, if completely dispersed into the water column by our detonation, is capable of explaining the measured decrease in Na. Ion exchange processes are rapid with essentially complete exchange occurring while sediments are in suspension in Lake Turkana (Yuretich & Cerling, 1983), which has an average depth of only 33 m, less than twice that of Lake Arenguade (average depth 19 m). $1 \mu\text{m}$ clay particles have a Stokes’ Law settling rate of less than 1 m/day, so would remain in suspension for the 11 days between the detonation and the final sampling. Although we lack a complete model for the observed changes to different species, we conclude that in Lake Arenguade it is at least plausible that interactions of bottom sediments with lake water temporarily disturbed the lake chemistry.

If indeed our seismic detonation disturbed the chemistry of Lake Arenguade, how long might this disturbance last, and how significant is it in comparison with long-term change? We have two time periods for comparison (Table 1, Figure 3a): 1960s-1992, and 1992-2003. During the former time period, a German seismic experiment in February 1971 detonated three seismic charges, of up to 1040 kg, on the lake-bed (Burkhardt & Veas, 1975b) that must have had at least the same and probably greater effects as our own detonation, if such effects exist. During the latter time period, no such events occurred. The significant changes before and after our seismic detonation were all decreases in concentration; in contrast, from the 1960s to 1992 K and Cl increased, and though Mg and Na decreased over the 40-year interval, Na did so by a proportionally smaller amount. Thus any equivalent disruption produced by the 1971 German seismic shots must have significantly (Na) or entirely (Ca, K) dissipated in the succeeding 20 years to 1992.

Not only must the major effects of seismic detonations dissipate over decadal time-scales, the magnitude of many of these effects is less than the long-term change in the absence of seismic detonations. In Lake Arenguade Cl apparently decreased by 15% and K and Mg by 20% over 10 days due to our detonation, but during the preceding decade Cl and K decreased by 50% and Mg doubled! Because the decadal changes are so extreme, repeat measurements made in Lake Arenguade will probably not be able to distinguish lingering chemical effects due to our detonation from long-term environmental change. Other evidence for major cyclical changes in lake chemistry unrelated to seismic detonations is the record of change in dominant phytoplankton. The loss of *Spirulina platensis* (*Arthrospira fusiformis*) from the phytoplankton community accompanying the gradual dilution of Lake Beseka (Kebede et al., 1994), and the known effect of high salinity in reducing *Spirulina* growth rates (Kebede, 1997), both suggest that *Spirulina* is a partial proxy for lake chemistry. Multiple reports from 1963 to 1966 documented an abundant unialgal suspension of the blue-green *Spirulina* with corresponding chlorophyll-a concentrations of 0.4-5 mg/l (Wood & Talling, 1988), and Zinabu (1994) found an overlapping range, 0.3-0.8 mg/l chlorophyll-a, from 1990 to 1992. Thus effects of the 1971 seismic detonations on biomass, if any, had been mitigated by 1990. Nonetheless, *Spirulina* had “nearly disappeared” from Lake Arenguade by 1998 but was “dominant and abundant” again in

2003 when observed both five days before and 11 days after the seismic detonation (Mengistou et al., 2003; Mengistou, 2004). Thus far larger changes occur naturally in phytoplankton communities than occurred within the 11 days following our detonation.

We conclude that mixing clay particles into Lake Arenguade may have leached many chemical constituents from the lake water; but these changes are temporary (certainly lasting less than a decade, perhaps lasting for only months), and in general are smaller than natural variations on this decadal time-scale. Nonetheless, since it seems possible that the observed chemical anomalies can be ascribed to our detonation, caution is indicated in future seismic experiments seeking to use bottom charges in soda lakes such as Lake Arenguade. Lakes with a more normal geochemical balance ($\text{Ca} > \text{Mg} > \text{Na} > \text{K}$), or lacking smectite bottom sediments, or having sediments with a larger mean grain size ($> 10 \mu\text{m}$), should be less susceptible to seismic disturbance.

Chemical impact of borehole detonations

For the samples collected from the five streams and two lakes (Lake Awasa and Lake Beseka) in close proximity to borehole shots (Fig. 1), large variations between individual water bodies were observed (Table 4, Figure 5), but samples collected at the same location showed negligible variations in concentration levels before and after the shots (always less than the estimated uncertainty in individual determinations). The five streams measured (Table 4) have major-element concentrations consistent with other streams from the Lakes region of the Rift Valley (Chernet et al., 1982; Table 5). For Lakes Awasa and Beseka, as for Lakes Shala and Arenguade, the difference between water chemistry before and after our detonations is small compared to the long-term variations in lake chemistry (major elements: Table 1; minor and trace elements: Table 4). We conclude that there is no evidence for water contamination by our borehole detonations.

Non-chemical impacts of detonations

No rock-fall, triggered seismicity, changes in stream-flow, or changes in hot-spring activity (only applicable to the Shala site) have been reported from any of our lake or borehole shots. At Shala, no wave run-up was observed (the detonation was 1 km offshore), and no effects

to lake-bottom-sediments were observed at the surface (no mud plume in the water). At Arenguade a tiny wave, < 10 cm in height, ran < 1 m up the shore at the point closest to the shot. Photographs and videos taken during the detonation show upwelling of bottom mud into the water column and spreading out across the lake surface (Figure 4), but within 18 hours all the visible particles appeared to have settled: no unusual quantities sediments were seen in the water samples taken the following day and the original green color of the lake had been restored. A comparison of data from one day before and two weeks after the detonations shows that the shallow oxygenated layer (above 5 m) deepened in both lakes, possibly due to surficial mixing, with resultant increase in primary productivity (Mengistou, 2004).

No significant shot-related biological impacts were observed in either lake. Although local inhabitants had previously reported that Shala had no fish population, a small school (<100) of small fish (< 5 cm) surfaced after the detonation, mostly stunned, though we found a few (< 10) dead individuals. The dead fish were collected for analysis immediately after the detonation, and later identified as probably *Aplocheilichthys sp* (Mengistou, 2004). Interviews with local people found no reports of dead fish along the shoreline after the detonation (Mengistou, 2004). No birds were in the vicinity of the shot at Lake Shala, and there was no impact on humans. Tens of people viewed the shot from shore without harm. At Arenguade, the crater was closed to non-science personnel and cleared of cattle immediately prior to the shot as a precaution against wave run-up, or triggered landslides. Over 100 people viewed the shot from the crater rim, without harm. Lake Arenguade has no fish population. After the shot, water-birds and those in trees inside the crater briefly took flight. At both lakes, a census two weeks after the detonations revealed an increase in bird populations compared to the census conducted the day prior to the shots, probably random variation, but possibly due to a near-surface increase in primary productivity (Mengistou, 2004).

CONCLUSION

Detonation of an explosive charge placed on the floor of Lake Arenguade dispersed mud throughout the lake, which may have interacted with the saline alkaline lake water to leach out numerous constituents. This reverse-weathering effect relies on the high salinity and alkalinity of

the lake waters, and also requires presence of smectite-illite bottom clays, so that explosive charges in more typical (more dilute) lakes elsewhere in the world, even if placed on the bottom, are unlikely to show the effects reported here. Detonation of an explosive charge suspended in the water column in Lake Shala produced no chemical changes that we could relate to the detonation.

A literature survey suggests that annual-to-decadal variations of the chemistry of Lake Shala (site of submerged detonation) and Lakes Awasa and Beseka (sites of borehole detonations) far exceed the trivial chemical changes found in this study. Even in Lake Arenguade, the change in lake chemistry from 1992 to 2003 dominates over any effects that might be related to our detonation, so further study and sampling probably cannot confirm the hypotheses presented here as related to the 2003 seismic detonation. It would be of geochemical interest to carry out an even more comprehensive study before and after any future seismic detonations in saline-alkaline lakes such as these.

Our survey of 25 major, minor and trace elements did not reveal any changes in water chemistry attributable to borehole chemical detonations, or attributable to an explosive charge suspended in the water column of Lake Shala. Thus, we do not find important environmental impact associated with chemical detonations in lakes or boreholes during active-source seismic surveys.

ACKNOWLEDGEMENTS

We gratefully acknowledge the help and co-operation of EAGLE participants led by Peter Maguire and Laike Asfaw. Gerry Wallace managed design, deployment and detonation of the submerged charges. Bill Teasdale provided safe management of the small boat operation, and Tom Burdette, Per Joergensen, Gray Jensen and Steve Harder collected surface water samples adjacent to borehole shots. Tilahun Mammo and Seyoum Mengistou collected additional samples from Lakes Shala and Arenguade. The Ethiopian Science and Technology Commission and the Ethiopian Environmental Protection Agency initiated this study, and the Fisheries and Aquatic Sciences Stream (FASS) at Addis Ababa University Department of Biology, in particular Dr.

Seyoum Mengistou, managed the biological censusing before and after the shots and provided the boats we used. At Stanford University, Karen McLaughlin helped prepare samples, Guangchao Li ran the ICP-OES, Ben Kocar and Matt Ginder-Vogel ran the IC, and Adina Paytan offered much helpful advice on water chemistry and analysis. Emma Mansley at University of Leicester measured chemistry of the “Stream 5” samples (Table 4). Stephen Boss and one anonymous scientist provided many helpful suggestions that materially improved this paper. US-EAGLE is funded by the NSF-EAR-CD-0208475.

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TABLES

Table 1

Chemical analyses, previously reported and from this work, for Ethiopian lakes Shala, Arenguade, Awasa, and Beseka.

Table 2

Chemical analyses of Lake Shala before and after seismic detonation suspended in the lake

Table 3

Chemical analyses of Lake Arenguade before and after lake-bottom seismic detonation.

Table 4

Chemical analyses of lakes and streams before and after nearby borehole seismic detonations.

Table 5

Standard and reference solutions used for ICP-OES and IC analysis.

FIGURE CAPTIONS

Figure 1

Sites for water-sampling superimposed on grey-scale relief map of central Ethiopia. Open stars are seismic shot-points. Streams were sampled at shot-points (SP) 14, 15, 16, 33 and “Test shot”; and Lakes Awasa, Shala, Beseka, and Arenguade were sampled at SP 21, 22, 26 and 31. (Lake Arenguade is smaller than the star signifying the location of the shot-point.) Main Ethiopian Rift lies between the inward-facing normal faults (black lines) down-dropped on the side of the short tick-marks (faults generalized from Bonini et al., 2005).

Figure 2

(a) Major-element determinations (Table 1) for Lake Shala from 1961 to 2003. Concentrations are in ppm, but note different divisors applied to each ion to allow visual separation of the curves. New results presented in this paper are shown with error bars of 5% (Ca and Mg), 10%

(K and Cl) or 15% (Na). Our January 2003 data are presented as the means of three groups of measurements: before the seismic detonation; up to 24 hours after the detonation; and more than one week after the detonation. These three groups are plotted at 2002, 2003, and 2004 to allow easy visualization, and their component values are given in Table 2 and plotted in (b).

(b) Major element and (c) selected minor and trace element concentrations (including those species for which potentially significant variation was found with respect to the seismic detonation in Lake Arenguade) and pH (see Table 2). Concentrations are in ppm, but note different divisors applied to each species to allow a visual separation of data. Error bars are standard deviations of the entire suite of 23 measurements of each ion/element for Lake Shala, and are intended to indicate significance of relative changes, not absolute uncertainties. Concentrations are plotted against sampling time with respect to the seismic detonation (h=hour, d=day). Samples collected 1 km from the shot location are indicated (D=1km). Numbers below pH values are water depths from which each sample was taken and also apply to data in (b). No statistically significant variation with location or depth or time is seen.

(d) Depth profiles for eight species from (b) and (c) above, to show the lack of stratification with depth. Dotted lines: samples collected 1 km from shot location; solid line: samples collected at shot point, both the day after the detonation. Concentrations are in ppm, but note different divisors applied to each species to allow a visual separation of data.

Figure 3

(a) Major-element determinations (Table 1) for Lake Arenguade from 1963 to 2003. Concentrations are in ppm, but note different divisors applied to each ion to allow visual separation of the curves. New results presented in this paper are shown with error bars of 5% (Ca and Mg) and 10% (Na, K and Cl). Our January 2003 data are presented as the means of three groups of measurements: before the seismic detonation; up to 24 hours after the detonation; and more than one week after the detonation. These three groups are plotted at 2002, 2003, and 2004 to allow easy visualization, and their component values are given in Table 3 and plotted in (b).

(b) Major element and (c) selected minor and trace element concentrations (focussing on species for which potentially significant variation was found with respect to the seismic detonation) and pH (see Table 3). Concentrations are in ppm, but note different divisors applied to each species to allow a visual separation of data. Error bars are standard deviations of the entire suite of 20

measurements of each ion/element for Arenguade and are intended to indicate significance of relative changes, not absolute uncertainties. Concentrations are plotted against sampling time with respect to the seismic detonation (h=hour, d=day). Samples collected 300 m from the shot location are indicated (D=0.3km). Numbers below pH values are water depths from which each sample was taken and also apply to data in (b). No statistically significant variation with location or depth is seen; potentially significant variations with time are discussed in the text.

(d) Depth profiles for eight species from (b) and (c) above, to show the lack of stratification with depth. Dotted lines: samples collected 3 hours before shot detonation; solid line: samples collected the day after the detonation. Concentrations are in ppm, but note different divisors applied to each species to allow a visual separation of data.

Figure 4

Views of detonation in Lake Arenguade taken from rim of crater. Top: approximately one second after initiation a water spout is present above the 100m x 25 m area beneath which the explosives were placed, and reaches a maximum height of 10 - 20 m. Middle: approximately 20 seconds after detonation, dark turbid water spreads outwards from the central white area in which bubbles are still rising to the surface. Bottom: approximately one minute after detonation, muddy boils continue to rise to the surface. Width of photographs is c. 300 m (top and middle) and c. 200 m (bottom). Photographs courtesy G.R. Keller (top and middle) and G. Kaip (bottom).

Figure 5

Major element concentrations measured in waters adjacent to borehole detonations, from Table 4. Concentrations are in ppm, but note different divisors (listed to right of the two measurements to which each applies) applied to each ion and each sampling location to allow approximate alignment and separation of each species. Uncertainties are shown as 10% for Na, Cl and K, and 5% for Ca and Mg, based on repeatability of measurements on standard solutions (Table 5). Location of each pair of measurements is indicated along base of plot; left and right concentration in each pair is from samples taken before and after the detonation, respectively. Each pair of samples is constant within uncertainty: no statistically significant variation due to detonation is apparent.

Table 1. Previously reported chemical analyses for Ethiopian lakes Shala, Arenguade, Awasa and Beseka

Reference	Date Sampled	(ppm)						(ppb)			pH	Notes		
		Li ⁺	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	Cl ⁻	SO ₄ ²⁻	Cu	Pb			Zn	
Shala	*Loffredo & Maldura, 1941 Apr. 1938		5890	440	10.	8.80	3130	129						
	Talling & Talling, 1965 May 1961		6250	252	<3	<7.5	3300	650				9.24	surface waters	
	Wood & Talling, 1988 Jan. 1964		6990	280	<2	<1.2	2730	1200					0.1 to 0.5 m depth	
	Wood & Talling, 1988 Mar. 1964		6920	278	2.00	1.22	2800	1201				9.9	0.1 to 0.5 m depth	
	Wood & Talling, 1988 Oct. 1966		6800	199	2.00	1.22	3120	648				9.9	0.1 to 0.5 m depth	
	Baumann et al., 1975 May 1971	0.09	5900	112	5.00	0.74	2790	143	6	6	25	10.0	surface waters, mean of two samples	
	Baumann et al., 1975 May 1971	0.09	6950	137	4.92	0.82	3117	167	7	40	13	10.0	bottom waters, mean of nine samples	
	Von Damm & Edmond, 1984 Jan./Feb. 1976	0.06	7020	275	3.69	0.97	3200	156				9.62	surface to 195 m	
	Chernet, 1982 about 1980		5600	200	1.	1.	2660	100				9.6	not stated	
	Tudorancea et al., 1989 April 1983		6250	248	<2	<1.2	3010	275				9.5		
	Kebede et al., 1994 Mar. 1991		5990	158	3.81	0.85	1680	706				9.65	0-4 & 16-17 m depth, mean of two samples	
	Gizaw, 1996 Apr. 1992		6700	216	2.	0.40	3170	205				9.97	sampled from shore	
	Zinabu, 2002a 1990-2000 dry season		6670	212	2.40	0.36	3240	143				9.67	surface water, center of lake	
	Zinabu, 2002a range of 3 samples		6510-7040	194-241	2.00-2.61	0.12-0.61	3190-3300	140-146				8.31-9.00	range of 3 samples (6 for pH)	
	Zinabu, 2002a 1990-2000 wet season		6600	219	2.20	0.73	2650	474				9.76	surface water, center of lake	
	Zinabu, 2002a range of 3 samples		6260-6950	178-261	1.40-3.01	0.61-0.85	1910-3400	164-783				9.4-10.2	range of 3 samples (6 for pH)	
	Reimann et al., 2002 2000	0.10	7030	240	3.88	0.81	3010	133	6.7	0.1	1.9	10.01	surface waters, from shore	
	This paper, before shot Jan. 2003	0.08	~6100	278	2.16	0.68	1050	151	0.6	1.0	11.0	9.70	average of 5 samples, 1 - 20 m depth	
	This paper, up to 24 hrs after shot Jan. 2003	0.09	~6600	294	2.04	0.75	1070	155	0.3	1.0	6.8	9.70	average of 14 samples, 1 - 90 m depth	
	This paper, 13 days after shot Jan. 2003	0.10	~6800	288	1.88	0.78	1100	164	0.6	1.7	12.8	9.70	average of 4 samples, 5 - 30 m depth	
	This paper, all samples range of 23 samples	0.09-0.10	133-346	2.47-3.99	0.50-0.79	1040-1106	147-167	0.0-10.0	0.0-12.0	2.1-21.3	9.69-9.71		range of 23 samples	
	Wood & Talling, 1988 1964		2550	27	<2	<6	1470	360					hot spring on shore	
	Baumann et al., 1975 May 1971	0.23	1248	18	5.83	0.71	750	25	4	27	6	8.8	hot springs on shore, mean of 21 samples	
	**United Nations, 1973 1973		2340	69	<3	<2	1530	31				8.9	hot spring on shore	
Arenguade	Prosser et al., 1968 Apr. 1963		1540	317	13.43	<7	780	34				10.3	surface waters	
	Wood & Talling, 1988 Feb. 1964		1500	375	14.03	6.08	606	269					0.1 to 0.5 m depth	
	Zinabu, 1994 April 1992		1360	450	16.00	4.86	780	2				10.0	surface water, center of lake	
	This paper, before shot Jan. 2003	0.01	1420	203	7.19	8.21	406	15	0.0	1.2	2.8	9.64	average of 4 samples, 1 - 30m depth	
	This paper, up to 24 hrs after shot Jan. 2003	0.01	1420	201	6.34	8.14	406	15	0.0	2.1	0.8	9.67	average of 12 samples, 1 - 30m depth	
	This paper, 11 days after shot Jan. 2003	0.01	1150	168	7.35	6.58	352	15	0.0	5.9	4.9	9.68	average of 4 samples, 1 - 30m depth	
	This paper, all samples range of 20 samples	0.005-0.007	1070-1450	139-279	5.27-9.22	6.11-8.33	336-425	13.1-16.4	0.0-0.46	0.0-9.6	0.0-59.6	9.58-9.74	range of 20 samples	
Awasa	Talling & Talling, 1965 May 1961		235	45	4.40	4.70	34	27.0				8.79	surface waters	
	Wood & Talling, 1988 Mar. 1964		218	41	11.62	1.22	30	43.2					0.1 to 0.5 m depth	
	Wood & Talling, 1988 Aug. 1966		175	35	4.00	3.66	32	28.8				9.2	0.1 to 0.5 m depth	
	Von Damm & Edmond, 1984 Jan./Feb. 1976	0.12	212	32	4.81	5.35	30	0.5					surface waters	
	Chernet, 1982 about 1980		225	39	7.	5.5	34	2.				9.15	not stated	
	Tudorancea et al., 1989 April 1983		170	35	8.22	5.47	41	1.4				9.0		
	***Kifle, 1985 Nov. 83 - Mar. 85		70-185	15-40	9-12	5.1-6.1	32-37	48-125						
	Kebede et al., 1994 Mar. 1991		137	27	8.62	5.83	14	35.1				8.75	0 to 3 m depth	
	Gizaw, 1996 Nov. 1992		165	30	9.	5.	32	<0.5				8.72	sampled from shore	
	Zinabu, 2002a 1990-2000 dry season		175	30	10.42	5.47	34	3.8				8.79	surface water, center of lake	
	Zinabu, 2002a range of 4 samples		160-188	24-34	9.0-12.0	5.11-6.08	30-37	0.0-9.1				8.31-9.00	range of 4 samples (12 for pH)	
	Zinabu, 2002a 1990-2000 wet season		147	44	9.82	6.08	23	18.3				8.87	surface water, center of lake	
	Zinabu, 2002a range of 3 samples		138-156	27-61	9.6-10.0	5.83-6.32	14-32	1.0-35.1				8.7-9.1	range of 3 samples (14 for pH)	
	Zinabu & Pearce, 2003 Nov.1995/Mar. 1996								0.0	0.0	1.6		center of lake	
	Reimann et al., 2002 2000	0.11	161	31	10.63	6.20	28	0.4	1.8	0.8	5.9	8.79	surface waters, from shore	
	This paper, before shot Jan. 2003	0.12	177	33	9.05	5.80	26	12.4	0.0	0.0	5.0	8.88	surface sample taken before shot	
	This paper, after shot Jan. 2003	0.12	176	33	9.33	5.90	25	12.4	0.0	0.0	1.1	8.56	surface sample taken after shot	
Beseka	Talling & Talling, 1965 May 1961		17800	406	<3	<7.5	5480	4680				9.94	surface waters	
	Kebede et al., 1994 Mar. 1991		1810	67	2.20	0.49	450	600				9.4	0 to 1.2 m depth	
	Gizaw, 1996 Feb. 1993		1900	60	1.	0.40	572	540				9.55	sampled from shore	
	Reimann et al., 2002 2000	0.04	1740	64	3.15	0.70	542	494	8.3	1	39.5	9.71	surface waters, from shore	
	This paper, before shot Jan. 2003	0.05	2160	80	2.18	0.38	421	620	5.3	2.5	6.8	9.54	surface sample taken before shot	
	This paper, after shot Jan. 2003	0.05	2090	78	2.28	0.42	408	586	1.7	0.3	6.4	9.53	surface sample taken after shot	
	**United Nations, 1973 1973		450	31	<3	2.	175	86				8.6	hot spring on shore	

Only species reported by multiple previous studies and by our study are shown here; for species reported only by this paper and Riemann et al., 2002, see Tables 2, 3 & 4.

Bold values are original data from this work; bold italicized values are those for which absolute values are less accurate (recorded outside linear range of instrument) but relative values are useful: see text for discussion

*Loffredo & Maldura, 1941: original not consulted; values cited are from Talling & Talling, 1965

**United Nations, 1973: original not consulted; values cited are from Gizaw, 1996

***Kifle, 1985: original not consulted; values cited are from Zinabu et al., 2002

Italicized rows represent hot springs; all others are lake waters

Precise sampling locations not known except for this work and Reimann et al., 2002 (for which see Tables 2 and 4)

Table 2. Chemical analyses of Lake Shala before and after seismic detonation suspended in the lake

Time relative to shot time (c. 1730 local)			As	B	Ba	Be	Ca	Cd	Cl	Co	Cu	Fe	K	Li	Mg	Mn	Mo	**Na	Ni	P	Pb	SO ₄	Sr	Ti	U	V	Zn	
Depth (m)	x-offset		ppb	ppm	ppb	ppb	ppm	ppb	ppm	ppb	ppb	ppb	ppm	ppm	ppb	ppm	ppb	per.mil	ppb	ppm	ppb	ppm	ppb	ppb	ppb	ppb	ppb	ppb
T-24 hours	1		46.2	11.9	35.0	0.01	3.95	2.67	1049	0.39	**[9.96]	14.8	214	95.2	0.783	8.17	654	6.6	2.3	2.85	*[11.9]	147	81.9	7.12	190	19.5	21.3	
	10		50.8	12.1	36.3	0.00	3.99	2.19	1067	0.37	0.00	10.2	214	96.3	0.794	9.71	657	6.6	2.6	1.93	2.07	154	76.6	6.60	149	18.8	19.6	
	20		52.0	12.2	35.3	0.01	3.93	1.70	1056	0.98	2.50	33.3	290	97.9	0.791	9.36	663	6.7	1.7	2.94	2.07	151	76.4	8.99	256	20.3	8.3	
T- 1 hour	1		46.6	11.7	29.7	0.05	2.55	1.85	1052	1.39	0.00	19.3	336	65.2	0.507	7.64	630	6.1	51.9	3.88	0.00	153	46.2	13.82	141	8.8	2.5	
	1		45.8	10.3	27.6	0.00	2.47	2.38	1047	1.39	0.00	15.3	338	63.7	0.500	7.16	557	4.4	49.7	3.94	0.00	150	47.8	13.98	152	6.4	3.3	
T + .5 hours	1		51.2	12.0	31.9	0.00	2.55	2.17	1083	1.43	0.00	16.6	346	63.5	0.512	7.62	642	4.8	49.1	4.02	0.00	165	50.4	13.59	118	7.9	4.3	
	1		51.6	11.9	34.3	0.06	3.78	2.54	1061	1.70	0.00	18.3	341	94.2	0.772	7.79	649	6.7	50.0	4.04	3.24	155	77.6	14.48	196	18.6	5.5	
T + 17.5 hours	1		51.6	12.0	33.0	0.00	3.67	2.33	1040	0.27	0.00	12.3	328	94.3	0.751	8.39	657	6.9	48.3	3.91	0.00	146	81.1	12.70	155	18.0	2.5	
	10		49.3	12.1	32.8	0.00	3.69	2.02	1045	0.61	0.00	35.2	315	94.4	0.764	6.85	661	6.9	0.6	2.96	0.00	149	78.5	11.51	278	19.1	5.2	
	20		49.7	12.1	31.9	0.00	3.70	2.08	1041	0.74	0.35	11.8	211	93.6	0.763	7.77	661	6.9	0.0	2.44	2.30	148	83.0	7.31	165	17.1	2.1	
	30		48.5	12.1	36.7	0.00	3.65	1.83	1046	0.06	0.00	12.3	210	94.4	0.763	8.50	666	6.9	1.1	2.87	0.00	148	76.6	6.04	212	18.0	4.7	
	60		48.1	12.1	36.8	0.01	3.65	2.30	1045	0.37	0.91	9.3	312	93.8	0.758	7.40	664	6.8	0.0	2.91	0.00	148	75.2	8.40	262	17.2	4.0	
	90		39.3	12.1	33.0	0.00	3.68	1.77	1046	0.59	0.46	7.7	315	93.8	0.761	8.52	664	6.8	1.9	2.91	0.01	148	81.5	8.87	216	19.0	2.4	
T +18.5 hours	1	1 km	47.4	12.2	34.7	0.01	3.72	2.04	1045	0.47	0.00	11.7	133	96.1	0.778	7.71	663	6.9	0.0	1.96	0.00	147	75.6	5.45	84	16.4	5.6	
	10	1 km	52.8	12.1	34.0	0.00	3.76	1.76	1050	0.74	0.92	8.6	209	94.1	0.775	7.46	659	6.8	0.0	1.98	0.00	148	79.2	6.79	166	18.3	6.5	
	20	1 km	52.4	12.2	33.3	0.04	3.77	1.38	1052	0.55	0.24	7.0	212	97.7	0.782	8.28	667	6.8	0.0	1.94	2.53	150	82.8	6.63	84	19.7	3.2	
	30	1 km	46.6	12.2	34.3	0.00	3.75	1.75	1041	0.80	0.24	13.9	208	97.7	0.783	8.68	667	6.8	1.1	2.94	0.47	145	76.7	6.37	197	18.9	6.1	
	60	1 km	48.5	12.1	34.8	0.01	3.72	1.75	1048	0.49	0.00	9.5	319	98.6	0.761	8.05	654	6.6	2.6	2.91	0.00	149	75.9	8.73	176	17.5	2.8	
	90	1 km	50.1	12.0	32.0	0.00	3.69	1.89	1059	0.37	0.00	7.6	210	97.2	0.761	8.41	654	6.6	1.2	2.60	0.00	150	70.4	6.34	208	17.8	3.3	
T + 13 days	5		46.2	12.3	40.9	0.00	3.77	1.87	1099	1.27	0.00	14.8	315	99.1	0.785	8.47	668	6.9	0.0	2.91	1.16	163	77.6	7.53	263	19.4	13.9	
	10		43.5	12.3	35.5	0.01	3.86	1.84	1101	0.51	0.00	9.1	316	100.1	0.778	9.94	660	6.8	0.0	2.92	0.24	164	82.9	8.73	276	20.3	8.6	
	20		49.7	12.1	44.9	0.00	3.92	1.76	1106	0.88	1.48	8.7	309	98.3	0.794	8.19	655	6.8	0.0	2.93	5.50	167	76.1	9.02	301	17.7	18.5	
	30		56.2	12.1	38.5	0.01	3.72	2.04	1084	0.94	0.80	10.5	214	96.1	0.759	8.20	657	6.7	0.0	2.97	0.00	160	83.5	5.82	170	17.3	10.2	
Before shot	5	# samples:	Mean	48.3	11.6	32.8	0.01	3.38	2.16	1054	0.90	0.62	18.6	278	83.6	0.675	8.41	632	6.1	21.6	3.11	1.04	151	65.8	10.10	177	14.8	11.0
			Std. Deviation	2.9	0.8	3.9	0.02	0.79	0.39	8	0.51	1.25	8.8	62	17.6	0.157	1.10	44	1.0	26.7	0.83	1.20	3	17.3	3.58	48	6.6	8.9
			Relative Std. Dev.	6%	0.3%	12%	161%	23%	18%	1%	56%	200%	48%	22%	21%	23%	13%	7%	16%	123%	27%	115%	2%	26%	35%	27%	45%	81%
Up to 24 hrs after shot	14		Mean	49.1	12.1	35.8	0.01	3.64	2.04	1066	0.78	0.33	13.9	294	93.0	0.747	8.14	659	6.6	12.6	3.15	1.04	155	77.0	9.50	218	17.5	6.8
			Std. Deviation	3.4	0.1	4.0	0.02	0.35	0.25	26	0.49	0.49	7.5	51	9.6	0.075	0.77	7	0.6	22.1	0.53	1.77	8	8.9	2.90	58	3.2	5.1
			Relative Std. Dev.	7%	0.3%	11%	261%	10%	12%	2%	62%	148%	54%	17%	10%	10%	9%	1%	9%	175%	17%	171%	5%	12%	31%	27%	18%	75%
13 days after shot	4		Mean	48.9	12.2	39.9	0.00	3.82	1.88	1097	0.90	0.57	10.8	288	98.4	0.779	8.70	660	6.8	0.0	2.93	1.72	164	80.0	7.77	252	18.7	12.8
			Std. Deviation	5.5	0.1	4.0	0.00	0.09	0.12	9	0.31	0.72	2.8	50	1.7	0.015	0.84	6	0.1	0.0	0.03	2.57	3	3.7	1.46	57	1.4	4.4
			Relative Std. Dev.	11%	0.3%	10%	117%	2%	6%	1%	34%	125%	26%	17%	2%	2%	10%	1%	1%	---	1%	149%	2%	5%	19%	23%	8%	34%
All samples	23		Mean	48.9	12.0	34.7	0.01	3.61	1.99	1059	0.75	0.36	13.8	270	92.0	0.738	8.18	653	6.6	11.5	2.94	0.89	152	74.5	8.90	192	17.0	7.1
			Std. Deviation	3.5	0.4	3.6	0.02	0.44	0.30	21	0.43	0.63	7.3	63	11.2	0.093	0.76	23	0.6	20.7	0.66	1.47	7	10.9	2.94	60	3.9	5.8
			Relative Std. Dev.	7%	0.3%	10%	185%	12%	15%	2%	57%	176%	53%	23%	12%	13%	9%	3%	10%	180%	22%	165%	4%	15%	33%	31%	23%	81%
*** # deviations difference, before vs. 24 hrs after:			Student t-test, significant at:	0.2	1.0	0.4	-0.2	0.5	-0.6	0.4	-0.5	-0.6	-0.7	-0.2	0.8	0.7	-0.6	1.1	0.8	-0.5	-0.3	-0.4	-0.3	0.9	-0.4	0.0	0.6	-1.3
*** # deviations difference, before vs. 13d after:			Student t-test, significant at:	0.2	0.9	1.4	-0.6	0.7	-0.9	1.8	0.0	-0.1	-1.0	0.2	1.0	0.8	0.3	0.8	0.9	-1.0	-0.3	0.4	1.8	1.0	-0.8	1.2	0.8	0.3
range of all 23 samples				39-56	10-12.	28-45	0-62	2.5-4.0	1.4-2.7	1040-1111	0.1-1.17	0-10	7.0-35	130-350	64-100	500-790	7.2-9.9	560-670	4.4-6.9	0-52	1.9-4.0	0-12	145-167	46-84	5.5-14	84-301	6.4-20	2.1-21
Reimann et al., 2002; surface waters				95.8	11.7	27.5	40.0	3.88	0.66	3012	0.47	6.65	16.0	240	96.6	812	<0.1	746	7.03	2.17		0.10	61.0	0.80	31	28.0	1.9	

* Value in [] is an extreme outlier (more than 3 deviations from the mean, when calculated including the potential outlier) and was omitted for the calculation of the mean and deviation.

** Na concentration was outside the linear range of the ICP-OES, and absolute values have low accuracy, though relative values remain diagnostic.

*** (mean up to 24 hrs after shot - mean before shot)/(deviation of these 19 samples)

**** (mean 13 days after - mean before)/(deviation of these 9 samples)

Bold, italicized values are discussed in the text (> 1.5 standard deviations difference between all before values and all 13-day-after values)

Shot location and principal sampling location was UTM zone 37N 457527, 825492; Reiman et al., 2002, sampling location was 458996, 827870, c. 2.5 km distant

Table 3. Chemical analyses of Lake Arenal before and after lake-bottom seismic detonation

			As	B	Ba	Be	Ca	Cd	Cl	Co	Cu	Fe	K	Li	Mg	Mn	Mo	Na	Ni	P	Pb	SO ₄	Sr	Ti	U	V	Zn		
			ppb	ppm	ppb	ppb	ppm	ppb	ppm	ppb	ppb	ppb	ppm	ppb	ppm	ppb	ppb	ppm	ppb	ppm	ppb	ppm	ppb	ppb	ppb	ppb	ppb	ppb	
<u>Time relative to shot time</u>	<u>Depth (m)</u>	<u>x-offset</u>																											
(c. 1630 local)																													
T - 3 hours	1		22.0	2.34	12.1	0.02	5.78	0.7	410	0.4	0.0	1.6	187	7.0	8.08	2.2	109	1385	3.3	7.8	0.0	15.1	73.1	3.15	144	10.1	0.1		
	10		12.3	2.37	18.4	0.00	9.12	0.8	404	0.0	0.0	6.7	252	7.8	8.29	12.8	108	1431	2.4	8.3	2.1	14.2	85.1	2.69	145	10.4	8.5		
	20		17.0	2.35	13.8	0.00	5.90	0.7	406	0.0	0.0	8.4	186	6.8	8.23	4.6	107	1451	2.3	6.1	2.1	14.6	71.7	3.54	161	9.7	0.5		
	30		17.7	2.35	16.5	0.02	7.96	1.1	402	0.0	0.0	3.2	186	7.1	8.25	10.9	110	1415	3.5	7.0	0.7	14.1	81.1	2.70	90	9.3	1.9		
T + 0.5 hours	1		14.6	2.36	15.5	0.00	7.19	1.1	408	0.0	0.0	2.6	188	6.8	8.21	4.9	106	1423	1.0	7.2	3.2	15.3	80.6	2.72	165	9.7	1.0		
	10		16.6	2.36	17.6	0.00	9.22	0.8	398	0.1	0.0	4.5	184	7.0	8.33	17.9	107	1443	0.0	7.1	0.0	14.5	85.6	2.98	115	10.2	4.0		
	20		15.0	2.36	14.0	0.00	5.96	1.2	399	0.0	0.0	3.9	186	7.5	8.14	4.7	108	1433	1.6	6.7	5.0	14.4	74.2	1.74	108	10.1	0.4		
	30		20.0	2.34	12.7	0.00	5.59	1.0	425	0.4	0.0	2.1	178	6.7	8.10	1.6	107	1413	0.9	5.5	0.0	15.1	71.7	2.39	116	8.9	0.0		
T + 18.5 hours	1		14.3	2.34	13.1	0.04	5.98	1.2	406	0.0	0.0	3.3	186	6.7	8.09	4.0	107	1408	2.3	7.7	0.0	14.7	72.4	2.67	48	9.5	0.5		
	10		25.8	2.34	11.5	0.01	5.27	1.1	400	0.5	0.0	1.0	187	6.6	8.01	1.7	107	1386	1.6	6.6	4.8	15.0	60.1	1.82	177	9.0	0.4		
	20		17.7	2.34	14.6	0.04	6.06	0.9	406	0.9	0.0	2.3	187	7.1	8.07	4.7	106	1413	5.7	8.2	0.9	13.9	76.1	2.81	183	9.7	0.0		
	30		22.0	2.36	13.5	0.01	6.08	0.9	410	0.4	0.0	9.2	279	7.2	8.11	4.7	105	1423	5.2	8.1	0.0	15.1	75.9	3.93	140	9.9	0.9		
T + 19 hours	1	300 m	18.1	2.36	12.7	0.01	5.66	1.0	405	0.3	0.0	4.6	191	6.5	8.17	4.4	108	1441	0.0	8.2	0.0	15.1	74.3	3.40	109	9.8	0.8		
	10	300 m	20.4	2.37	16.4	0.00	6.90	0.9	401	0.8	0.0	5.3	275	6.9	8.24	7.3	108	1428	2.6	8.2	3.2	14.5	74.3	3.60	65	8.4	0.3		
	20	300 m	13.9	2.35	16.0	0.05	6.50	0.9	401	0.6	0.0	1.7	189	7.0	8.15	5.5	106	1420	2.4	8.2	1.4	14.1	73.1	2.95	154	9.2	1.2		
	30	300 m	15.0	2.34	11.4	0.00	5.64	1.2	416	0.6	0.0	2.7	186	6.2	8.09	2.2	107	1435	2.3	8.1	6.2	14.8	75.0	2.39	95	8.2	0.1		
T + 11 days	1		11.2	1.93	17.2	0.00	7.53	1.2	353	0.5	0.0	2.6	153	6.2	6.83	7.8	87	1187	2.7	4.8	4.8	16.4	70.9	1.07	127	8.3	[59.6]		
	10		7.7	1.99	19.0	0.00	7.74	1.0	367	0.2	0.0	3.8	157	5.5	6.95	12.7	91	1213	2.0	6.9	1.8	13.6	71.6	2.05	86	8.8	6.9		
	20		11.6	1.86	17.8	0.00	7.25	1.3	336	0.0	0.0	4.8	222	5.5	6.41	8.0	84	1124	1.6	6.5	7.3	13.1	72.1	1.60	167	9.2	6.0		
	30		4.2	1.76	15.4	0.00	6.89	1.2	351	0.1	*[0.5]	9.9	139	5.3	6.11	2.8	79	1069	4.5	5.6	9.6	15.1	72.6	1.68	97	7.3	1.7		
# samples:																													
Before shot	4	Mean	17.2	2.35	15.2	0.01	7.19	0.8	406	0.1	0.0	5.0	203	7.2	8.21	7.6	108	1420	2.9	7.3	1.2	14.5	77.7	3.0	135	9.9	2.8		
		Std. Deviation	3.9	0.01	2.8	0.01	1.63	0.2	3	0.2	0.0	3.1	33	0.4	0.09	5.0	1	28	0.6	0.9	1.0	0.5	6.4	0.4	31	0.5	3.9		
		Relative Std. Dev.	23%	0.3%	19%	116%	23%	24%	1%	200%	---	63%	16%	6%	1%	66%	1%	2%	21%	13%	86%	3%	8%	13%	23%	5%	141%		
Up to 24 hrs after shot	12	Mean	17.8	2.35	14.1	0.01	6.34	1.0	406	0.4	0.0	3.6	201	6.9	8.14	5.3	107	1422	2.1	7.5	2.1	14.6	74.4	2.8	123	9.4	0.8		
		Std. Deviation	3.7	0.01	2.0	0.02	1.06	0.1	8	0.3	0.0	2.2	36	0.3	0.09	4.3	1	16	1.8	0.9	2.3	0.4	5.9	0.7	42	0.6	1.1		
		Relative Std. Dev.	21%	0.3%	14%	138%	17%	13%	2%	79%	---	61%	18%	5%	1%	81%	1%	1%	84%	12%	112%	3%	8%	23%	34%	7%	133%		
11 days after shot	4	Mean	8.7	1.89	17.4	0.00	7.35	1.2	352	0.2	0.0	5.3	168	5.6	6.6	7.8	85	1148	2.7	5.9	5.9	14.6	71.8	1.6	119	8.4	4.9		
		Std. Deviation	3.4	0.10	1.5	0.00	0.37	0.1	13	0.2	0.0	3.2	37	0.4	0.39	4.1	5	64	1.3	1.0	3.3	1.5	0.7	0.4	37	0.8	2.7		
		Relative Std. Dev.	40%	5%	9%	---	5%	10%	4%	104%	---	61%	22%	7%	6%	52%	6%	6%	47%	16%	57%	10%	1%	25%	31%	10%	56%		
All samples	20	Mean	15.9	2.26	15.0	0.01	6.71	1.0	395	0.3	0.0	4.2	195	6.7	7.8	6.3	103	1367	2.4	7.1	2.7	14.6	74.6	2.6	124	9.3	1.9		
		Std. Deviation	5.1	0.20	2.4	0.02	1.15	0.2	24	0.3	0.0	2.6	36	0.7	0.67	4.3	9	116	1.5	1.0	2.8	0.7	5.5	0.8	38	0.8	2.6		
		Relative Std. Dev.	32%	9%	16%	160%	17%	17%	6%	98%	---	61%	19%	10%	9%	69%	9%	9%	63%	15%	106%	5%	7%	29%	30%	9%	137%		
** # deviations difference, before vs. 24 hrs after:		Student t-test, significant at:	0.2	0.0	-0.5	0.3	-0.7	1.1	0.1	0.9	0.0	-0.6	0.0	-0.8	-0.8	-0.5	-1.2	0.1	-0.5	0.2	0.4	0.3	-0.5	-0.4	-0.3	-0.8	-0.9		
*** # deviations difference, before vs. 11d after:		Student t-test, significant at:	---	---	---	---	---	---	---	---	---	---	---	---	---	---	95%	---	---	---	---	---	---	---	---	---	---	---	
		Student t-test, significant at:	95%	99.9%	---	---	---	95%	99.9%	---	---	---	---	---	99%	99.9%	---	99.9%	99.9%	---	---	95%	---	---	99%	---	95%	---	

* Values in [] are extreme outliers (more than 3 deviations from the mean, when calculated including the potential outlier) and were omitted for the calculation of the mean and deviation.
 ** (mean up to 24 hrs after shot - mean before shot)/(deviation of these 16 samples) *** (mean 11 days after - mean before)/(deviation of these 8 samples)
 Bold, italicized values are discussed in the text (> 1.5 standard deviations difference between all before values and all 11-day-after values)

Table 4. Chemical analyses of lakes and streams before and after adjacent borehole seismic detonations

Shot name	Shot size	*Location	Time	<u>As</u>	<u>B</u>	<u>Ba</u>	<u>Be</u>	<u>Ca</u>	<u>Cd</u>	<u>Cl</u>	<u>Co</u>	<u>Cu</u>	<u>Fe</u>	<u>K</u>	<u>Li</u>	<u>Mg</u>	<u>Mn</u>	<u>Mo</u>	<u>Na</u>	<u>Ni</u>	<u>P</u>	<u>Pb</u>	<u>SO₄</u>	<u>Sr</u>	<u>Ti</u>	<u>U</u>	<u>V</u>	<u>Zn</u>	
				ppb	ppb	ppb	ppb	ppm	ppb	ppm	ppb	ppb	ppm	ppb	ppb	ppm	ppb	ppm	ppb	ppb	ppm	ppb	ppb	ppb	ppm	ppb	ppb	ppb	ppb
Lake Awasa 50 m west of SP 21	1775 kg	Zone 37N	128 hrs before	6.9	156	22.4	0.012	9.05	0.8	26.1	0.1	0.0	0.0	33.1	122.1	5.8	0.5	8.4	177	0.0	0.8	0.0	12.4	80.8	0.0	14.5	4.5	5.0	
			441578 34 hrs after shot	3.5	181	20.5	0.015	9.33	0.9	24.8	0.0	0.0	0.0	0.0	33.1	121.3	5.9	0.5	7.4	176	0.0	18.7	0.0	12.4	86.0	0.0	13.9	1.9	1.1
			785718 mean	5.2	169	21.4	0.013	9.19	0.9	25.5	0.1	0.0	0.0	0.0	33.1	121.7	5.9	0.5	7.9	177	0.0	9.7	0.0	12.4	83.4	0.0	14.2	3.2	3.0
Zinabu & Pearce, 2003 Reimann et al., 2002	center lake	Nov. 95/Mar. 96	2000	3.4		16.2		10.63	0.0		0.0	0.0	0.0			2.6	1.8			0.0		0.0	101.6	20.5		3.1	1.6		
			441176 779766	1.7	149	14.6	0.059	10.63	0.0	27.8	0.2	1.8	368.0	31.2	114.0	6.2	33.3	7.8	161	0.7		0.8		98.0	33.5	0.2	2.0	5.9	
Lake Beseka 200 m north of SP 26	1150 kg	Zone 37P	8.5 hrs before	39.7	4460	19.7	0.037	2.18	1.1	421	0.6	5.3	0.0	79.8	48.9	0.4	11.0	247	1505	0.0	1393	2.5	620	55.8	3.8	8.8	110.7	6.8	
			513296 9 hrs after shot	42.8	4398	18.2	0.013	2.28	1.1	408	0.7	1.7	0.0	0.0	78.5	49.6	0.4	10.7	246	1479	0.0	1358	0.3	586	64.8	3.8	15.3	105.9	6.4
			976028 mean	41.2	4429	18.9	0.025	2.23	1.1	414	0.6	3.5	0.0	0.0	79.1	49.2	0.4	10.9	246	1492	0.0	1376	1.4	603	60.3	3.8	12.1	108.3	6.6
Lake Beseka Reimann et al., 2002	599361 984170			67.3	3550	17.9	0.033	3.15	0.3	542	0.6	8.3	663.0	63.8	40.9	0.7	28.4	250.0	1740	3.8		1.0	60.0	65.2	22.6	108.0	39.5		
Stream 1 SP 14	375 kg	Zone 37P	8.5 hrs before	6.6	10.5	104.2	0.027	35.0	0.9	8.3	0.0	0.8	0.0	6.5	3.0	9.2	0.2	4.6	22.6	0.0	6.1	0.0	16.2	235.4	0.0	9.2	7.3	5.2	
			513296 9 hrs after shot	7.3	6.2	116.3	0.000	36.8	0.9	7.4	0.0	0.0	30.8	6.3	2.9	9.4	57.5	2.3	21.7	0.0	6.6	0.0	15.8	242.4	0.0	16.3	6.2	11.9	
			992641 mean	6.9	8.4	110.3	0.014	35.9	0.9	7.8	0.0	0.4	15.4	6.4	2.9	9.3	28.8	3.5	22.1	0.0	6.3	0.0	16.0	238.9	0.0	12.7	6.7	8.5	
Stream 2 SP 15	50 kg	Zone 37P	9 hrs before	0.4	55.7	36.6	0.017	18.4	1.1	13.6	0.0	0.0	0.0	5.0	8.2	3.4	0.0	4.2	36.0	0.0	14.0	1.7	18.3	95.1	0.0	10.0	11.4	16.8	
			562849 7 hrs after shot	12.0	53.2	37.8	0.035	18.0	0.9	10.8	0.2	0.1	0.0	4.5	8.2	3.3	0.0	4.0	36.1	0.0	10.5	3.1	18.5	88.9	0.0	0.0	9.9	12.1	
			942509 mean	6.2	54.5	37.2	0.026	18.2	1.0	12.2	0.1	0.1	0.0	4.7	8.2	3.3	0.0	4.1	36.0	0.0	12.2	2.4	18.4	92.0	0.0	5.0	10.6	14.5	
Stream 3 SP 16	1100 kg	Zone 37P	8 hrs before	9.2	5.38	70.9	0.000	26.4	0.8	6.9	0.5	0.0	0.0	6.0	2.0	6.1	368.8	0.0	5.3	0.0	18.2	6.1	13.1	159.7	0.0	11.8	0.9	12.0	
			575823 9 hrs after shot	10.0	3.60	75.1	0.000	26.4	1.2	6.7	0.6	0.0	0.0	6.0	1.5	6.1	503.8	0.3	5.2	0.0	17.9	0.0	13.3	149.8	0.0	5.9	0.0	8.9	
			886441 mean	9.6	4.49	73.0	0.000	26.4	1.0	6.8	0.6	0.0	0.0	6.0	1.7	6.1	436.3	0.2	5.3	0.0	18.0	3.1	13.2	154.8	0.0	8.8	0.4	10.5	
Stream 4 SP 33	200 kg	Zone 37P	8 hrs before	0.0	0.00	30.2	0.000	12.5	0.7	4.8	0.0	0.0	0.0	1.0	0.0	4.0	0.0	0.6	1.5	0.0	7.4	21.4	15.7	83.7	0.0	12.7	0.0	15.3	
			598445 6.5 hrs after shot	1.5	0.00	29.3	0.007	12.8	0.5	4.5	0.0	0.0	0.0	0.8	0.0	4.2	2.0	0.8	1.4	0.0	1.3	3.3	14.2	80.2	0.0	9.2	1.3	6.2	
			924991 mean	0.8	0.00	29.8	0.003	12.7	0.6	4.6	0.0	0.0	0.0	0.9	0.0	4.1	1.0	0.7	1.4	0.0	4.3	12.4	15.0	82.0	0.0	11.0	0.7	10.7	
Stream 5 Test Shot	100 kg	Zone 37P	before shot	0.0	0.00	60.0	0.000	32.9			0.0	0.0	24.1	0.2	5.8	16.8	0.0	0.0	10.9	0.0		0.0	250.0	0.0		30.0	0.0		
			464199 before shot	0.0	0.00	50.0	0.000	32.0			0.0	0.0	24.1	0.2	5.8	16.1	0.0	0.0	10.8	0.0		10.0	240.0	0.0		20.0	0.0		
			1034792 after shot	0.0	0.00	80.0	0.000	32.0			0.0	0.0	30.0	0.3	5.8	16.8	0.0	0.0	10.8	0.0		10.0	240.0	0.0		30.0	0.0		
			after shot	0.0	0.00	50.0	0.000	32.1			0.0	0.0	24.1	0.3	0.0	16.9	0.0	0.0	11.0	0.0		0.0	240.0	0.0		30.0	0.0		
			mean	0.0	0.00	60.0	0.000	32.2			0.0	0.0	25.6	0.2	4.3	16.7	0.0	0.0	10.9	0.0		5.0	242.5	0.0		27.5	0.0		
14 streams Chernet, 1982	Lakes region	mean of 14 streams range					15.8 5-41	6.07 1-18					5.43 1-12	6.50 2-17				15.6 1-73											

* Locations are provided in UTM co-ordinates easting then northing, precise to 1 m; see also Figure 1.

All original data recorded in January 2003 and analyzed at Stanford (see text), except "Test shot" data, recorded December 2002 & analyzed by Emma Mansley at University of Leicester, U.K., on a JY Horiba Ultima 2 Sequential ICP-OES system. Samples typically taken in the afternoon before a shot in the middle of the night and again the following morning; for Stream 5 / Test Shot samples were taken respectively in morning and afternoon of same day.

Stream 1 = stream conditions not recorded; 20 m south of shotpoint 14.

Stream 2 = irrigation ditch, 6 m northwest of shotpoint 15. Water slightly turbid, but good flow.

Stream 3 = greenish water, water not flowing at time of sampling, some parts of the stream are dry; stream probably only flows seasonally.

Stream 4 = clear water flowing from a muddy area. 15 m west of shotpoint 33.

Stream 5 = stream conditions were not recorded. 600 m from shotpoint 13 used in January 2003.

Table 5. Standard and reference solutions used for ICP-OES and IC analysis.

		<u>As</u>	<u>B</u>	<u>Ba</u>	<u>Be</u>	<u>Ca</u>	<u>Cd</u>	<u>Cl</u>	<u>Co</u>	<u>Cu</u>	<u>Fe</u>	<u>K</u>	<u>Li</u>	<u>Mg</u>	<u>Mn</u>	<u>Mo</u>	<u>Na</u>	<u>Ni</u>	<u>P</u>	<u>Pb</u>	<u>SO₄</u>	<u>Sr</u>	<u>Ti</u>	<u>U</u>	<u>V</u>	<u>Zn</u>		
		ppb	ppb	ppb	ppb	ppm	ppb	ppm	ppb	ppb	ppb	ppm	ppb	ppm	ppb	ppb	ppm	ppb	ppm	ppb	ppm	ppb	ppb	ppb	ppb	ppb		
Standard																												
NIST 1643c	Certified concentrations	82.1	119.9	49.6	23.2	36.8	12.2		23.5	22.3	106.9	2.3	16.5	9.5			12.2	60.6		35.3		263.6				31.4	73.9	
	Standard Deviation	0.6	0.7	1.6	1.1	0.7	0.5		0.4	1.4	1.5	**	0.5	0.1			0.2	3.7		0.5		1.3				1.4	0.5	
	Relative Std. Dev.	1%	1%	3%	5%	2%	4%		2%	6%	1%		3%	1%			1%	6%		1%		0.5%				4%	1%	
ICP-OES determinations																												
	# samples																											
NIST 1643c	6	Mean	83.4	129.9	49.9	23.1	36.7	12.2		24.0	21.8	135.9	2.8	16.6	9.4		12.8	61.0		34.9		261.5	8.2			29.6	74.1	
		Standard Deviation	4.7	6.7	0.1	0.2	0.2	0.5		0.3	2.8	11.3	0.5	0.2	0.1		1.4	0.7		3.6		4.5	1.4			1.2	0.2	
		Relative Std. Dev.	6%	5%	0.3%	1%	1%	4%		1%	13%	8%	18%	1%	1%		11%	1%		10%		2%	17%			4%	0.3%	
Salt Solution	5	Mean		68.4	785.5						6059	5.2		4.4	34.7	101.9	13.1	62.5	0.3	4.6		255.3	53.3	540.1	28.9	75.7		
		Standard Deviation		6.1	5.1						44	0.7		0.0	0.1	1.1	1.5	2.7	0.0	2.9		7.0	1.5	38.7	0.7	3.9		
		Relative Std. Dev.		9%	1%						1%	13%		1%	0.3%	1%	12%	4%	5%	64%		3%	3%	7%	2%	5%		
IC determinations																												
Salt Solution	4	Mean						102.6													35.6							
		Standard Deviation						9.1													2.6							
		Relative Std. Dev.						9%													7%							
Detection limits, Stanford analyses		7.0		0.6		0.006	0.6		3.0	0.4	0.3	0.010		0.020	18.0		0.007	5.0	0.002	9.0	0.006	10.0		110.0		1.0		
Estimated upper limit of linear range				300000		300		500				500					500				500	200000						

NIST (National Institute of Standards and Technology) SRM (Standard Reference Material) 1643c "Trace Elements in Water" was used for ICP-OES analysis.

** Element for which concentration of NIST 1643c is not certified, and for which no standard deviation is provided

Salt Solutions were prepared by us to contain additional trace elements for ICP-OES analyses, and as a reference for Cl and S for IC analyses.

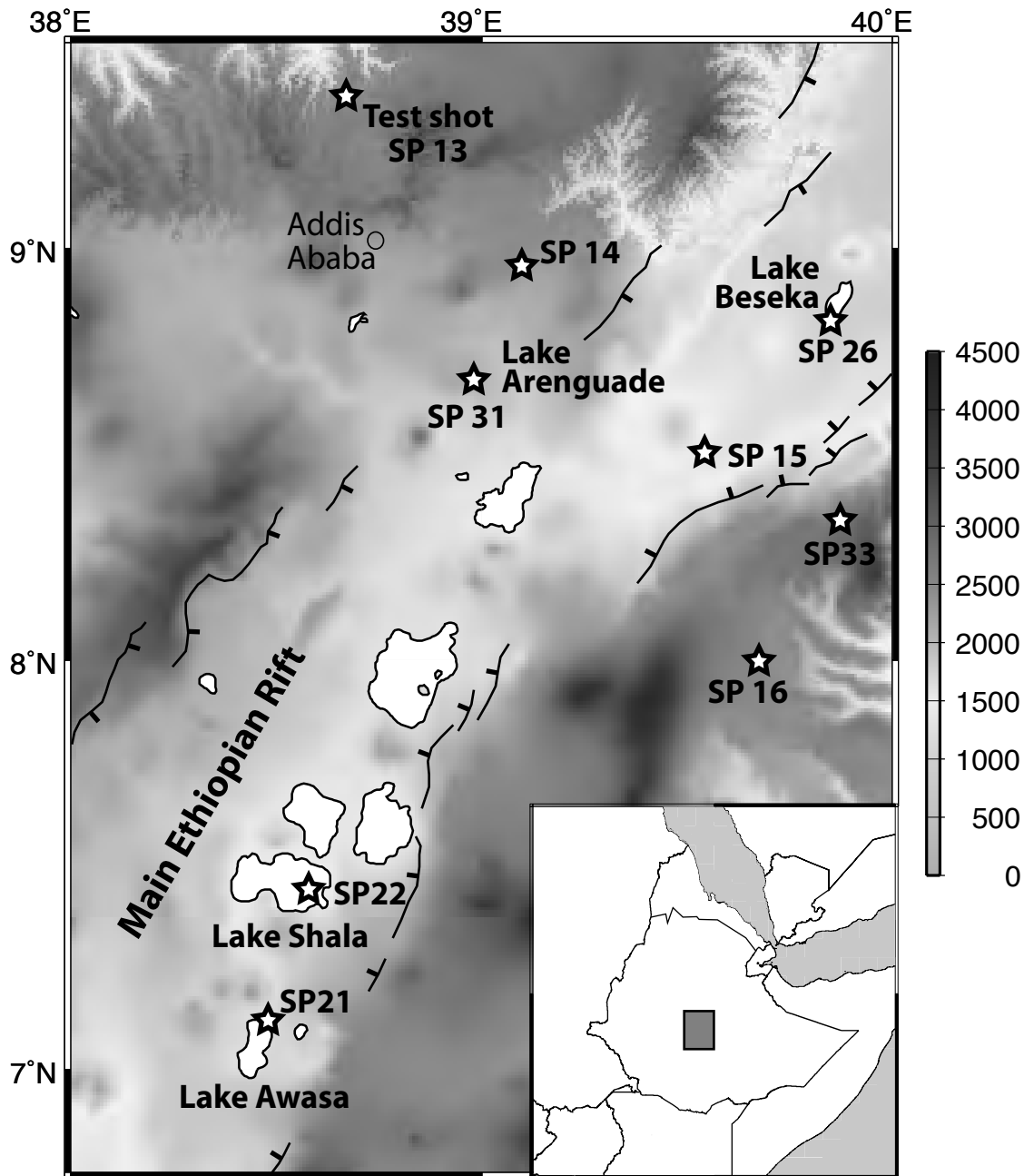


Figure 1

Sites for water-sampling superimposed on grey-scale relief map of central Ethiopia. Open stars are seismic shot-points. Streams were sampled at shotpoints (SP) 14, 15, 16, 33 and "Test shot"; and Lakes Awasa, Shala, Beseka and Arenguade were sampled at SP 21, 22, 26 and 31. (Lake Arenguade is smaller than the star signifying the location of the shot point.) Main Ethiopian Rift lies between the inward facing normal faults (black lines) down-dropped on the side of the short tick-marks (faults generalised from Bonini et al., 2005).

Klemperer & Cash, Figure 2

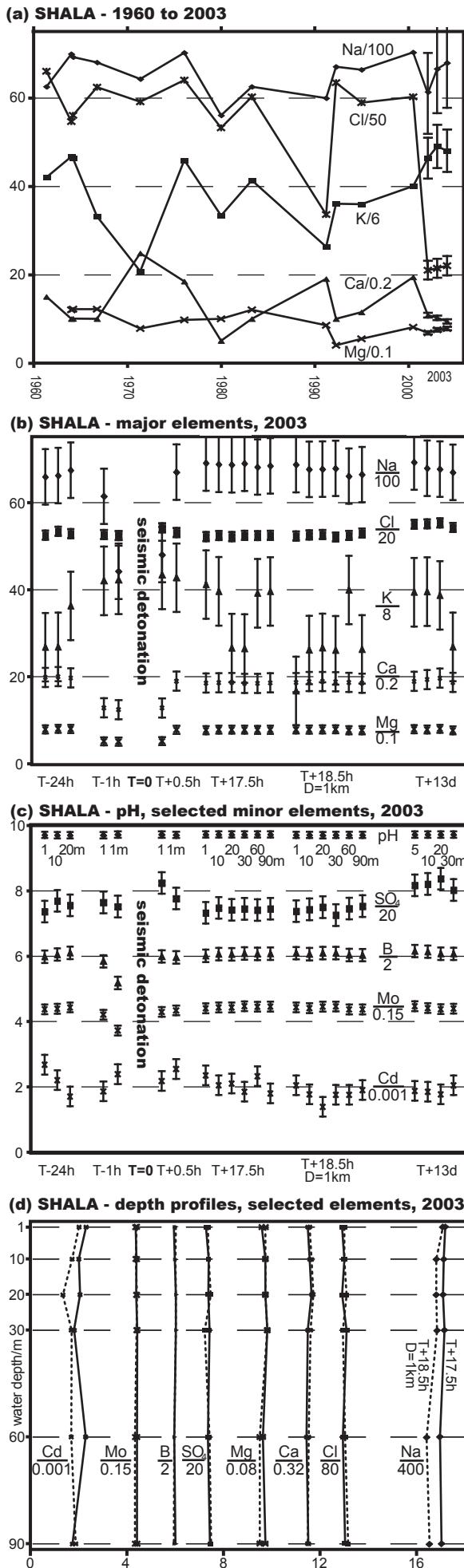


Figure 2

(a) Major-element determinations (Table 1) for Lake Shala from 1961 to 2003. Concentrations are in ppm, but note different divisors applied to each ion to allow visual separation of the curves. New results presented in this paper are shown with error bars of 5% (Ca and Mg), 10% (K and Cl) or 15% (Na). Our January 2003 data are presented as the means of three groups of measurements: before the seismic detonation; up to 24 hours after the detonation; and more than one week after the detonation. These three groups are plotted at 2002, 2003 and 2004 to allow easy visualization, and their component values are given in Table 2 and plotted in (b).

(b) Major element and (c) selected minor and trace element concentrations (including those species for which potentially significant variation was found with respect to the seismic detonation in Lake Arenguade) and pH (see Table 2).

Concentrations are in ppm, but note different divisors applied to each species to allow a visual separation of data. Error bars are standard deviations of the entire suite of 23 measurements of each ion/element for Shala, and are intended to indicate significance of relative changes, not absolute uncertainties. Concentrations are plotted against sampling time with respect to the seismic detonation (h=hour, d=day). Samples collected 1 km from the shot location are indicated (D=1km). Numbers below pH values are water depths from which each sample was taken and also apply to data in (b). No statistically significant variation with location or depth or time is seen.

(d) Depth profiles for eight species from (b) and (c) above, to show the lack of stratification with depth. Dotted lines: samples collected 1 km from shot location; solid line: samples collected at shot point, both the day after the detonation. Concentrations are in ppm, but note different divisors applied to each species to allow a visual separation of data.

Klemperer & Cash, Figure 3

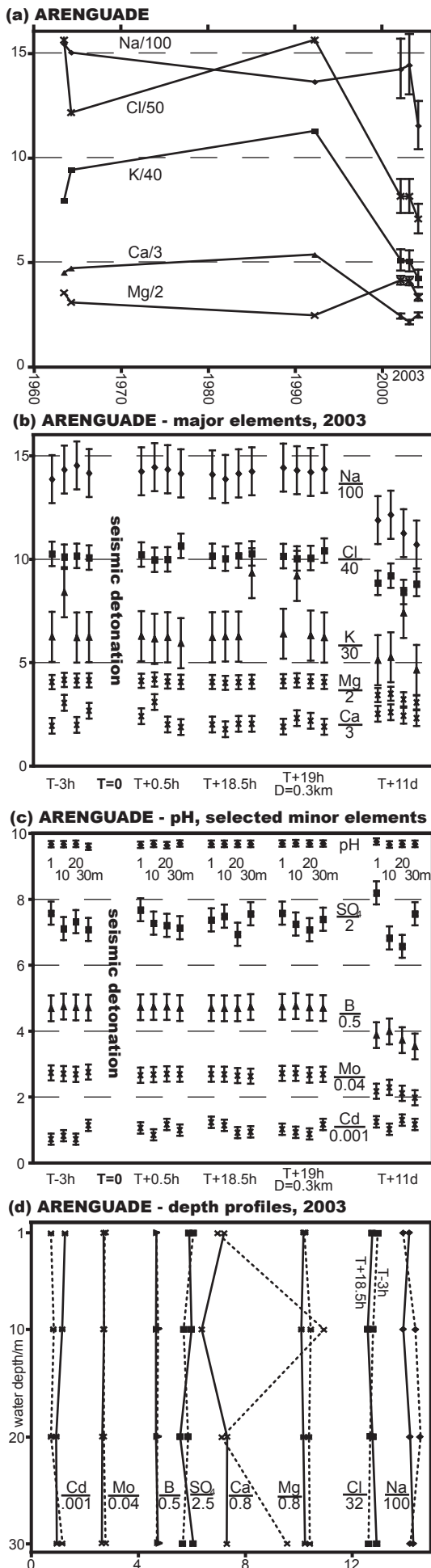


Figure 3

(a) Major-element determinations (Table 1) for Lake Arenguade from 1963 to 2003. Concentrations are in ppm, but note different divisors applied to each ion to allow visual separation of the curves. New results presented in this paper are shown with error bars of 5% (Ca and Mg) and 10% (Na, K and Cl). Our January 2003 data are presented as the means of three groups of measurements: before the seismic detonation; up to 24 hours after the detonation; and more than one week after the detonation. These three groups are plotted at 2002, 2003 and 2004 to allow easy visualization, and their component values are given in Table 3 and plotted in (b).

(b) Major element and (c) selected minor and trace element concentrations (focussing on species for which potentially significant variation was found with respect to the seismic detonation) and pH (see Table 3). Concentrations are in ppm, but note different divisors applied to each species to allow a visual separation of data. Error bars are standard deviations of the entire suite of 20 measurements of each ion/element for Arenguade and are intended to indicate significance of relative changes, not absolute uncertainties. Concentrations are plotted against sampling time with respect to the seismic detonation (h=hour, d=day). Samples collected 300 m from the shot location are indicated (D=0.3km). Numbers below pH values are water depths from which each sample was taken and also apply to data in (b). No statistically significant variation with location or depth is seen; potentially significant variations with time are discussed in the text.

(d) Depth profiles for eight species from (b) and (c) above, to show the lack of stratification with depth. Dotted lines: samples collected 3 hours before shot detonation; solid line: samples collected the day after the detonation. Concentrations are in ppm, but note different divisors applied to each species to allow a visual separation of data.



Figure 4

Views of detonation in Lake Arenguade taken from rim of crater.

Top: approximately one second after initiation a water spout is present above the 100m x 25 m area beneath which the explosives were placed, and reaches a maximum height of 10 - 20 m.

Middle: approximately 20 seconds after detonation, dark turbid water spreads outwards from the central white area in which bubbles are still rising to the surface.

Bottom: approximately one minute after detonation, muddy boils continue to rise to the surface.

Width of photographs is c. 300 m (top and middle) and c. 200 m (bottom).

Photographs courtesy G.R. Keller (top and middle) and G. Kaip (bottom).

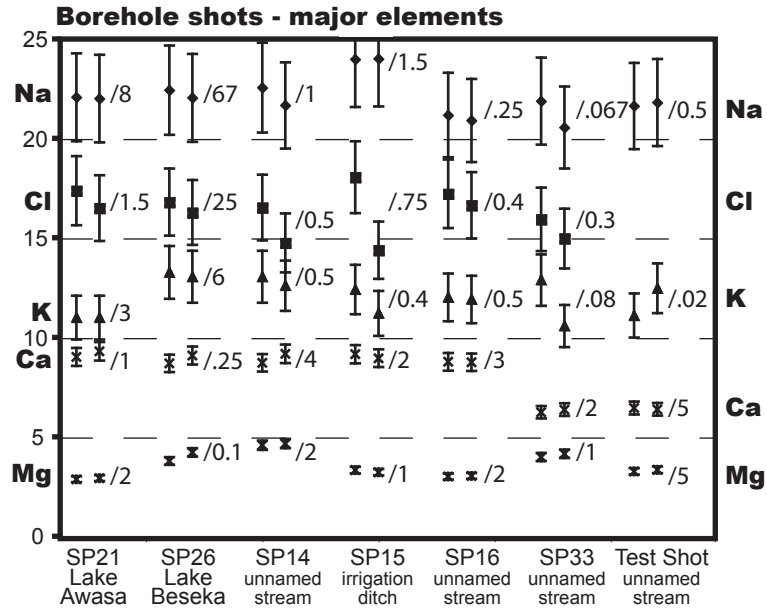


Figure 5

Relative major element concentrations measured in waters adjacent to borehole detonations, from Table 4. Concentrations are in ppm, but note different divisors (listed to right of the two measurements to which each applies) applied to each ion and each sampling location to allow approximate alignment and separation of each species. Uncertainties are shown as 10% for Na, Cl and K, and 5% for Ca and Mg, based on repeatability of measurements on standard solutions (Table 5). Location of each pair of measurements is indicated along base of plot; left and right concentration in each pair is from samples taken before and after the detonation, respectively. Each pair of samples is constant within uncertainty: no statistically significant variation due to detonation is apparent.