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Lake Afrera, a structural depression in the Northern Afar Rift (Red Sea)

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Abstract

The boundary between the African and Arabian plates in the Southern Red Sea region is displaced inland in the northern Afar rift, where it is marked by the Red Sea-parallel Erta Ale, Alaita, and Tat Ali volcanic ridges. The Erta Ale is offset by about 20 and 40 km from the two en echelon ridges to the south. The offset area is highly seismic and marked by a depression filled by lake Afrera, a saline body of water fed by hydrothermal springs. Acoustic bathymetric profiles show ≈ 80 m deep canyons parallel to the NNW shore of the lake, part of a system of extensional normal faults striking parallel to the Red Sea. This system is intersected by oblique structures, some with strike-slip earthquakes, in what might evolve into a transform boundary. Given that the lake's surface lies today about 112 m below sea level, the depressed (minus ≈ 190 m below sea level) lake's bottom area may be considered the equivalent of the "nodal deep" in slow-slip oceanic transforms. The chemistry of the lake is compatible with the water having originated from hydrothermal liquids that had reacted with evaporites and basalts, rather than residual from evaporation of sea water. Bottom sediments include calcitic grains, halite and gypsum, as well as ostracod and diatom tests. The lake's level appears to have dropped by over 10 m during the last ≈ 50 years, continuing a drying up trend of the

last few thousand years, after a “wet” stage 9,800 and 7,800 years before present when according to Gasse (1973) Lake Afrera covered an area several times larger than at present. This “wet” stage corresponds to an early Holocene warm-humid climate that prevailed in Saharan and Sub Saharan Africa. Lake Abhé, located roughly 250 km south of Afrera, shows similar climate-driven oscillations of its level.

Keywords: Geology

1. Introduction

The Northern Afar Depression is a region adjacent to the Southern Red Sea on the African side, where the transition from a continental to an oceanic rift is taking place today, related to the separation of Arabia from Africa (Fig. 1). The first modern geological expeditions to the Afar region took place in the years 1969–1974 under the leadership of G. Marinelli and H. Tazieff. Much additional field work has been carried out in the area since that time; in particular, UK-USA (see Wright et al., 2006) and French (see Manighetti et al., 1998) projects.

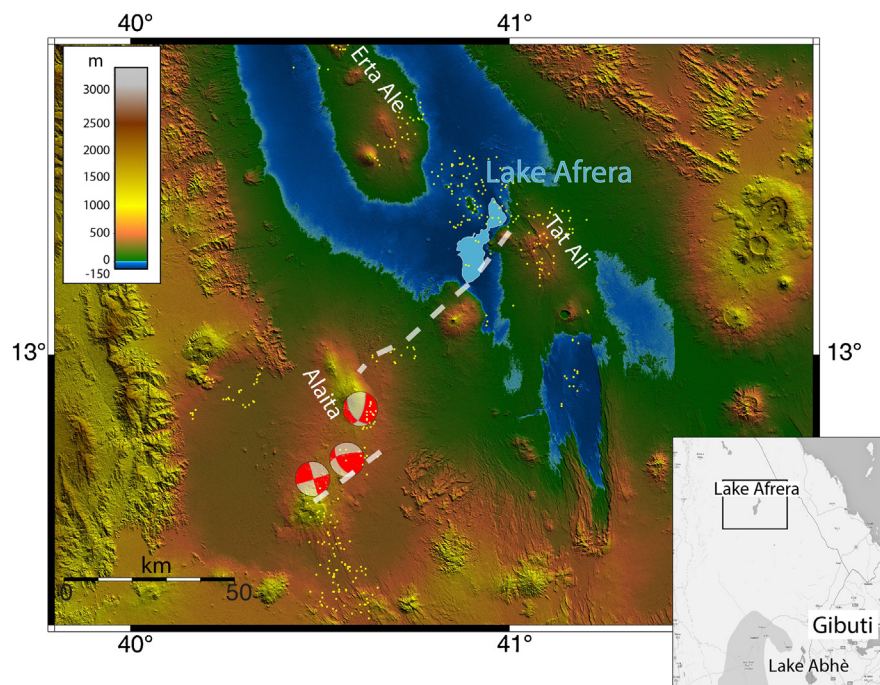


Fig. 1. Shaded-relief map of the Northern Afar rift showing the Erta Ale, Alaita and Tat Ali volcanic ridges and Lake Afrera compiled using altimetry from the SRTM 90 m Digital Elevation Database v4.1. Location of earthquakes with $M > 2$ (Belachew et al., 2011) is indicated by yellow dots. Focal mechanisms compatible with strike-slip motion (Ayele et al., 2009) are shown for some events located in an alignment SE of the lake. White dashed lines indicate possible location of an embryonic transform boundary.

Northern Afar is a depressed region partly below sea level, located between the western scarp of the Ethiopian-Eritrean Plateau and the Danakil Alps, a fragment of continental lithosphere that separated from the Ethiopian Plateau roughly 9.4 My ago (McClusky et al., 2010). Northern Afar is characterized by intense seismicity, hydrothermal activity and basaltic volcanism, focused particularly on a number of axial volcanic ranges oriented NNW-SSE, i.e., parallel to the Red Sea axis. The northernmost is the ~100 km long Erta Ale Ridge (Barberi et al., 1970; Barberi and Varet, 1977), an active segment of basaltic magmatism that includes a number of volcanic centers and displays one of the few permanent lava lakes of the Earth. Further south, we have the Alaita and Tat Ali Ridges, centers of basaltic volcanism also oriented NNW-SSE but placed en echelon relative to the Erta Ale Ridge (Fig. 1). The lavas erupted by these systems have affinity with MORB, except for mild enrichments possibly due to the influence of the Afar plume; no significant contamination from sub-continental mantle components has been detected (Barberi and Varet, 1970; Barrat et al., 1998). An additional axial range, very active recently, is the Dabbahu-Manda Hararo segment, located south of the Alaita-Tat Ale ranges (Fig. 1). These axial ridges mark the development of a new boundary between the African and the Arabian plates, displaced inland from the axis of the Red Sea, opening at an average rate of less than 1 cm/yr (Ar Rajehi et al., 2010). Magnetic stripes from these northern Afar axial ranges (Hall, 1970, Bridges et al., 2012) also suggest very low (<1 cm/yr) half-spreading rates.

Between the Erta Ale and the Alaita-Tat Ali ridges lies a depression occupied by lake Afrera, consisting of two basins communicating through a narrow passage (Fig. 1). The surface of the lake was around 90 m below sea level in 1970 (Gasse et al., 1974), when it covered an area of roughly 70 km². The lake contained in 1969 highly saline water (≈ 159 g/l, Martini, 1969). The bathymetry of the lake was unknown.

We report in this paper some old, but as yet unpublished data resulting from a bathymetric survey of the lake's bottom that took place in 1969 during one of the Marinelli-Tazieff expeditions to Afar. The reason for their delayed publication is that the echosounder profiles, lost during transport, have been retrieved only recently. We will then discuss the structural/tectonic significance of the Afrera depression, as well as paleoclimatic implications of changes of the lake's level.

2. Methods

Profiles across the lake were carried out by G. Ferrara and one of us (EB) on a rubber boat equipped with a portable echosounder, powered by a car battery. Position was determined considering that the profiles were collected at constant speed and tied to reference points on land targets. The thermal-paper bathymetric records (Fig. 2) were converted in echograms using the SeisPrho software (Gasperini and Stanghellini, 2009). Each profile was subsequently digitized and

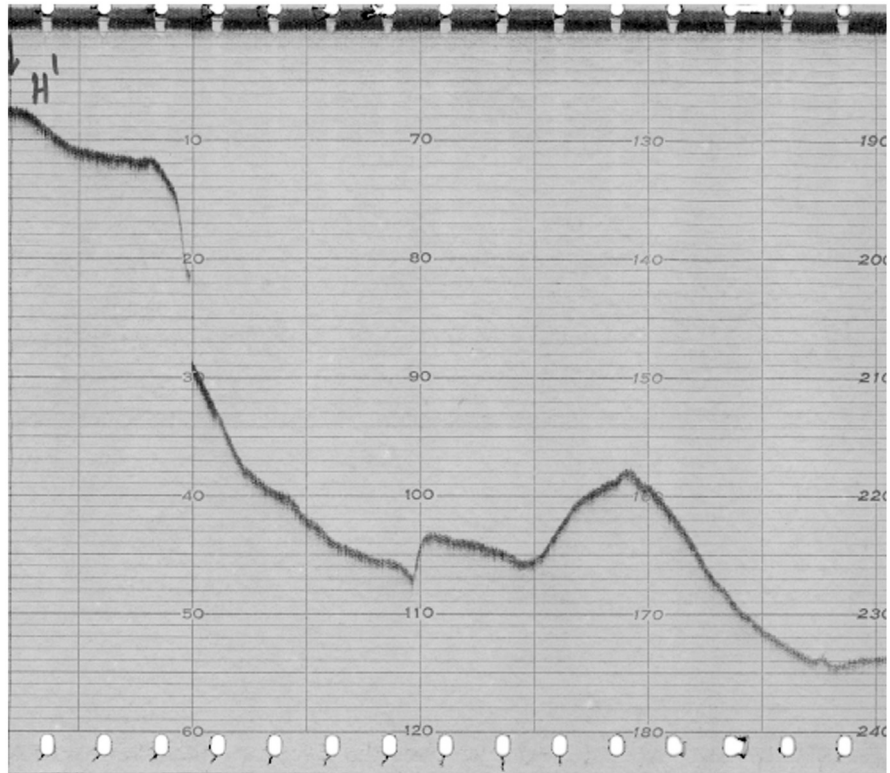


Fig. 2. Example of echogram collected from Lake Afrera in 1969.

georeferenced using notes recorded in the field, producing bathymetric profiles that assumed a constant-velocity propagation of the echosounder signal in “normal” seawater conditions. Given the high salinity of the lake’s water, a correction factor of 1.2 was applied to the soundings, according to standard formulas relating sound velocity and salinity (Mackenzie, 1981). The present-day (2016) lake’s level has been determined by satellite altimetry (Google Earth 7.1.5.1557, data build 5/20/2015, Fig. 1).

A short (≈ 35 cm) sediment core (AF-1C) was recovered about 50 m off the SW shore of the lake below ≈ 1 m of water (Fig. 3) by inserting a Plexiglas liner into the sediment. The sediment was extruded and sampled in the field. Texture, mineralogy and chemistry of samples of this core were studied by Scanning Electron Microscopy (SEM Zeiss, LS10 model) at CNR (Bologna, Italy) and by X-ray diffraction at the University of Bologna, using a XRD diffractometer. Rock-magnetic investigations have been carried out on samples of the core in the paleomagnetic laboratory at the ISMAR-CNR Bologna. The measured parameters include: 1) magnetic susceptibility (κ), measured by using a Bartington MS2 susceptibility meter; 2) anhysteretic remanent magnetization, applied by subjecting the samples to an alternating field (AF) of 100 millitesla (mT) biased by a 0.1 mT direct field; the acquired ARM was demagnetized by applying an AF field of

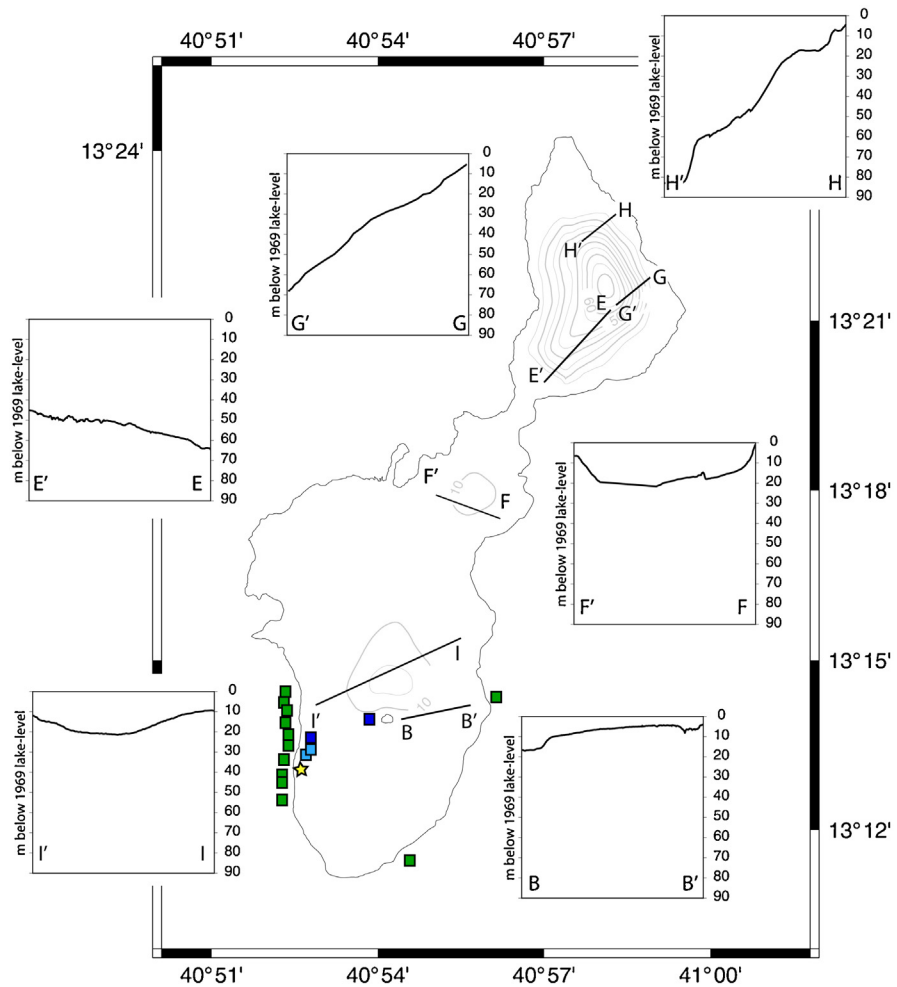


Fig. 3. Bathymetric profiles collected in Lake Afrera (multiple vertical exaggerations are used). Filled squares indicate location of water samples from hot springs (green), and from the lake (blue squares); location of the sediment core is indicated by a yellow star.

20mT; 3) isothermal remanent magnetization (IRM), applied up to a maximum field of 1 tesla (T). The acquired IRM is here referred as saturation isothermal remanence, SIRM.

Water samples were collected from the same area in 2012 and 2013. Water cations and anions content was determined by ion-chromatography using a 861 advanced compact EC-metrohm for cations, and a 761 compact EC-metrohm for anions at the Department of Earth Sciences of the University of Firenze

3. Results

3.1. Topography

Both of the lines perpendicular to the NNE shore of the lake show a topographic minimum over 80 m below the lake's 1969 surface (Fig. 3 and Supplementary

Material), marking probably the bottom of a canyon oriented parallel to a set of normal faults exposed on shore (Fig. 3). A few lines scattered in the lake's SW basin show a relatively flat bottom lying roughly 20 m below the 1969 surface (Fig. 3). The narrow channel connecting the NE and the SW basins lies also about 20 m below the 1969 lake's level.

We attempted to estimate the extent to which the lake's level changed relatively to sealevel, from 1969 to present (2016), i.e., through almost half a century. We estimated by satellite altimetry (SRTM global database) at 112 m the present-day (2016) level of the lake's surface relative to today's sea level. The lake's level appears to have decreased significantly from ≈ 90 m below sea level in 1969, to 112 m below sea level. Satellite images show present-day dried flat sedimented areas around the edge of the lake that may have resulted from lowering of the lake's level (Fig. 4).

3.2. Bottom deposits

The 35 cm-long sediment core shows a ≈ 10 cm thick light gray upper zone, a darker 10 cm thick intermediate zone, and a gray 15 cm thick bottom zone (Fig. 5). Optical and scanning electron-microscopy and X-ray diffraction show the prevalence throughout the core of round calcite aggregates ranging in size up to 500 μm . They are frequently encrusted by halite that forms also cubic crystals scattered in the sediment (Fig. 6). Tests of ostracods, gastropods and diatoms are



Fig. 4. Google Earth satellite-derived 3-D image (vertical exaggeration 3x) of the southern shore of Lake Afrera's eastern basin, showing sedimented beaches that may have resulted from lowering of the lake's level. Differences in level from the water edge and the base of the volcanic scarp is about 5 m.

also present. Rounded sulfide (pyrite) and platy sulfate (gypsum) crystals were also observed, as well as a few scattered basaltic glass shards. A low detrital content reflects the low magnetic components concentration, as indicated by the low κ and SIRM values. Their values are constant throughout the sequence, except for a small increase is observed in the lowermost unit (Fig. 5). A peak corresponding to a dark layer at around 9 cm of depth is also characterized by the presence of antiferromagnetic minerals as indicated by a low S-ratio (not shown in the figure). Analysis of grain size interparametric ratios SIRM/ARM (increasing with the grain size) and ARM/ κ (decreasing with the grain size) reflect the subdivision into three intervals, indicating that the magnetic grain size is correlated with the detrital fraction.

3.3. Water chemistry

The Na-Ca-Mg ratio of the lake's water measured in 1968 by Martini (1969), was similar to that of thermal springs feeding the lake on the SW side and to that of water sampled in 2008 and 2009 (Fig. 7). These waters fall in a separate cluster of Na-Ca-Mg ternary plots relative to Standard seawater and Dead Sea waters (Fig. 7)

4. Discussion

4.1. Tectonics

The depression filled by Lake Afrera corresponds to an offset in the axial volcanic range of northern Afar: the southern termination of the Erta Ale ridge is offset by ≈ 20 km relative to the northern tips of the Alaita ridge on one side, and by ≈ 40 km relative to the Tat Ali ridge on the other side (Fig. 1). The topographic/structural

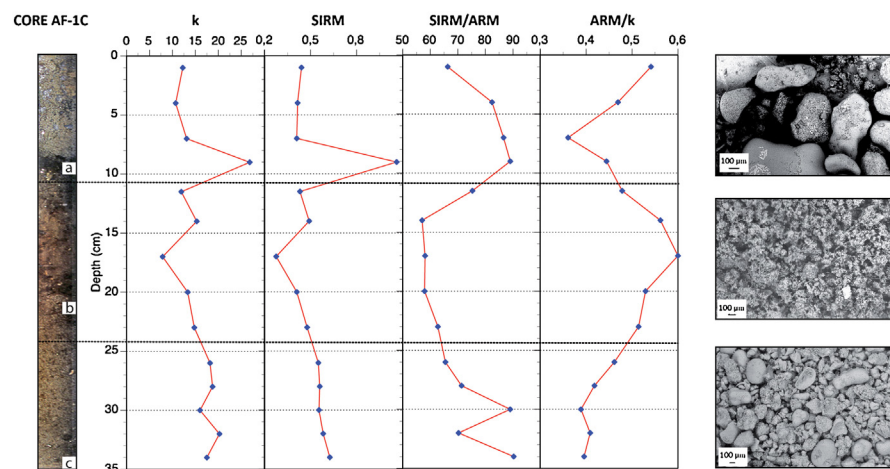


Fig. 5. Core AF-1C collected off the SW shore of Lake Afrera (see Fig. 3 for location). From left to right: photo; magnetic properties; SEM images from the 3 units a, b and c, showing different textures of grains.

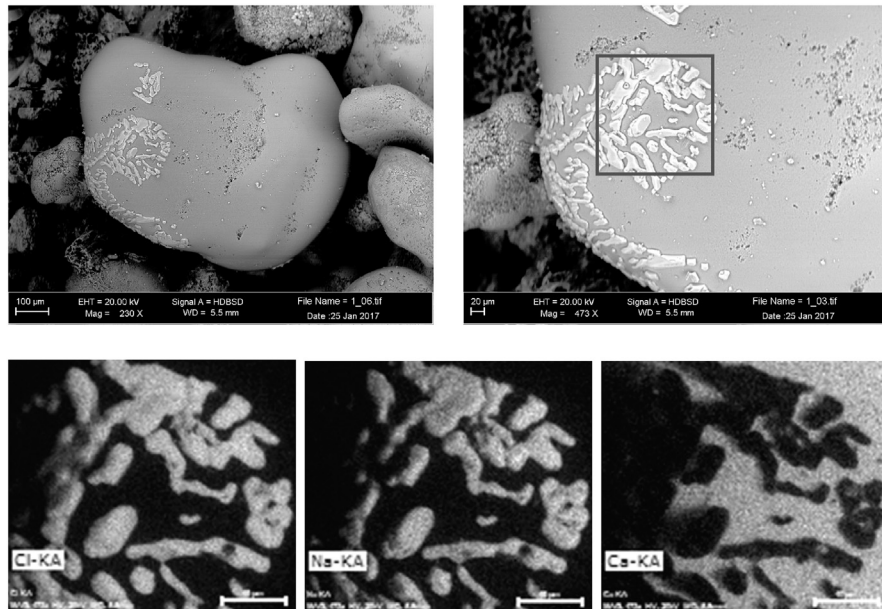


Fig. 6. Scanning electron-microscope image of a sample collected from core AF-1C showing halite cubic crystals encrusting sediment grains.

features of the lake's bottom and of the areas surrounding the lake suggest the interaction of two main structural directions, one oriented NNW-SSE, i.e., parallel to the Red Sea axis; the other NNE-SSW, oblique although not perpendicular to the Red Sea axis (Fig. 1). The small NNW-SSE graben identified in the lake's floor, parallel to a normal faults system exposed along the NE shore of the lake (Fig. 3), is probably part of this system. The floor of this graben, reaching about 80 below the 1969 lake's level (i.e., ≈ 190 m below sea level) is probably the lowest topographic level of the entire Afar region. On the other hand, the scant topographic data from the lake's bottom suggest NE-SW oriented structures intersecting those parallel to the Red Sea axis. The Lake Afrera topographic minimum marks an area where "oblique" trends intersect "axial" structures, in a setting that in mid-ocean ridges would correspond to a "nodal deep".

A seismic network system operating in northern Afar during the 2007–2009 time interval (Belachew et al., 2011) revealed a dense cluster of earthquakes (mostly magnitude 3 and 4) in the assumed proto-transform depressed area between the southern tip of the Erta Ale and the northern tip of the Alaita and Tat Ali ranges (Fig. 1). Although the absence of seismometers in Eritrea (eastern part of study area) prevented focal mechanism determination, the spatial distribution of well located earthquakes supports the idea that Lake Afrera depression might evolve into a transform boundary. In addition, a number of earthquakes aligned SW-NE west of Afrera show a strike-slip component (Ayele et al., 2009) compatible with this idea.

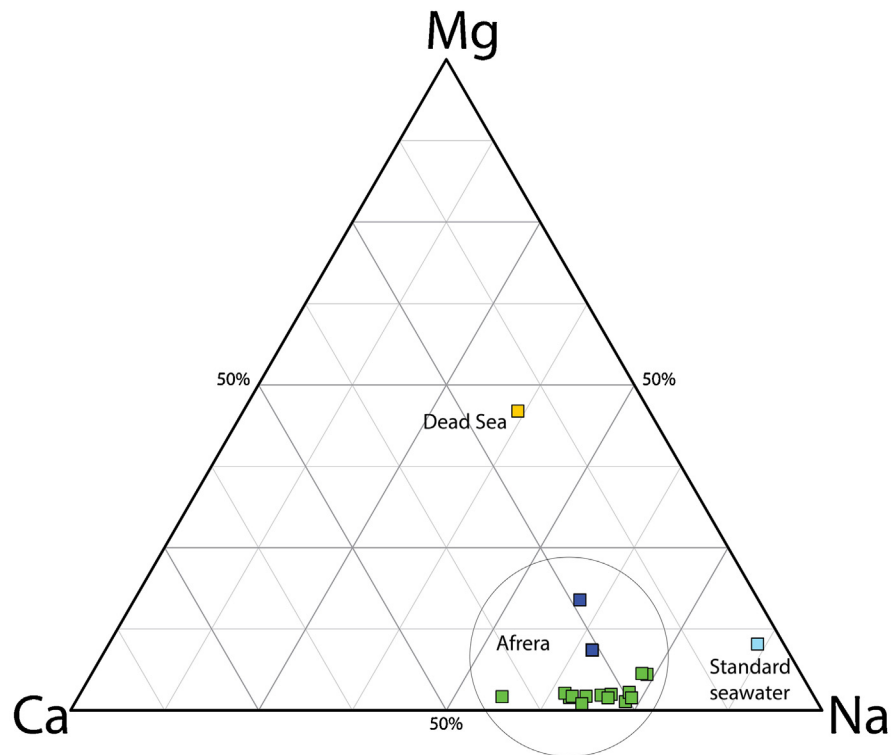


Fig. 7. Ternary diagram showing ratio of Na-Mg-Ca in the water samples from Lake Afrera (blue squares) and from hot springs feeding the lake (green squares), compared with Dead Sea (yellow squares) and Standard seawater (cyan squares) analysis, from Mason (1966) and Stein et al. (1997), respectively.

NE of the lake shore along the extension of the sublacustrine “oblique” structures, a hyaloclastite ring with a phreatic explosion crater has been found; it consists of alkali basalt, (i.e., of basalt with a composition different from that of the Erta Ale and Alaita axial ranges), that contains peridotites nodules (Barberi et al., 1974). We note that throughout northern Afar volcanism aligned in the axial, Red Sea-parallel ranges, such as Erta Ale, produced basalts with elemental/isotopic composition approaching that of MORB, indicating mantle-derived melts uncontaminated by continental lithosphere components. In contrast, volcanism associated to a number of structures oriented oblique or normal to the Red Sea axis produced alkali basalts, often containing peridotite xenoliths (Barberi et al., 1974; Barberi and Varet, 1977). Based on the similarity to kinematics of the <4 Ma seafloor spreading segments on the Red Sea rift, the NNE-striking faults may transfer strain from NNW-trending magmatic segments (or axial volcanic ranges).

Beyond the NNW tip of the Erta Ale ridge the occurrence of dyke intrusions and of a shallow (2.4 km deep) magma chamber beneath evaporites in the Dallol area (Fig. 1) and of intense shallow seismicity (Nobile et al., 2012), suggest NNW propagation of the Erta Ale magmatic/tectonic activity linked to rifting. It is

possible that a similar activity took place beyond the SSE tip of the Erta Ale, where lake Afrera is located. In fact, zones of rapid uplift or subsidence in response to magmatic intrusions or to tectonic extension are scattered throughout Northern Afar (Amelung et al., 2000; Pagli et al., 2014). A 7,800 yrs BP sudden increase of lake Afrera's level and salinity may have been caused by a tectonic/magmatic/hydrothermal event that took place in that area (Gasse et al., 1974).

4.2. Water and sediment composition

We compared the chemistry of the two water samples collected by us in 2012 and 2013 with that of a water sample collected in 1968 by Martini (1969) and with that of hot springs from the western side of the lake plus one from the SE side (Fig. 3) also from Martini (1969). Most of the northern Afar depression was probably covered by the Red Sea up to about 30 ka (Bonatti et al., 1971). However, the Na-Ca-Mg ratio of lake Afrera's water suggests that the lake is not residual after evaporation of a Red Sea branch, but is fed by numerous hydrothermal springs, some surfacing close to the lake's shores after having reacted with evaporites and basalts, leaching Ca and to a lesser extent, Mg. These springs were injected into the lake in 1968 at temperatures ranging from 43 to 50 °C (Martini, 1969).

The prevalence of calcite spherules in the sediments off the SW side of the lake, plus ostracod, gastropod and diatom tests, is consistent with the present-day lake's deposits being dominated by the influx of those components from areas surrounding the lake. In fact, similar assemblages are prevalent in the region, having originated from a Holocene proto-Afrera basin much wider than the present lake (Gasse et al., 1974; Martini, 1969). Halite, gypsum and sulfides may in part be deposited within the present-day saline lake.

4.3. Paleoclimate

The evolution of Lake Afrera has significant paleoclimatic implications. Based on diatom stratigraphy and C-14 ages of lacustrine deposits exposed in a wide area around present day lake Afrera, Gasse et al. (1974) indicated that from 9,800 yrs BP to 7,800 yrs BP lake Afrera covered roughly 250 km², i.e., an area several times larger than its present surface. This "wet" stage can be related to an early Holocene warm/humid climate that prevailed in sub-Saharan Africa forming widespread lacustrine deposits; their ages range from 12,000 yrs BP to 5,000 yrs BP (Gasse, 2000; Servant and Servant, 1980). Humid conditions prevailed also in the present hyper-arid Sahara region during the same time interval, except for a short cold/dry spell lasting about 1 kyrs, corresponding to the Younger Dryas of southern Europe (Gasse, 2000; De Menochal et al., 2000). This pattern was interrupted also around 7,800 yrs BP by the sudden increase of the lake's level and salinity cited above (Gasse et al., 1974).

The present-day (2016) surface of the lake, measured by satellite altimetry, is minus 112 m below sea level. In 1969, the lake's surface was estimated at 90 to 100 m below sea level. It would then appear that the lake's surface dropped by 10 to 20 m in half a century, thus continuing a desiccation trend that started several thousand years ago, although we cannot exclude that some changes in the level of the lake's floor might have been triggered by magmatic-tectonic activity and/or that the lake's level was influenced by increased evaporation owing to recent salt mining activities.

Lake Abhé, located roughly 250 km south of Afrera (Fig. 1), also underwent strong water level oscillations in the late Pleistocene (Gasse, 1977). The lake in the nineteen seventies covered an area of $\approx 350 \text{ km}^2$ with its surface laying 240 m above sea level. Present-day satellite altimetry of Lake Abhé indicates a surface area of 290 km^2 and a surface at 233 m above sea level (SRTM altitude data), suggesting a partial drying up in the last 50 years, as in Lake Afrera further north. Lake Abhé was dry from 17,000 yrs BP to 10,000 yrs BP; it then became much "wetter" than at present in the 8,000–4,000 yrs BP interval (Gasse, 1977). In interpreting these data, we should keep in mind that lake Abhé is fed by the Awash River that comes down from the Ethiopian Plateau. Thus, variations of the lake's level are affected in part by precipitation patterns on the Plateau, contrary to the case of lake Afrera.

5. Conclusions

The highly saline Lake Afrera fills a topographic depression in the northern Afar Rift at the offset between the southern tip of the Erta Ale volcanic ridge and the northern tips of the Alaita and Tat Ali ridges. Bathymetric profiles revealed $\approx 80 \text{ m}$ deep canyon (minus $\approx 190 \text{ m}$ below sea level) parallel to NNW normal faults exposed at the NE shore of the lake. The Afrera depression is located at the intersection of NNW-SSE extensional features parallel to the Red Sea axis, with oblique features marked by alignments of strike-slip earthquakes. The Afrera depression might evolve into an embryonic transform boundary. The surface of the lake in 1969 was roughly 90 to 100 m below sea level, while today is about 112 m below sea level, suggesting a drop of several meters in half a century. This is consistent with a drying trend for the last several thousand years after a "wet" interval that, according to Gasse (1973) lasted from 9,800 to 7,800 yrs BP. These changes of lake's level resulted mostly from sub-Saharan climatic variations, although local tectonic-magmatic-hydrothermal events may also have had an influence. The Ca-Na-Mg ratio of the lake's water, similar to that of circum-lake hot springs, suggests that the lake is not residual after evaporation of sea water.

Declarations

Author contribution statement

Enrico Bonatti: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Elia Gasperini, Alina Polonia: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Luigi Vigliotti, Luca Lupi, Orlando Vaselli: Contributed reagents, materials, analysis tools or data.

Luca Gasperini: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

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References

Ar Rajehi, A., McClusky, S., Reilinger, R., Daoud, M., Alchalbi, A., Ergintav, S., Gomez, F., Sholan, J., Bou-Rabee, F., Ogubazghi, B., Haileab, B., Fisseha, S., Asfaw, L., Mahmoud, S., Rayan, A., Bendik, R., Kogan, L., 2010. Geodetic constraints on present-day motion of the Arabian Plate: Implications for Red Sea and Gulf of Aden rifting. *Tectonics* 29, TC3011.

Ayele, A., Keir, D., Ebinger, C., Wright, T.J., Stuart, G.W., Buck, W.R., Jacques, E., Ogubazghi, G., Sholan, J., 2009. September 2005 megadike emplacement in the

- Manda-Harraro nascent oceanic rift (Afar Depression). *Geophys. Res. Lett.* 36, L20306.
- Amelung, F., Oppenheimer, C., Segall, P., Zebker, H., 2000. Ground deformation near Gada 'Ale volcan. Afar, observed by radar interferometry. *Geophys. Res. Lett.* 27, 3093–3096.
- Barberi, F., Bonatti, E., Marinelli, G., Varet, J., 1974. Transverse tectonics during the split of a continent: data from Afar Rift. *Tectonophysics* 23, 17–29.
- Barberi, F., Borsi, S., Ferrara, G., Marinelli, G., Varet, J., 1970. Relations between tectonics and magmatology in the northern Danakil Depression (Ethiopia). *Phil. Transaction. Roy. Soc. London A* 267, 293–311.
- Barberi, F., Varet, J., 1970. The Erta Ale volcanic range (Danakil Depression, Northern Afar, Ethiopia). *Bull. Volcanologique* 34, 848–917.
- Barberi, F., Varet, J., 1977. Volcanism in Afar: small scale plate-tectonics implications. *Bull. Geol. Soc. Am.* 88, 1251–1266.
- Barrat, J.A., Fourcade, S., Jahn, B.M., Cheminée, J.L., Capdevila, R., 1998. Isotope (Sr, Nd, Pb, O) and trace-element geochemistry of volcanics from the Erta'Ale range (Ethiopia). *J. Volcanol. Geotherm. Res.* 80, 85–100.
- Belachew, M., Ebinger, C., Coté, D., Keir, D., Rowland, J.V., Hammond, J.O.S., Ayele, A., 2011. Comparison of dike intrusion in an incipient seafloor spreading segment in Afar, Ethiopia: seismicity perspectives. *J. Geophys. Res.* 116, 1–23.
- Bonatti, E., Emiliani, C., Ostlund, G., Rydell, H., 1971. Final desiccation of the Afar Rift, Ethiopia. *Science* 172, 468–469.
- Bridges, D.L., Mickus, S.S., Gao, M.G., Alemu, A., 2012. Magnetic Stripes of a Transitional Continental Rift in Afar. *Geology* 40, 203–206.
- De Menochal, P., Ortiz, J., Guilderson, T., Adkinns, J., Sarntheim, M., Baker, L., Yarusisky, M., 2000. Abrupt onset and termination of the African Humid Period: rapid climate responses to gradual insolation forcing. *Quat. Sci. Rev.* 19, 347–361.
- Gasperini, L., Stanghellini, G., 2009. SeisPrho: an interactive computer program for processing and interpretation of high-resolution seismic reflection profiles. *Comput. Geosci.* 35, 1497–1507.
- Gasse, F., 1973. Diatomées des sédiments holocènes du lac Afrera (Afar Septentrional Ethiopia). *Intern. Rev. Ges. Hydrobiol.* 58, 941–964.
- Gasse, F., 1977. Evolution of lake Abhè (Ethiopia and TFAI) from 70,000 BP. *Nature* 265, 42–45.

- Gasse, F., 2000. Hydrological changes in the African tropics since the Last Glacial Maximum. *Quat. Sci. Rev.* 19, 189–211.
- Gasse, F., Fontes, J.C., Rognon, P., 1974. Variations hydrobiologiques et extension des lacs Holocene au desert Danakil. *Palaeogeogr. Palaeoclimat. Palaeosecol.* 15, 109–148.
- Hall, S., 1970. Total intensity of magnetic anomaly chart of the junction of the Red Sea, Gulf of Aden and Ethiopian rifts. S Hall – Hunting Service Ltd., Borehan Wood, Great Britain.
- Mackenzie, K.V., 1981. Nine-term equation for the sound speed in the oceans. *J. Acoust. Soc. Am.* 70, 807–812.
- Manighetti, I., Tapponier, P., Gillot, P.Y., Jacques, E., Courtillot, V., Armijo, R., Ruegg, J.C., King, G., 1998. Propagation of rifting along the Arabia-Somalia plate boundary into Afar. *J. Geophys. Res.* 103, 4947–4974.
- Martini, M., 1969. La geochimica del lago Giulietti. *Rend. Soc. Mineral. Italiana* 25, 1–16.
- Mason, B., 1966. *Principles of Geochemistry*, third ed. John Wiley & Sons Inc, pp. 346.
- McClusky, S., Reilinger, R., Ogubazghi, G., Amleson, A., Healeb, B., Vernant, P., Sholan, J., Fisseha, S., Asfaw, L., Bendick, R., Kogan, L., 2010. Kinematics of the Southern Red Sea–Afar Triple Junction and implications for plate dynamics. *Geophys. Res. Lett.* 37, L05301.
- Nobile, A., Pagli, C., Keir, D., Wright, T.J., Ayele, A., Runch, J., Acocella, V., 2012. Dike-fault interaction during the 2004 Dallol intrusion at the northern edge of the Erta Ale Ridge (Afar Ethiopia). *Geophys. Res. Lett.* 39, L19305.
- Pagli, C., Wang, H., Wright, T.J., Calais, E., Lewi, E., 2014. Current plate boundary deformation of the Afar ridge from a 3-D velocity field inversion of InSAR and GPS. *J. Geophys. Res.* 119, 8562–8575.
- Servant, M., Servant, S., 1980. L'environnement quaternaire du bassin du Chad in The Sahara and the Nile. In: William, M., Faure, H. (Eds.), *Balkema Rotterdam*, pp. 133–162.
- Stein, M., Starinsky, A., Katz, A., Goldstein, S.L., Machlus, M., Schramm, A., 1997. Strontium isotopic, chemical and sedimentological evidence for the evolution of lake Lisan and the Dead Sea. *Geochimica Cosmoch. Acta* 61, 3975–3992.

Wright, T.J., Ebinger, C., Biggs, J., Ayele, A., Yirgu, G., Keir, D., Stork, A., 2006. Magma-maintained rift segmentation at continental rupture in the 2005 Afar dyking episode. *Nature* 442, 291–294.