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Recurrent explosive eruptions from a high-risk Main Ethiopian Rift volcano throughout the Holocene

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ABSTRACT

Corbetti caldera is the southernmost large volcanic system in Ethiopia, and has been categorized at the highest level of uncertainty in terms of hazard and risk. Until now, the number and frequency of past explosive eruptions at Corbetti has been unknown, due to limited studies of frequently incomplete and patchy outcrop sequences. Here we use volcanic ash layers preserved in sediments from three Main Ethiopian Rift lakes to provide the first detailed record of volcanism for the Corbetti caldera. We show that lake sediments yield more comprehensive, stratigraphically resolved dossiers of long-term volcanism than often available in outcrop. Our eruptive history for Corbetti spans the past 10 k.y. and reveals eruptions at an average return period of ~900 yr. The threat posed by Corbetti has until now been underestimated. Future explosive eruptions similar to those of the past 10 k.y. would blanket nearby Awassa and Shashamene, currently home to ~260,000 people, with pumice-fall deposits, and would have significant societal impacts. A lake sediment tephrostratigraphic approach shows significant potential for application throughout the East African Rift system, and will be essential to better understanding volcanic hazards in this rapidly developing region.

INTRODUCTION

The Main Ethiopian Rift (MER) is a volcanically and tectonically active rifting zone and home to a population of more than 10 million people (Center for International Earth Science Information Network, 2005). However, few volcanoes are currently monitored and little is known about the magnitude and frequency of more recent (e.g., Holocene) eruptions, data fundamental to providing reliable hazard assessment (Hutchison et al., 2016a; Vye-Brown et al., 2016).

An explosive eruption may deposit tephra over distances of hundreds to thousands of kilometers within a period of hours to days, and therefore a tephra layer forms a time-parallel marker horizon (isochron). Tephra deposits from a common eruptive event can be identified and correlated based on their distinctive glass shard chemistries. Identifying tephra in sedimentary archives and linking it to a volcanic source provides complementary details on eruption dynamics and timing. Lake sediment tephra archives catalogue long-term volcanism from multiple sources (Begét et al., 1994; Wulf et al., 2004; Van Daele et al., 2014; Martin-Jones et al., 2017) and allow the dispersal and thickness of eruptions to be mapped, providing first-order indications of eruption frequency and magnitude.

Using a tephrostratigraphic approach, we have reconstructed the first Holocene (~10 k.y.) record of explosive volcanism for the Corbetti caldera, the southernmost explosive volcano in the central MER. The 15-km-wide Quaternary Corbetti caldera is superimposed on the Pliocene 30-km-wide Awassa caldera. The largest caldera-forming eruption from Corbetti is associated with a welded ignimbrite dated to 182 ± 28 ka (Hutchison et al., 2016a). Postcaldera activity has been concentrated at two Holocene centers in the caldera, Chabbi and Urji (Wendo Koshe), emplacing many meters of complex and undifferentiated tephra deposits (Di Paola, 1971; Rapprich et al., 2016; Hutchison et al., 2016a). Rapprich et al. (2016) dated and constrained the magnitude of the younger than 2.3 ka Wendo Koshe Younger Pumice (WKYP), the most distinctive and widespread of these proximal tephra deposits. The rapidly developing cities of Awassa and Shashamene, home to ~260,000 inhabitants (Center for International Earth Science Information Network, 2005), are both ~10 km from the Corbetti caldera. Ongoing episodes of deformation at Corbetti (Biggs et al., 2011) are testament to the continued volcanic threat posed to the nearby population and infrastructure. However, there is no eruptive history for Corbetti listed on the Global Volcanism Program database (http://volcano.si.edu; Siebert et al., 2010), and monotonous tephra deposits within the caldera (Rapprich et al., 2016; Hutchison et al., 2016a) hamper interpretations of true eruption frequency.

CHRONICLING ERUPTIVE HISTORY USING LAKE SEDIMENTS

We studied Holocene sediment cores from three lakes in the central and southern MER, Awassa, Tilo, and Chamo (Fig. 1), that collectively contain 23 tephra layers (Table 1). We present ~1200 glass shard major and trace element analyses characterizing 19 of these tephras.

Our most proximal record is from Lake Awassa, located on the southern periphery of the Corbetti caldera (Fig. 1). The original tephrostratigraphy for the Lake Awassa core used in this study was described by Telford et al. (1999). The sequence contains 7 (identified as AWT-1 to AWT-7), 0.5–73-cm-thick, fine to coarse ash and lapilli tuff layers. We can no longer define the original tephrostratigraphy within the Awassa sediment cores, which have been heavily sampled (see the GSA Data Repository[1]). However, we characterize three of the better preserved Awassa tephras here, both to confirm that nearby Corbetti is their source and to provide a broad glass shard geochemical signature for the caldera with which to link our more distal and

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[1]GSA Data Repository item 2017389, analytical details, age models, eruption statistics and geochemical data, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

Data Repository item 2017389 | https://doi.org/10.1130/G39594.1

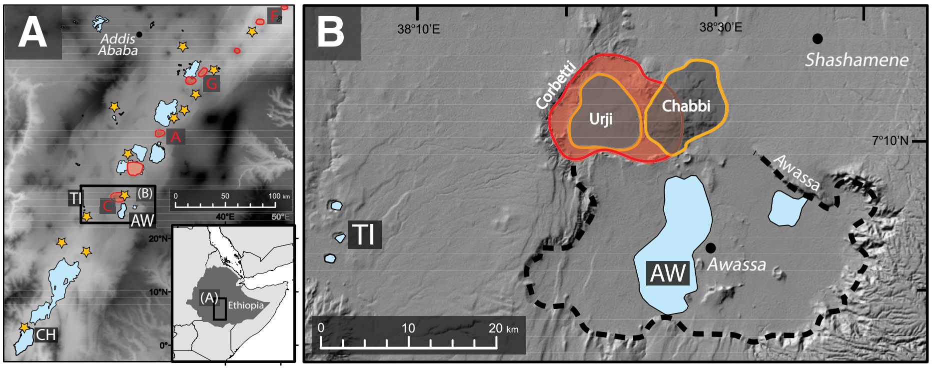

Figure 1. A: Study sites in the Main Ethiopian Rift. AW—Lake Awassa, TI—Lake Tilo, CH—Lake Chamo. Quaternary calderas (red outlines): F—Fentale, G—Gedemsa, A—Alutu, C—Corbetti. Stars mark Holocene volcanic centers (Siebert et al., 2010) B: Digital elevation hillshade map of the Corbetti caldera (red outline) and surrounding area. Lake Awassa is on the southern extremity of the Corbetti caldera, within the Pliocene Awassa caldera (black dashed outline). Lake Tilo is located <40 km west of Corbetti.

clearly resolved sites. Figure 2 compares the glass shard composition of the Awassa tephras to glass analyses of Corbetti volcanic deposits, which include the Holocene WKYP and Chabbi Obsidian. The Awassa tephras clearly correlate to Corbetti volcanic deposits based on their glass chemistry. While they temporally overlap with

TABLE 1. TEPHRAS IN LAKES TILO, AWASSA, AND CHAMO SEDIMENT CORES, THEIR BASAL DEPTHS, THICKNESSES, AND BAYESIAN MODELED AGES

Tephra ID	Core depth (cm)	Thickness (cm)	Modeled age (calibrated ^{14}C yr B.P.)†
Tilo			
TT-1	103	4.5	1280–460
TT-2	220	20	1526–1263
TT-3*	238	0.5	1773–1276
TT-4	272.5	2	2368–1365
TT-5	292	5	2462–1711
TT-6*	321	1	2672–2159
TT-7	385	1	3092–1998
TT-8	427	37	3258–1998
TT-9	588	38	4804–4530
TT-10	710	30	5932–4871
TT-11	763.5	6	6386–5754
TT-12	915	35	6679–6291
TT-13	1623	5	8701–8275
TT-14	2272	48	10,098–9751
Awassa			
AWT-1	253	14	1474–1250
AWT-2	550	4	3779–3435
AWT-3	818	10	5934–5440
AWT-4	928	73	6190–5693
AWT-5	1087	6	7150–6765
AWT-6	1160.5	0.5	>7420
AWT-7	1189	24	>7420
Chamo			
CHT-1	702	< 0.5	1919–1524
CHT-2	1361	1	8270–7783

Note: Correlations between TT-2 and CHT-1 are in bold and equivalent to the Wendo Koshe Younger Pumice, and those between TT-13 and CHT-2 are underlined.

*Volcanic source of TT-3 and TT-6 is unknown (see Data Repository DR2d [see text footnote 1]).

†Bayesian modeled ages at 68.2% confidence intervals.

some Tilo tephras, their mixed glass compositions preclude correlation to specific horizons. They have incompatible element ratios distinct from other active volcanoes in the MER based on published, although limited, glass and whole-rock data (Fig. 2B).

Our principal tephrostratigraphic study site is Lake Tilo, an ~1-km-diameter maar lake located ~40 km west of the Corbetti caldera and within a topographically closed, steep-sided catchment (Telford, 1998; Lamb, 2000). Tilo's lake catchment morphology makes it an ideal repository for primary tephra-fall preservation, and the clearly resolved stratigraphy catalogues the true frequency of Corbetti's past eruptions. The Lake Tilo core records 14 gray fine to coarse ash and lapilli tuff layers ranging in thickness from 1 to 48 cm, and labeled here TT-1 to TT-14 (from youngest to oldest). The tephras show normal grading and contain fresh angular glass shards, all indications of primary air fall (Walker, 1971). Of these tephras, 12 (excluding TT-3 and TT-6) have similar major and trace element compositions that indicate a cogenetic origin, exemplified by comparable Zr/Th ratios (Fig. 2B). These Tilo tephras have glass chemistries analogous to those of the Lake Awassa tephras and the Corbetti tephra and obsidian deposits, implying that Corbetti is their source. Glass shards in TT-3 and TT-6 have distinct Zr/Th ratios and at present cannot be correlated to other volcanic sources in the MER, all of which erupt compositions very different from those of the Corbetti caldera (Fig. 2B).

After establishing the eruptive history for Corbetti, we studied a more distal tephra record from Lake Chamo, located 170 km south west of Lake Tilo (Fig. 1), in order to constrain the dispersal of Corbetti's most explosive eruptions. A 1-cm-thick gray fine to coarse ash layer tephra (CHT-2) was identified by visual inspection of the core. We also carried out cryptotephra analyses using standard density separation techniques (Blockley et al., 2005) to identify one far-traveled, nonvisible tephra layer (CHT-1; see the Data Repository). Glass shards in CHT-1 and CHT-2 have Zr/Th ratios comparable to those of the Tilo and Awassa tephra glass shards, indicating that they originate from Corbetti (Fig. 2B). Based on their similar glass compositions and ages (Figs. 2C and 2D), CHT-1 (1.9–1.5 ka) and CHT-2 (8.3–7.9 ka) correlate to two of the thickest Tilo tephras, TT-2 (1.5–1.3 ka) and TT-13 (8.7–8.3 ka), respectively.

HOLOCENE ERUPTION RECORD FOR THE CORBETTI CALDERA

Our new tephra framework provides the first Holocene volcanic history for Corbetti caldera. The Lake Tilo tephra record demonstrates that 12 explosive eruptions occurred at Corbetti during the past 10 k.y., only one of which has been previously documented. We use the Tilo tephra record to calculate an average eruption recurrence rate of ~900 yr (see the Data Repository). Six tephra layers in the Lake Tilo archive are between 20 cm and 50 cm in thickness, indicating that at least 6 highly explosive eruptions have occurred from Corbetti caldera during the past 10 k.y. Two of these larger eruptions, dated to 1.5–1.3 ka (TT-2) and 8.7–8.3 ka (TT-13) in the Tilo archive, have correlatives in the Lake Chamo sequence (CHT-1 and CHT-2), 170 km to the south (Fig. 3). The most recent of these thick tephra deposits, TT-2, and its correlative CHT-1 have glass compositions identical to that of the younger than 2.3 ka WKYP (Rapprich et al., 2016) sampled from inside the Corbetti caldera (Figs. 2C and 2D). Glass shards in CHT-1 have a more evolved composition than the WKYP; however, the glass composition of TT-2 encompasses the range of both CHT-1 and the WKYP. We infer that the eruption tapped a compositionally heterogeneous magma system that was either zoned or had multiple pockets of chemically distinct melt (e.g., Williams et al., 2014), and only the more evolved compositions, associated with higher eruption columns, were deposited at distal locations.

The correlation of TT-2 and CHT-1 to the Wendo Koshe eruption allows us to refine the existing maximum age for the event from Rapprich et al. (2016), which we date to 1.9–1.3 ka. Since this event, one further previously undocumented eruption from Corbetti (TT-1) took place between 1.3 and 0.5 ka (Table 1), depositing 4.5 cm of ash in Lake Tilo. It is likely that the WKYP, and other Holocene tephras erupted from Corbetti caldera, will be identified in additional sediment records from the region in the future.

IMPACT OF FUTURE EXPLOSIVE ERUPTIONS AT CORBETTI

As well as establishing an average return rate for past eruptions of Corbetti, we use our new data and published proximal thickness measurements for the WKYP (Rapprich et al., 2016) to calculate (Pyle, 1989; Fierstein and Nathenson,

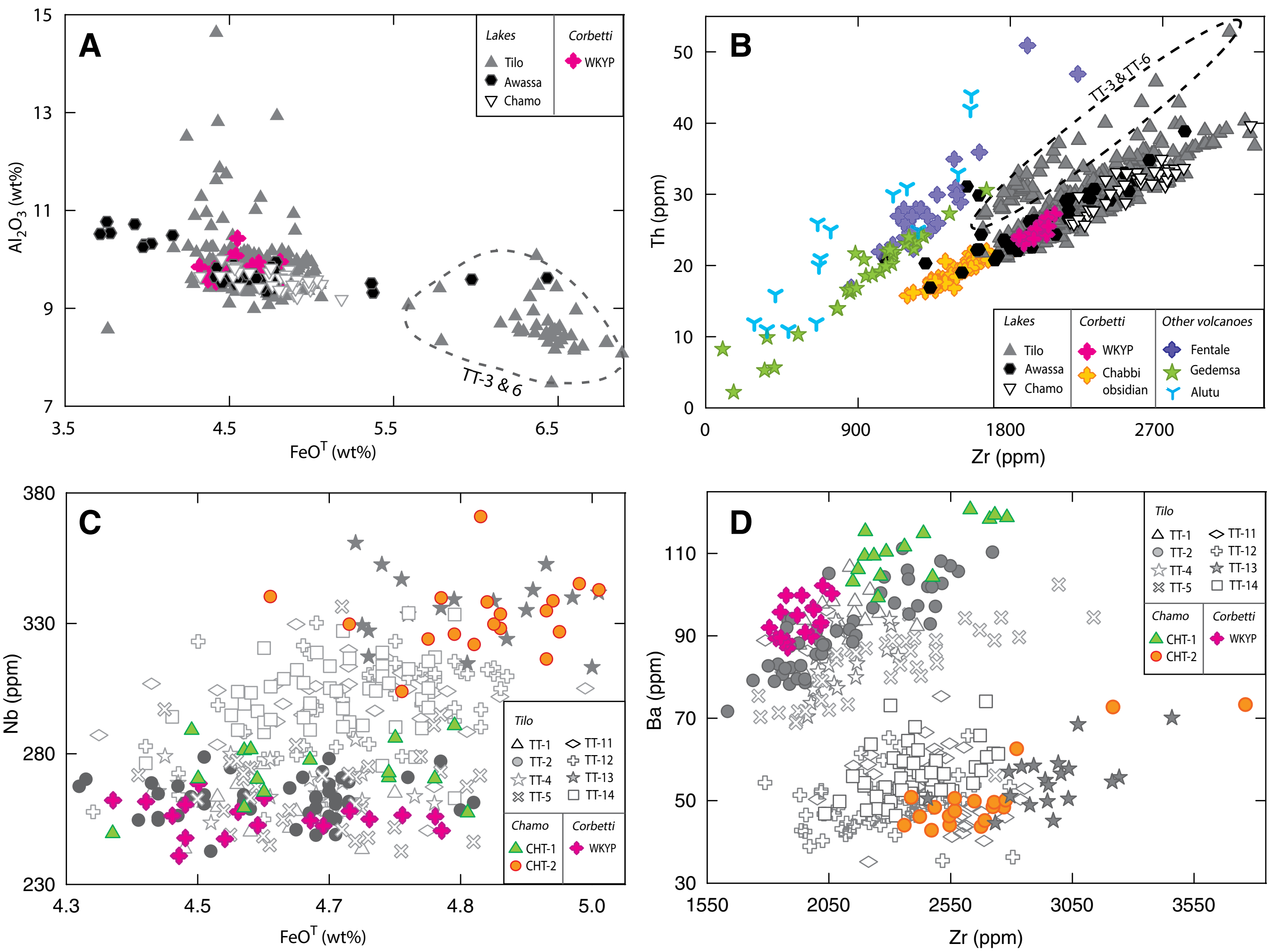

Figure 2. Glass shard compositions of analyzed tephra from the Tilo, Awassa, and Chamo sediment cores (Ethiopia) alongside available published reference data for surrounding volcanic centers. A: Major element compositions. B: Trace element compositions. Compositional similarities indicate that all tephra (except TT-3 and TT-6, dashed lines) are cogenetic. Most Tilo, Awassa, and Chamo glass shards have incompatible element ratios similar to those of the Wendo Koshe Younger Pumice (WKYP) and Chabbi Obsidian, which are distinct from bulk tephra compositions from Gedemsa (Peccerillo et al., 2003) and Alutu (Hutchison et al., 2016b) and melt inclusions from Fentale (Taylor et al., 1997). C, D: Correlation of tephras CHT-1 and CHT-2 to TT-2 and TT-13, respectively. Glass shards in CHT-1 and TT-2 correlate to the WKYP.

1992; see the Data Repository) that the eruption likely generated ~3 km^3 of tephra (equivalent to ~1.5 km^3 of silicic magma), typical of a Volcanic Explosivity Index (VEI) 5 eruption.

To understand the possible impacts of future explosive eruptions from Corbetti, we also look to the documented, albeit limited, historic record of volcanism for other regional volcanoes. Only 2 VEI ≥ 4 historical eruptions are recorded in the East African Rift System, at Dubbi (Eritrea) in 1861 and at Nabro (Eritrea) in 2011 (Wadge et al., 2016). Africa's largest historic eruption was of Dubbi in A.D. 1861 (Wiart and Oppenheimer, 2000). During this event, volcanic ash was dispersed to Ethiopia, 400 km away. Maritime traffic was disrupted and more than 100 people were killed by pyroclastic flows (Wiart and Oppenheimer, 2000). The 2011 eruption of Nabro displaced thousands over the border into Ethiopia and international air traffic over East Africa and the Middle East was significantly disrupted (Goitom et al., 2015).

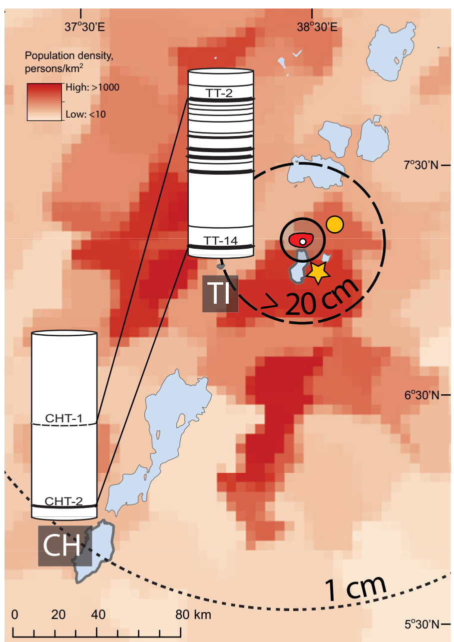

Figure 3. Corbetti caldera (C), Ethiopia, and correlations of tephras between Lakes Tilo and Chamo, overlain on a population density (persons/km²) map of the central Main Ethiopian Rift (MER) (2005 population count from the Socioeconomic Data and Applications Center; Center for International Earth Science Information Network, 2005) Star shows Awassa (A), and circle shows Shashamene (S). Isopachs for the Wendo Koshe Younger Pumice (WKYP) (dashed lines) are calculated using the exponential thinning relationship (Pyle, 1989; Fierstein and Nathenson, 1992), based on tephra thicknesses in Lakes Tilo and Chamo (this study) and at outcrops within the Corbetti caldera (Rapprich et al., 2016). Current distal data are limited to one dispersal axis; however, proximal data indicate a weak wind influence, thus simplified circular isopachs are inferred. We calculate that the Wendo Koshe eruption generated ~3 km³ of tephra (equivalent to ~1.5 km³ of silicic magma), blanketing the contemporary towns of Awassa and Shashamene with >20-cm-thick tephra deposits.

Dependent upon eruption characteristics and wind direction, future explosive events from Corbetti, at the scale of the WKYP eruption, could potentially cover Awassa and Shashamene in pumice and ash fall-out, attaining decimeters in thickness. Even a smaller eruption, similar to Nabro in 2011, would damage properties, water and power supplies, and disrupt communications and transportation.

MULTIFACETED APPROACH TO VOLCANIC HAZARDS ASSESSMENT

Of the ~65 currently active volcanoes in Ethiopia, 49 are within the highest category of hazard uncertainty, and this is due in part to the lack of complete eruption records and geological observations (Aspinall et al., 2011). We have shown that stratigraphically resolved lake sediment tephra records are able to constrain past volcanism throughout the East African Rift System. Our study provides the most comprehensive recent eruptive history for any Ethiopian Rift volcano; however, our new understanding of tephra dispersal from Corbetti is based only on correlations between archives along the same southwest axis from the vent. To further investigate the character and frequency of past eruptions, a greater network of archives from lakes along different trajectories must now be studied, in synergy with detailed mapping of proximal tephra outcrops. More comprehensive dispersal data will allow probabilistic hazard modeling to be undertaken with precision, enabling the likelihood of tephra fallout over this highly populous area to be quantified. Only with an interdisciplinary approach can the uncertainty of volcanic hazards assessments in this rapidly developing region be reduced.

ACKNOWLEDGMENTS

Martin-Jones was funded by a Natural Environment Research Council (NERC) Algorithm Ph.D. (grant NE 10983–01). Field work at Lake Chamo was funded by the German Research Foundation (DFG) within the scope of the CRC 806 (Our Way to Europe). Smith acknowledges funding from the Natural Environment Research Council (grant NE/L013932/1), Brown and Frank acknowledge DFG SPP 1488 grant KO2870/4–1. Georgina Ettritch and Andrew Hardy (Aberystwyth University) assisted with geographic information system mapping. We thank Clive Oppenheimer (University of Cambridge) for encouraging discussions.

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Manuscript received 5 August 2017
Revised manuscript received 8 September 2017
Manuscript accepted 9 September 2017

Printed in USA