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Hydrothermal carbonate chimneys from a continental rift (Afar Rift): Mineralogy, geochemistry, and mode of formation

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ABSTRACT

Carbonate chimney-like deposits up to 60 m high are scattered or arranged in rows at the shores of a desiccating hypersaline and alkaline lake from a continental rift setting (Lake Abhé, Afar Rift, Djibouti). The chimneys formed sub-aqueously in the lake water body at a higher water level than observed today. Alternating calcite and low-Mg calcite + silica concentric layers compose the chimney structures. Mineralogical and geochemical investigations of the chimneys, lake water, and hot spring (hydrothermal) fluids suggest that the chimneys are a result of rapid carbonate precipitation during the mixing of hydrothermal fluids with lake water. In contrast to the hot spring fluid, lake water is enriched in HREE and possesses a pronounced positive Ce anomaly, features that are preserved in the carbonate chimney layers. Mixing calculations based on Sr-isotope and concentration data indicate a hydrothermal fluid contribution of ~45% in the chimney interior, which decreases to ~4% in the external chimney layer. Sr in the hydrothermal fluids is predominantly leached from the underlying volcanic rocks, whereas the lake's Sr budget is dominated by riverine input. Considering the fluid mixing ratios calculated by Sr-data, the measured C and O isotope compositions indicate that chimney carbonates precipitated at temperatures between 14 °C (internal part) and 22 °C (external part) with δ^{13}C-carbonate mainly controlled by isotope equilibrium exchange of lake water with atmospheric CO_2. The low-Mg calcite layers, including the outermost layer, have enhanced signals of lake water inheritance based on elevated concentrations of immobile elements, ΣREE, and Sr and Ca isotope compositions. Ca-isotope data reveal that internal chimney layers formed by non-equilibrium calcite precipitation with a predominantly hydrothermal Ca source. The external low-Mg calcite layer received Ca contributions from both hydrothermal fluid and lake water, with the latter being the dominant Ca source. Highly positive $\delta^{44/40}$Ca of lake water likely reflects non-equilibrium Ca-carbonate precipitation during lake water evaporation with resulting ^{44}Ca enrichment of residual lake water. The strong degree of ^{44}Ca enrichment may point towards multiple lake drying and Ca-reservoir depletion events. Coupled C–O–Ca-isotope data of the sampled carbonate chimney suggest late-stage (low-temperature) hydrothermal carbonate chimney formation during strongly evaporative lake conditions at the time of low-Mg calcite precipitation. U–Th age dating suggests that the chimneys formed no earlier than 0.82 kyr BP (0.28 ± 0.54).

1. Introduction

Since the discovery of hydrothermal activity at seafloor spreading centers (Corliss et al., 1979; Spiess et al., 1980), over 300 seafloor vent fields have been investigated in diverse settings spanning oceanic ridges, volcanic arcs, and hot spots (Hannington et al., 2011). While hydrothermalism and related mineral deposits have been well characterized in oceanic extensional settings (German and Von Damm, 2004), little is known regarding hydrothermal activity and deposits in areas of continental break-up and at the transition from continental rifting to seafloor spreading. Only a few works address sub-lacustrine hydrothermal activity in active continental rifts: e.g., the East African Rift system [Lakes Tanganyika (Tiercelin et al., 1989, 1993; Pflumio et al., 1994; Barrat et al., 2000), Malawi (Müller and Förstner, 1973;

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Branchu et al., 2005) and Bogoria (Renaut et al., 2013)], the Baikal Rift (Crane et al., 1991; Granina et al., 2007), and the Basin and Range Province (western United States) (Bischoff et al., 1993; Benson, 1994; Rosen et al., 2004).

Sub-lacustrine hydrothermal activity in the East African Rift system is particularly interesting due to its diverse tectonic settings. The southern part of the East African Rift (e.g., Tanganyika and Malawi Lakes) is a typical continental rift with thinned continental crust (Tiercelin et al., 1988), whereas the northern part (Afar Rift) constitutes the best modern example of a transition from continental rifting to incipient oceanic spreading (Ebinger and Casey, 2001). Despite significant efforts to investigate the tectonics and volcanism of the Afar Rift (De Chabalier and Avouac, 1994; Deniel et al., 1994; Hayward and Ebinger, 1996; Beyene and Abdelsalam, 2005; Wright et al., 2006; Bastow and Keir, 2011; Moucha and Forte, 2011), hydrothermal activity and associated deposits remain uncharacterized [excluding drilled geothermal wells (Fouillac et al., 1989; D'Amore et al., 1998)]. Recent (from ~4000 BP onward; Gasse and Street, 1978) and progressive desiccation of the alkaline, salty Lake Abhé located in the Afar Rift reveals an impressive picture of sub-lacustrine hydrothermal activity: large, tower-like carbonate deposits (the majority are 1–20 m in height and 5–15 m in diameter at the base; the largest, named As Bahalto, is ~60 m in height and ~90 m in diameter) are scattered or grouped in rows and groves on the dry lake bottom (Fig. 1A, B, C) and the summits of some are steaming. These towers resemble low-temperature freshwater deposits called tufa that form, for example, in alkaline and salty lakes of the Basin and Range Province (Bischoff et al., 1993; Rosen et al., 2004), however their geothermal association and scarcity of plant or animal matter make them more properly considered travertine (Ford and Pedley, 1996).

In order to better understand the composition and mode of formation of hydrothermal carbonate deposits in a continental rift setting, we describe here the results of a multi-proxy, elemental, isotopic, and mineralogical investigation of an inactive hydrothermal chimney system, along with its associated modern fluids, at Lake Abhé in the Afar Rift.

2. Geological setting

Lake Abhé (Afar Rift) is located at the triple junction between two nascent mid-oceanic ridges (Red Sea and Gulf of Aden) and a continental rift [Main Ethiopian Rift (MER)] (Fig. 2A). The lake occupies the western part of the closed Gob Aad tectonic basin (Fig. 2B) (Beyene and Abdelsalam, 2005). It is the most elevated basin within a series of fan-arranged fault-controlled depressions (Fig. 2B). Whereas the easternmost Asal Rift (Fig. 2B) is known to be the onshore prolongation of the westward propagating Tadjoura Rift, the structural context of the Gob Aad basin is debatable. The Gob Aad basin has developed on a volcanic basement composed mainly of basalts (2.17–1.86 Ma) and subordinate acidic rocks during Pleistocene–Holocene times (Barberi and Varet, 1977). These lavas represent the upper unit of the trap-like Stratoid Series that floors a major part of the Afar Rift (Barberi and Varet, 1977; Gasse et al., 1987). The Pleistocene–Holocene sediments (mainly lacustrine) in the Gob Aad basin are slightly deformed and post-date a N100°E-trending horst–graben network comprising the highly fissured Stratoid basalts (Demange and Stieltjes, 1975). The oldest sediments exposed at the surface are of Early Pleistocene age: (a) lacustrine shales interstratified within Upper Stratoid basaltic lava flows (~2 Ma), and (b) calcareous diatomites, gypsum, and ash flows (Gasse and Street, 1978). The horst bordering the Gob Aad basin (Fig. 2B) is composed of Stratoid lavas (<3 Ma) and felsic domes, whereas the Lake Abhé floor is furnished entirely by Stratoid basalts (Deniel et al., 1994).

The hyperalkaline (pH = 10) and salty ([Na] = 13.3 ppt) Lake Abhé has substantially fluctuated in volume and surface elevation during the Quaternary (Gasse, 1977). Its evolution during the Late Pleistocene is marked by three successive transgressions (Demange et al., 1971). Two Holocene episodes of high-water levels are identified at 11–9 ka and 8–4 ka (Fontes and Pouchan, 1975; Gasse et al., 1987). The lake is mainly recharged by the Awash River draining the Ethiopian Plateau (~2500 m). The recently shrinking lake water body exhibits salt flats with hundreds of huge (<60 m) tower-like structures aligned generally WNW–ESE, parallel to the regional extensional fault network (Fig. 2B) (Demange and Stieltjes, 1975) and scattered on the east, south and

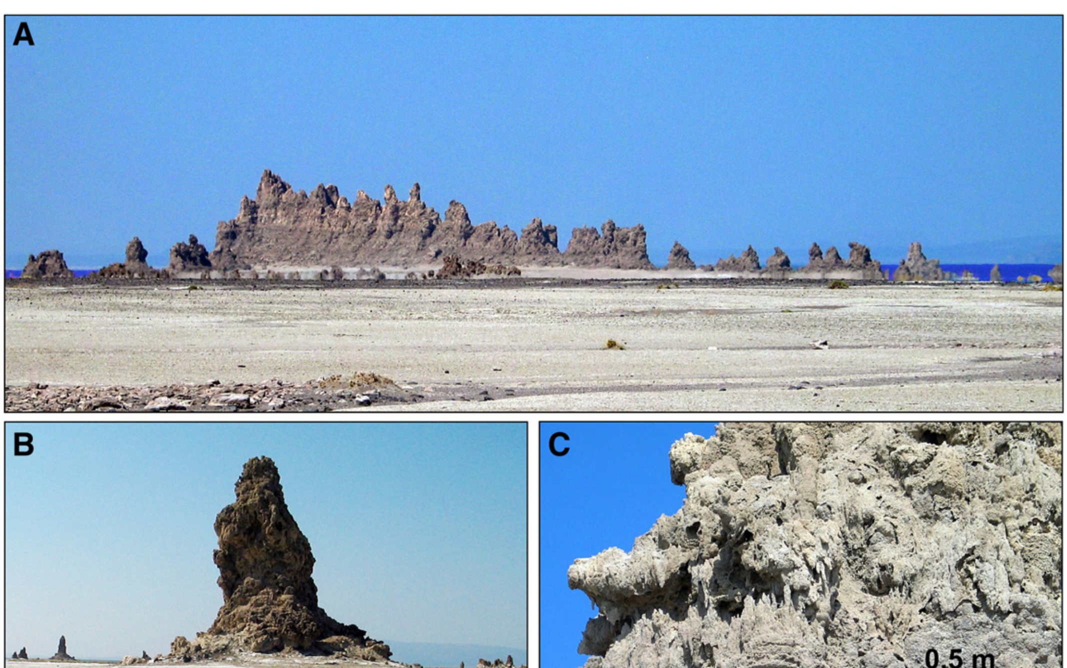

Fig. 1. Inactive carbonate chimneys from the desiccating bottom of Lake Abhé: (A) chain of coalescent chimneys (the tallest is ~35 m; Lake Abhé in blue behind the chimneys); (B) single chimneys (~15 m); (C) surface of a carbonate chimney (close up).