History of scoria-cone eruptions on the eastern shoulder of the Kenya–Tanzania Rift revealed in the 250-ka sediment record of Lake Chala near Mount Kilimanjaro

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ABSTRACT: Reconstructions of the timing and frequency of past eruptions are important to assess the propensity for future volcanic activity, yet in volcanic areas such as the East African Rift only piecemeal eruption histories exist. Understanding the volcanic history of scoria-cone fields, where eruptions are often infrequent and deposits strongly weathered, is particularly challenging. Here we reconstruct a history of volcanism from scoria cones situated along the eastern shoulders of the Kenya–Tanzania Rift, using a sequence of tephra (volcanic ash) layers preserved in the ~250-ka sediment record of Lake Chala near Mount Kilimanjaro. Seven visible and two non-visible (crypto-) tephra layers in the Lake Chala sequence are attributed to activity from the Mt Kilimanjaro (northern Tanzania) and the Chyulu Hills (southern Kenya) volcanic fields, on the basis of their glass chemistry, textural characteristics and known eruption chronology. The Lake Chala record of eruptions from scoria cones in the Chyulu Hills volcanic field confirms geological and historical evidence of its recent activity, and provides first-order age estimates for seven previously unknown eruptions. Long and well-resolved sedimentary records such as that of Lake Chala have significant potential for resolving regional eruption chronologies spanning hundreds of thousands of years.

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KEYWORDS: Chyulu Hills volcanic field; East African Rift; Lake Chala; Mount Kilimanjaro volcanic field; tephra glass geochemistry; tephrochronology.

Introduction

Volcanism in East Africa

The East African Rift system (EARS) marks one of Earth’s best-preserved continental rift systems—a fascinating natural laboratory in which to study compositionally diverse volcanism and wide-ranging volcanic hazards. Volcanism in Kenya and Tanzania tracks the eastern branch of the EARS, where rifting was initiated ~35 Ma in the Lokichar Basin of northern Kenya (Fig. 1; Macgregor, 2015). Twenty-one volcanoes in Kenya and ten in Tanzania are believed to have been active during the Holocene, on the basis of their morphology and evidence of historical or recent geological activity (Global Volcanism Program, 2013). While there are few data on past volcanism, an increasing number of volcanological, archaeological and palaeoenvironmental studies are beginning to compile and date eruptive deposits preserved both in terrestrial and lake-sediment sequences throughout East Africa (e.g. Poppe et al., 2016; Campisano et al., 2017; Fontijn et al., 2018; McNamara et al., 2018). These tephrostratigraphic studies indicate that many volcanoes of the Kenya–Tanzania Rift erupted explosively during the Holocene, depositing ash over hundreds of kilometres (Fontijn et al., 2010, 2018; Martin-Jones et al., 2017a,b; Lane et al., 2018; McNamara et al., 2018).

During the Late Pleistocene, volcanism within the EARS has been strongly bimodal. Silicic eruptions from central volcanoes occurred alongside less abundant basaltic eruptions from fissure vents, while intermediate compositions have been comparatively rare (Baker, 1987; Williams, 1983; MacDonald et al., 1995; McDougall and Brown, 2009). The volcanoes of the Kenya–Tanzania Rift were divided into northern and southern sectors by Williams (1978) and Baker (1987). In the north, Emurungogolak, Silali, Korosi and Ol Kokwe (Fig. 1) have erupted large volumes of basalts characterised by sparse pyroclastic activity (White et al., 2012). In the southern Kenya Rift, basaltic eruptions have been typically minor but have occurred in the Ndabidi, Tandamara and Elementeita lava fields adjacent to the Olkaria, Suswa and Eburru calderas (Fig. 1; White et al., 2012). Contemporary volcanism has also occurred to the east of the Rift, with Mt Kenya, Mt Meru and Mt Kilimanjaro having erupted basalts alongside more differentiated nephelinite and phonolite compositions (Baker, 1987).

Strombolian activity in the EARS

Scoria (or cinder) cones are one of the most common volcanic landforms on Earth. They are characterised by Strombolian explosions that eject predominantly basaltic lapilli and ash tens to hundreds of metres into the air (Vespermann and Scmincke, 2000; Fodor and Brož, 2015). Scoria cones are often described as parasitic, having formed due to eruptions...
along fissures on the flanks of a volcano rather than from the main vent. Hundreds of such cones form volcanic fields, which may be active over millions of years (Valentine and Connor, 2015) with average eruption recurrence intervals of hundreds to thousands of years (Ort et al., 2008). Scoria cones are typically monogenetic, i.e. formed by a single episode of volcanism usually lasting days to weeks, although the more complex polygenetic character of some cones is now being recognised (e.g. Poppe et al., 2016). The eruption styles and landforms within volcanic fields are often variable: if magma interacts with water, explosive (phreatomagmatic) activity may form maar crater lakes and tuff cones, whereas if low-viscosity magma is erupted as a fire fountain, spatter cones of welded, ropey lava fragments may develop.

In equatorial East Africa, small basaltic cones occur along the flanks of both Mt Meru and Mt Kilimanjaro. Those on Mt Meru are dated to 1.71 ± 0.06 Ma (Wilkinson et al., 1986), whereas those on Mt Kilimanjaro are more recent and dated to 200–150 ka (Nonnotte et al., 2008, 2011). Roughly 100 km to the east of the Kenya Rift, hundreds of basaltic scoria cones form the Hurri, Nyambeni and Chyulu Hills volcanic fields. Chyulu, the youngest and most southerly of these, hosts a minimum of 250 cones (as estimated from satellite imagery). Activity here is thought to have commenced around 1.4 Ma, and the young Shaitani and Chainu cones (Fig. 1) erupted as recently as the mid-19th century CE (Suggerson, 1963; Goles, 1975; Haug and Strecke, 1995; Späth et al., 2000, 2001). Detailed studies (Haug and Strecke, 1995; Späth et al., 2000, 2001) have resolved long-term trends in the volcanic history of the Chyulu Hills, but focussed on dating effusive rather than explosive eruptions. This study provides the first detailed reconstruction of scoria-cone eruptions from volcanic fields on the shoulders of the Kenya–Tanzania Rift, including the Chyulu Hills.

Scoria-cone eruptions recorded in lake sediments

Reconstruction of scoria-cone eruption histories is challenged by their association with lava flows and spatially restricted scoria deposits, meaning that the imprint of past scoria-cone eruptions may be unrecognisable. However, these eruptions are capable of generating high eruption columns and extensive tephra fallout (e.g. Pioli et al., 2008; Kawabata et al., 2015; Jordan et al., 2016). Scoria is particularly unstable and weathers readily, especially in tropical climates. Long inter-eruptive periods may therefore be associated with complex stratigraphic relationships, and deposits from older centres may be almost entirely denuded while new cones are developing (Németh et al., 2012, 2014). The extent of scoria weathering and shape of the (remnant) cone may provide relative age control but, with datable minerals and charcoal often lacking, determining the absolute age of past eruptions can be difficult (Jaimes-Viera et al., 2018; Nieto-Torres and Del Pozzo, 2019).

Sedimentation in many lakes is continuous and uniform over long periods, providing a better-resolved and potentially more complete archive of regional volcanic history. Tephra layers...
preserved in lake sequences can often be dated using age–depth models built from 14C dating of organic components, giving an indication of past eruption timing. Where comparative geochemical data are available for nearby volcanoes that erupt distinct magma compositions, the geochemistry of the glass shards composing the tephra can be used to identify their source. Tephra sequences in lake sediments have been widely used to constrain volcanic histories, typically from voluminous volcanic eruptions (e.g., Lane et al., 2017). However, several studies have also used lake-sediment tephrostratigraphy to unravel the complex history of basaltic cones (e.g., Green et al., 2014; Hopkins et al., 2015, Németh et al., 2008). Studies on East African lake sequences (Martin-Jones et al., 2017a, 2017b; McNamara et al., 2018; Lane et al., 2018) are beginning to shed light on EARS volcanism, revealing the frequency of past, sometimes undocumented, eruptions. When these records can be linked with their on-land equivalents, they can also give an indication of eruption size.

In this study we present an initial tephrostratigraphic record of scoria-cone eruptions from volcanic fields in southern Kenya and northern Tanzania, derived from a ~250-ka sediment sequence from Lake Chala, a deep crater lake bridging the Kenya–Tanzania border on the southeastern flank of Mt Kilimanjaro. Lake Chala is relatively unique in having permanently stratified and anoxic bottom waters (Buckles et al., 2014), providing excellent preservation conditions for even very fine tephra layers from relatively modest or distant eruptions.

**Lake Chala**

Lake Chala (3.3° S, 37.7° E) is situated in a steep-sided volcanic crater basin formed after a monogenetic parasitic eruption associated with Mt Kilimanjaro’s most recent phase of volcanic activity. Based on the basal age of 25 ka for the upper, 14C-dated, 21.65 m of profundal sediments (Blauw et al., 2011) and an extrapolated age model for the last 140 ka (Moernaut et al., 2010), Verschuren et al. (2013) estimated the age of the complete ~210-m sediment infill in Lake Chala at >250 000 years. The lake is 94 m deep with a surface area of 4.2 km², and receives water only from direct rainfall, runoff from its steep crater walls and subsurface inflow originating from the percolation of rainfall onto the forest zone on Mt Kilimanjaro (Verschuren et al., 2009). Its lower water column is permanently stratified, both today (Buckles et al., 2014; Wolff et al., 2014) and over at least the last 25 000 years (Verschuren et al. 2009). Consequently, Lake Chala accumulates undisturbed and near-continuously laminated diatomaceous organic sediments, interrupted only by turbidites and tephras (Verschuren et al., 2013).

With the aim of reconstructing the palaeoclimate and landscape history of equatorial East Africa, two sediment sequences have been extracted from Lake Chala by the CHALLACEA and DeepCHALLA projects. The 21.65-m long composite CHALLACEA sequence was constructed from four overlapping piston cores collected in 2003 and 2005, and provided insights into climate dynamics spanning the last 25 ka (e.g., Verschuren et al., 2009; Barker et al., 2011; Damsté et al., 2011). In November 2016, as part of the International Continental Scientific Drilling Program, the DeepCHALLA project (Verschuren et al., 2013) retrieved a 215-m long sediment sequence, nearly reaching the crater floor. This study utilises both the CHALLACEA and DeepCHALLA sequences to explore the record of basaltic scoria-cone volcanism in the Mt Kilimanjaro area.

**Methods**

**Locating and analysing tephras**

We identified and recorded basaltic tephra layers by visual inspection throughout the ~250-ka DeepCHALLA sequence, and documented their morphological features and crystal content under high-power microscopy. No visible tephra layers were detected in the CHALLACEA record; therefore, this sequence was analysed for the presence of crypto-tephra using a method adapted from Blockley et al. (2005) and guided by peaks in XRF data (Kriston, 2010) indicating high concentrations of glass shards. Contiguous 1-cm samples were collected from the 10-cm sediment interval surrounding an XRF peak, dried at 95 °C, wet-sieved to >25 μm and then density-separated using a sodium polytungstate solution of >1.95 g/cm³ to remove organic material. Extracted residues were counted under transmitted light microscopy and counts plotted against core stratigraphy to determine tephra isochrons (i.e., the depth of peak shard density), from which shards were then sampled for geochemical analysis. For this purpose, both macro- and microscopic tephras were re-extracted from the sediment cores and sieved. Glass shards were mounted in epoxy resin stubs, which were then ground and polished to expose the glass for analysis.

Each tephra layer was assigned either a CHALLACEA (CH-) or DeepCHALLA (DCH-) code referring to the depth (in metres) of its basal contact according to the composite depth scale of both sequences, which corrects for core gaps and drilling-related artefacts but not for event deposits such as turbidites and tephra layers. Indicative ages (rounded to the nearest 0.1 ka for the CHALLACEA tephras and 1 ka for the DeepCHALLA tephras) were assigned to each tephra using the CHALLACEA 14C-based chronology for the last 25 ka (CH-3.68 and CH-13.22; Blauw et al., 2011); links between Lake Chala seismic stratigraphy and known near-global climatic events back to 140 ka (DCH-57.60, DCH-58.03, DCH-58.41, DCH-69.24, DCH-75.53, DCH-111.72; Moernaut et al., 2010); and extrapolation of the average sedimentation rate over this 140-ka interval (0.80 m/ka) to the base of the DeepCHALLA sequence (DCH-228.60; this study). At this time, the associated 95% age uncertainties are estimated to be ±0.1 ka (2.4%) for CH-3.68 and ±0.45 ka (2.7%) for CH-13.22 (Blauw et al., 2011); ±2 ka (1.6–3%) for the six DeepCHALLA tephras <140 ka (Moernaut et al., 2010); and ±10 ka (4%) for DCH-228.60.

**Tephra geochemical analyses**

Individual glass shards from within all nine basaltic tephra layers, except CH-13.22, were analysed using a wavelength-dispersive Cameca SX-100 electron microprobe (WDS-EPMA) at the Department of Earth Sciences, University of Cambridge. CH-13.22 was analysed using a Jeol 8600 WDS-EPMA at the Research Laboratory for Archaeology and the History of Art, University of Oxford. Operating conditions were identical for both instruments, using a 10-μm diameter defocussed beam, a 15-kV accelerating voltage and 6-nA beam current. Sodium was collected for 10 s, Cl and P for 60 s and all other elements for 30 s. The instruments were calibrated against a series of mineral standards, and results were quantified using the PAP absorption correction method. Assays of the MPI-DING standards KL2-G (basalt) and St-Hs68/80-G (andesite) (Jochum et al., 2006) and an in-house Lipari obsidian (peralkaline rhyolite) were used to monitor accuracy across the two instruments. All major-element data presented in the text, tables and figures are normalised to 100% to account for variable secondary hydration of the glass. For raw data, see the Supplementary Material.
Trace-element concentrations in individual glass shards were determined using a Thermo Scientific Cique Q coupled to a Teledyne G2 Eximer laser in the iCRAG laboratory at Trinity College Dublin. Depending on available sample materials, analyses were used 20 µm², 30 µm² or 40 µm² laser spots. The laser was fired at a repetition rate of 5 Hz, with a count time of 40 s on both sample and gas blank. Concentrations were calculated via calibration against NIST612 and using ²⁵⁷Sm as the internal standard (concentrations determined via EPMA). Data reduction was performed in Iolite v.3.4, followed by a secondary correction using Ca as advocated in Tomlinson et al. (2010). To monitor instrument precision and accuracy, the MPI-DING reference materials GOR132-G (komatiite), St-Hs6/80-G (dacite) and ATHO-G (rhyolite) were analysed during each analytical run; see Supplementary Material for details.

Linking tephras to possible source regions

This study presents new glass data for nine tephra layers in Lake Chala sediments alongside published compositions of Kenya–Tanzania Rift volcanoes in order to identify their potential source volcanoes. When collating the reference dataset, we focussed on compositions of eruptions within the <250-ka time frame of the DeepCHALLA record. However, published compositional and chronological data from many EARS volcanoes are limited. Further, available compositions are frequently whole-rock data, which contain variable amounts of phenocrysts and hence preclude direct comparison of element concentrations (e.g. Smith et al., 2005; Hopkins et al., 2015; Pearce et al., 2019). We therefore use a total alkali-silica (TAS) plot (Le Bas et al., 1986) to draw broad comparisons between eruptive compositions, and ratios of incompatible elements in glass or whole-rock samples to differentiate between eruption centres. Incompatible elements (e.g. Zr, Nb, Ba, La and Pr) increase in abundance with magmatic differentiation, yet their ratios typically remain unchanged and can therefore be used as the chemical signature of an individual volcano. MacDonald (1987), Scott and Skilling (1999) and White et al. (2012) used Nb/Zr trends to discriminate among Kenyan Rift volcanoes, which are, however, more differentiated than the basaltic tephras in this study.

Results

Lake Chala tephrostratigraphy

This study focuses on nine basaltic tephras in the CHALLACEA and DeepCHALLA sequences (Table 1), which provide rare examples of far-travelled tephra from scoria-cone eruptions recorded in a lake-sediment archive. Seven of these tephras are macroscopically visible horizons in the DeepCHALLA record, containing light- to dark-brown scoriaceous, bubble-wall and ropey (＞1000 µm in length) shard morphologies (Fig. 2), indicative of fragmentation through Strombolian-style eruption. Olivine and clinopyroxene crystals frequently occur both as phenocrysts and free crystals (Fig. 2). The glass shards are predominantly of alkaline basaltic composition; however, one tephra at the base of the sequence contains foiditic (low SiO₂) glass (Fig. 3).

Cryptotephras investigation of the <25 ka sediments in the CHALLACEA sequence reveals regional volcanic activity into the Holocene. Background counts of glass shards are low, indicating that peaks in shard counts represent primary tephra deposition with little contamination from volcanic deposits forming the inner crater walls. Two cryptotephras horizons (a modest peak of 100 shards/g dry sediment at 13.22 m depth and a more pronounced peak of 2230 shards/g dry sediment at 3.68 m depth) contain brown glass shards of an alkaline basaltic composition (Fig. 3) similar to those in the DeepCHALLA sediments, and are therefore included in this study. For simplicity, these alkaline basaltic and foiditic tephras are hereafter referred to as mafic tephras.

Indicative ages for the nine mafic eruptions recorded in Lake Chala sediments are given in Table 1. The oldest tephra, found at the base of the DeepCHALLA sequence is dated to ~248 ka. All other investigated tephras were deposited during the last ~134 ka, with DCH-57.60 and DCH-58.03 and DCH-58.41 deposited over a relatively short period between ~66 and ~65 ka. The youngest eruptions, recorded as cryptotephras in the CHALLACEA sequence, are dated to ~16.8 and ~4.2 ka.

Composition of the mafic tephras in Lake Chala

Single-shard major and minor element concentrations are summarised in Table 2 and Figs. 3–5. Glass compositions and incompatible-element ratios permit discrimination between the individual tephras, as described below.

DeepCHALLA mafic tephras

The oldest of the mafic tephra layers in Lake Chala sediments (DCH-228.60; ~248 ka) occurs only 0.55 m above the base of the DeepCHALLA drill core. Glass shards within DCH-228.60 are foiditic and enriched in alkalis and the incompatible elements Zr, Nb, Ba, La and Pr and depleted in MgO and TiO₂ relative to the other mafic tephras (Fig. 3).

Tephra DCH-228.60 as well as DCH-111.72 (~134 ka) and DCH-75.53 (~87 ka) show wide intra-eruptive variation in CaO content, distinguishing them from the more tightly constrained CaO concentrations in the six other tephras.

Table 1. Identification code, location in the sediment sequence (core section and depth, at base of deposit), physical properties and age of the mafic DeepCHALLA tephras (DCH) and CHALLACEA cryptotephras (CH) analysed in this study. Minerals are abbreviated as cpx (clinopyroxene), ol (olivine) and fsp (feldspar). The listed ages are based on ¹⁴C dating for the two CHALLACEA cryptotephras (Blauw et al., 2011), and an extrapolated age model tied to seismic stratigraphy (Moernaut et al., 2010) for the seven DeepCHALLA tephras. Age uncertainties are 2.4–2.7% for CH tephras and 1.6–4% for DCH tephras; see text.

| Tephra ID | Core section | Section depth | Composite depth (m) | Thickness (cm) | Glass size | Crystals | Crystal size (µm) | Age (ka) |
|-----------|--------------|---------------|---------------------|---------------|------------|-----------|------------------|---------|
| CH-3.68   | 2PI          | 55.4          | 3.68                | -             | <100       | trace     | <50              | 4.2     |
| CH-13.22  | 3P-Va        | 104.6         | 13.22               | -             | <50        | trace     | <50              | 16.8    |
| DCH-57.60 | 1B-18H-2     | 56.5          | 57.60               | 0.5           | <1000      | cpx, ol   | <100             | ~65     |
| DCH-58.03 | 1B-18H-2     | 99.5          | 58.03               | 0.5           | <1000      | cpx, ol   | <100             | ~65     |
| DCH-58.41 | 1B-18H-3     | 21.5          | 58.41               | 0.3           | <1000      | cpx, ol   | <100             | ~66     |
| DCH-69.24 | 1A-23H-2     | 21.3          | 69.24               | 0.3           | <100       | trace     | <100             | ~79     |
| DCH-75.53 | 1B-23H-3     | 51.8          | 75.53               | 0.3           | <250       | trace     | <100             | ~87     |
| DCH-111.72| 1B-35H-1     | 34            | 111.72              | 0.5           | <600       | fsp, cpx  | <300             | ~134    |
| DCH-228.60| 1E-45E-3     | 122.5         | 228.60              | 1             | <1000      | fsp, cpx  | <250             | ~248    |
Trends of Ba/La in DCH-111.72 and DCH-75.53 glass shards are distinct from one another and from those in the other mafic tephras. Glass shards in DCH-111.72 can be readily distinguished from DCH-75.53, because the latter are enriched in TiO₂, MgO, FeO*, and CaO, and depleted in SiO₂, Al₂O₃, the alkalis and Ba (Table 2, Figs. 4–5).

The four younger macroscopic mafic tephras derive from eruptions dated to between ~79 and ~65 ka, and occupy a similar area in the incompatible-element plots. Tephra

**CHALLACEA mafic cryptotephras**

Brown glass shards in the CHALLACEA cryptotephras have major-element compositions that are most similar to the four youngest (~79–65 ka) visible tephras in the DeepCHALLA sequence (Figs. 3–4). The two cryptotephras cannot be distinguished from one another, as their composition is wide-ranging; each encompassing the entire range of MgO concentrations observed in the ~79–65 ka DeepCHALLA tephras. The cryptotephras do, however, contain slightly

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Table 2. Average major-, minor- (wt%) and trace-element (ppm) concentrations of the mafic DeepCHALLA and CHALLACEA tephras, with standard deviation added in italics and the number of shards analysed at the top of each data column. Major and minor elements are normalised to 100% analytical totals, <bd> indicates concentrations below instrument detection limit. See Supplementary Information for raw data and analyses of reference materials.

| CHALLACEA | CH-13.22 | CH-13.22 | DCH-57.60 | DCH-58.03 | DCH-58.41 | DCH-69.24 | DCH-75.53 | DCH-111.72 | DCH-228.60 |
|-----------|---------|---------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| n = 5     | n = 35  | n = 20  | n = 15    | n = 20    | n = 15    | n = 20    | n = 15    | n = 15    | n = 15    |
| SiO₂      | 45.24   | 46.48  | 45.06     | 45.25     | 45.26     | 45.81     | 45.46     | 46.07     | 44.89     |
| TiO₂      | 4.28    | 4.33   | 4.46      | 4.33      | 4.43      | 4.41      | 4.56      | 3.95      | 3.37      |
| Al₂O₃     | 14.30   | 14.59  | 15.05     | 15.23     | 14.64     | 13.75     | 13.74     | 15.61     | 16.03     |
| MgO       | 5.39    | 5.17   | 5.28      | 4.62      | 4.93      | 5.87      | 5.06      | 4.10      | 4.07      |
| FeO⁺      | 14.44   | 12.52  | 13.35     | 12.75     | 12.78     | 13.54     | 13.65     | 12.21     | 11.95     |
| MnO       | 0.21    | 0.18   | 0.18      | 0.20      | 0.22      | 0.21      | 0.23      | 0.21      | 0.26      |
| CaO       | 11.05   | 10.74  | 10.70     | 10.53     | 10.96     | 11.24     | 11.72     | 10.10     | 9.79      |
| Na₂O      | 3.74    | 3.53   | 3.76      | 4.35      | 4.09      | 3.71      | 4.03      | 4.42      | 6.15      |
| K₂O       | 1.55    | 1.70   | 1.48      | 1.79      | 1.80      | 1.68      | 1.61      | 2.33      | 2.91      |
| P₂O₅      | 0.80    | 0.77   | 0.67      | 0.94      | 0.90      | 0.78      | 0.85      | 0.97      | 1.33      |
| Rb        | 43.3    | 42.1   | 43.9      | 3.59      | 40.4      | 1.98      | 43.7      | 7.66      | 69.2      |
| Sr        | 80.6    | 94.0   | 96.3      | 114       | 87.8      | 41.6      | 1020      | 138       | 1212      |
| Y         | 30.2    | 37.1   | 35.2      | 3.67      | 32.3      | 1.82      | 30.0      | 4.14      | 36.4      |
| Zr        | 33.1    | 43.9   | 45.2      | 46.4      | 366       | 19.5      | 468       | 35.7      | 430       |
| Nb        | 79.6    | 106    | 108       | 11.8      | 93.2      | 3.19      | 126       | 14.2      | 151       |
| Cs        | 0.32    | 0.45   | 0.23      | 0.04      | 0.40      | 0.042     | 0.44      | 0.11      | 0.74      |
| Ba        | 462     | 614    | 647       | 73.6      | 542       | 22.0      | 598       | 81.0      | 1020      |
| La        | 58.3    | 82.1   | 84.8      | 9.40      | 71.6      | 3.37      | 102       | 12.0      | 115       |
| Ce        | 123     | 174    | 179       | 22.4      | 148       | 6.53      | 215       | 22.7      | 221       |
| Pr        | 14.0    | 20.1   | 20.6      | 2.64      | 16.7      | 1.04      | 24.1      | 2.60      | 23.3      |
| Nd        | 60.1    | 83.4   | 85.1      | 10.4      | 69.0      | 3.82      | 92.5      | 9.30      | 89.6      |
| Sm        | 11.9    | 15.2   | 15.8      | 2.26      | 13.1      | 0.912     | 16.6      | 2.22      | 15.3      |
| Eu        | 3.53    | 4.59   | 4.48      | 0.561     | 3.77      | 0.207     | 4.73      | 0.563     | <bd>      |
| Dy        | 7.11    | 9.52   | 8.61      | 1.42      | 7.48      | 0.520     | 8.94      | 1.32      | <bd>      |
| Er        | 2.94    | 3.96   | 3.54      | 0.678     | 3.17      | 0.263     | 3.76      | 0.520     | <bd>      |
| Yb        | 2.26    | 2.90   | 2.74      | 0.611     | 2.35      | 0.232     | 2.80      | 0.577     | <bd>      |
| Ho        | 7.55    | 10.7   | 10.1      | 1.61      | 8.32      | 0.766     | 10.7      | 1.50      | 8.84      |
| Tm        | 4.72    | 6.47   | 6.39      | 0.847     | 5.54      | 0.306     | 7.63      | 1.02      | 8.51      |
| Tb        | 4.17    | 5.83   | 6.74      | 3.08      | 5.03      | 0.643     | 6.25      | 1.54      | 10.0      |
| Yb        | 6.52    | 9.68   | 9.62      | 1.64      | 8.00      | 0.642     | 11.2      | 1.52      | 14.7      |
| U         | 1.65    | 2.71   | 2.62      | 0.491     | 1.98      | 0.169     | 2.93      | 0.424     | 3.46      |
higher CaO and lower Al₂O₃ than the two youngest DeepCHALLA mafic tephras (Fig. 4).

Discussion

Multicriteria correlations

Major-, minor- and trace-element compositions

The mafic tephras in Lake Chala are more alkaline than basalts erupted from the Kenya Rift volcanoes (Fig. 3), and more closely resemble basalts erupted from the off-Rift volcanic centres of Mt Kilimanjaro and the Chyulu Hills. The seven mafic DeepCHALLA tephras for which we have trace-element data show distinct linear arrays in plots of Ba/La, Pr/La and Zr/Nb (Fig. 5). The four younger tephras (DCH-69.24, DCH-58.41, DCH-58.03 and DCH-57.60) plot tightly along the same fractionation trends, whereas the three oldest tephras

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Figure 4. Single-shard major-element concentrations in the DeepCHALLA (grey symbols) and CHALLACEA (triangles) mafic tephras. Error bars (blue crosses, 2-sigma) are based on repeat analyses of the MPI-DING standard KL-2-G, averaged across all analytical sessions. The trajectories of Al₂O₃ (a), CaO (b) and TiO₂ (c) concentration against MgO (all as wt %) indicate magma evolution dominated by clinopyroxene and olivine fractionation; the vectors in each panel indicate the approximate crystallisation paths. [Color figure can be viewed at wileyonlinelibrary.com]

Figure 5. Relationships between concentrations of the incompatible elements La and Ba (a), La and Pr (b) and Nb and Zr (c) in single shards of the seven DeepCHALLA mafic tephras analysed (grey symbols), compared with those in lavas from Mt Kilimanjaro 200–150 ka parasitic cones (blue closed triangle; whole-rock analyses by Nonnotte et al., 2011) and in lavas from the Chyulu Hills volcanic field (green open triangles; whole-rock analyses by Späth et al., 2001). Average 2-sigma errors, from repeat analyses of the MPI-DING standard SH6b-80G over two analytical sessions (10.5 ppm for Zr, 6.94 ppm for Nb, 36.6 ppm for Ba, 1.16 ppm for La and 0.357 ppm for Pr) are smaller than symbol sizes in this plot. Vectors (with 10% steps) show modelled simple fractional crystallisation of olivine and clinopyroxene using IgPet software (Carr and Gazel, 2017), with DCH-69.24 (the most mafic tephra) as the starting composition and using mineral-melt partition coefficients compiled by Späth et al. (2001). [Color figure can be viewed at wileyonlinelibrary.com]
(DCH-228.60, DCH-111.72 and DCH-75.53) display incompatible-element trends that are distinct both from each other and from those younger tephras (Fig. 5).

Incompatible-element ratios of all mafic Chala tephras are broadly consistent with those of bulk alkaline lavas from the Chyulu Hills (Späth et al., 2001) and Mt Kilimanjaro’s parasitic cones (Nonnotte et al., 2011), which also plot within relatively well-defined values, particularly for Pr/La. Specifically, in plots of Pr/La and Zr/Nb, the four youngest mafic DeepCHALLA tephras track the same linear path as the Chyulu lavas, indicating that this is their likely source. Also, tephra DCH-75.53 shows broadly similar incompatible-element ratios as the Chyulu lavas in terms of Pr/La and Zr/Nb, but is distinct in terms of Ba/La. However, since the latter ratio is less tightly constrained for Chyulu lavas, we tentatively suggest that the Chyulu Hills is the most likely source for DCH-75.53. Without trace-element data we are unable to directly relate the <25-ka mafic cryptotehras to Chyulu or Mt Kilimanjaro volcanism, notwithstanding their similarity in major-element composition to the ~79–65 ka tephras.

In contrast, the foiditic composition of tephra DCH-228.60 is more similar to the high alkalinity of parasitic volcanic activity on Mt Kilimanjaro (Fig. 3). Both DCH-228.60 and DCH-111.72 follow a Pr/La trend similar to known Mt Kilimanjaro tephras (Fig. 5) and we thus tentatively relate these two older mafic tephras to the later phase of Mt Kilimanjaro volcanism as recognised by Nonnotte et al. (2011).

The compositional distinctions described above are subtle and it is therefore difficult, based on geochemistry alone, to confidently assign individual tephra layers to Mt Kilimanjaro or the Chyulu Hills. Trends in published incompatible-element ratios for the Mt Kilimanjaro and Chyulu lavas are not as tightly constrained as those in our glass data, and it is possible that only Pr and La, ratios of which are consistent between whole-rock samples and glass, behave as truly incompatible elements. The magmatic evolution of these two volcanic fields is likely to be complex, as both are fed by small magma batches derived from variable degrees of partial melting and crystal fractionation. The glass compositions of DCH-69.24, DCH-58.41, DCH-58.03 and DCH-57.60 follow crystallisation paths characteristic of olivine and clinopyroxene (Fig. 5). However, fluctuating concentrations of incompatible trace elements between them suggest a more complex magma evolution, possibly involving multiple influxes of fresh magma.

Haug and Strecker (1995) and Class et al. (1994) report both temporal and spatial variation in the geochemistry of lavas from the Chyulu Hills, with those erupted from cones in the south of the volcanic field enriched in SiO2 compared with older northern lavas. Späth et al. (2000) attribute this change to the degree of partial melting increasing towards the south. Such differences in melting can create heterogeneous magma compositions across a single volcanic field, challenging comparisons using incompatible-element ratios. Also, our understanding of compositional variation in magmas from the Chyulu volcanic fields is based only on studies of lava flows, which were erupted under different conditions, and likely at different times, to the tephras generated by explosive eruptions we observe in Lake Chala, further complicating direct comparisons.

**Constraints from known eruption histories**

Based on the compositional similarities discussed above, the two CHALLACEA cryptotehras and the five youngest DeepCHALLA tephras (DCH-75.53, DCH-69.24, DCH-58.41, DCH-58.03 and DCH-57.60) are attributed to previously undefined eruptions of the Chyulu Hills, while DCH-228.60 and DCH-111.72 are tentatively correlated to Mt Kilimanjaro. Further support for these proposed attributions is found in the known eruption history of these volcanic fields.

The Chyulu Hills is unique in the EARS for its prevalent Holocene volcanism (Saggerson, 1963; Haug and Strecker, 1995; Späth et al., 2000, 2001). Lavas decrease in age from the northwest (~1.4 Ma) towards the southeast, where a lava flow east of Mzima Springs (Fig. 1b) overlays lake sediments radiocarbon-dated to ~26 ka (Späth et al., 2000). Omenge and Okela (1992) provide oral accounts of <100-year-old flows from the Shaitani and Chainu cones in the south (Fig. 1). The Chyulu Hills is therefore younger than the most recent parasitic activity along the southeastern flank of Mt Kilimanjaro, which is dated to ~200–150 ka (Nonnotte et al., 2008). Concordant with this older age, the Mt Kilimanjaro scoria cones are typically more denuded and more densely vegetated than the Chyulu cones. The age of the two oldest (~248 ka and ~134 ka) mafic DeepCHALLA tephras is thus in line with the known timing of the final phases of volcanism on Mt Kilimanjaro; and the prevalence of younger volcanic activity in the Chyulu Hills supports our geochemical correlation of the two <25-ka CHALLACEA cryptotehras (4.2 and 16.8 ka) and five <100-ka DeepCHALLA tephras (between ~65 and ~87 ka) to that volcanic field. It should be noted, however, that the known eruption histories of Mt Kilimanjaro and Chyulu are based on K/Ar dating of lavas collected from select areas of these volcanic fields, and hence may not capture all phases of their activity. Moreover, a complete cryptotephra scan of the long DeepCHALLA sediment record would likely document additional Chyulu Hills and Mt Kilimanjaro eruptions.

**Indications of source proximity**

Mount Kilimanjaro and the Chyulu Hills, the volcanic centres closest to Lake Chala that erupt basals, are located respectively ~1–30 km to the west, and 60–120 km to the northeast (Fig. 1). Tephra deposits typically become thinner and finer-grained with increasing distance from their source. Consistent with our source attributions, DCH-228.60 and DCH-111.72 contain broadly coarser (~300 μm) free crystals than the seven younger tephras (~100 μm; Table 1). Assuming modern wind patterns over the region, dispersal of tephra from the Chyulu Hills towards Lake Chala would vary seasonally, being promoted from November to April by northeasterly winds, and hampered from May to October by southeasterly winds (Wolf et al., 2014).

**Scoria-cone eruption records from lakes: potential and challenges**

This study highlights the exceptional preservation conditions offered by lake systems such as Lake Chala, and their value in documenting eruptions otherwise unrecognised in the geological record. Tying the tephras incorporated in such lake records to their source is mainly challenged by the scarcity of published glass data characterising individual EARS volcanoes. This problem is amplified for intermittently active volcanic fields generating localised and rapidly-weathered basaltic scoria deposits. This study uses incompatible-element ratios to compare glass from mafic Chala tephras with published whole-rock analyses of lavas allowing their correlation to the Chyulu Hills and Mt Kilimanjaro volcanic fields. Our geochemical correlations remain tentative, however, as they are substantiated only by examining the Lake Chala tephr stratigraphy against existing, but skeletal, stratigraphical and geochronological outcrop data.
Further, whereas geochemical and chronologial constraints allowed us to trace the mafic Chala tephras to two volcanic fields, correlating them to individual scoria cones is more challenging. As historical (<100 years) eruptions have been documented from the southerly Shaitani and Chaimu cones in the Chyulu Hills, these, or cones nearby, are a likely source of the most recent (>4.2 ka) mafic cryptotephras recorded in Lake Chala. Späth et al. (2001) report that many of the Chyulu Hills cones, particularly from the southern sector, cannot be distinguished from one another based on their petrographic and geochemical characteristics. These difficulties call for a more detailed study of the Chyulu Hills and Mt Kilimanjaro volcanic fields, focussing not only on the lava flows but also past pyroclastic activity. Such compositional and chronological analysis should target the full temporal and spatial extent of these volcanic fields, allowing a detailed understanding of their eruptive history and magma genesis. Long sediment sequences, such as that of Lake Chala, have great potential to feed into our understanding of complex monogenetic volcanic fields, yet this potential can only be fully realised in the presence of detailed comparative eruption data from on-land records.

Conclusions

Mafic tephras preserved in Lake Chala sediments provide a new record of volcanic activity in the Chyulu Hills and Mt Kilimanjaro volcanic fields spanning ~250 000 years. Excellent preservation conditions reveal tephra deposits from distant, and previously undocumented, scoria-cone eruptions. We tentatively attribute the two oldest mafic Chala tephras (dated to ~248 and ~134 ka) to Mt Kilimanjaro, and seven younger tephras (dated to between ~87 and 4.2 ka) to volcanism in the Chyulu Hills. We show that pyroclastic activity has occurred in the Chyulu Hills over at least the last ~87 ka, and the ash deposited within the late-Holocene section of the Chala sequence supports the documented evidence of more recent volcanism. Pyroclastic activity will likely continue to be a common feature of future volcanism in the Chyulu Hills; however, detailed research into the volcanological hazard and associated sociocultural implications is needed to evaluate the extent of any risks to the local population.

Supporting information

Additional supporting information can be found in the online version of this article.

Acknowledgements. This research was funded jointly by a UK Natural Environment Research Council standard grant (NE/P011969/1) and the International Continental Scientific Drilling Program through the DeepCHALLA project (https://www.icdp-online.org/projects/world/afrika/lake-challa-kenya-tanzania/). The authors thank the DeepCHALLA science team and Karen Fontijn for their contributions and discussion of ideas. Cryptotephras analyses were carried out in the Cambridge Tephra Laboratory, within the Department of Geography Science Laboratories at the University of Cambridge. Alma Piermattei and Friederike Murach-Irvine analyses were carried out in the Cambridge Tephra Laboratory, assisted with cryptotephras analysis, which were begun as part of an Early Career Fellowship from the Leverhulme Trust to CSL. Iris Buisman and Victoria Smith kindly supported EPMA analysis. We thank Karoly Németh and an anonymous reviewer for their suggestions, which greatly improved an earlier draft of this paper.

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