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Key Points:
- The locus of magmatism appears to migrate eastward over time
- The Ethiopian flood basalt province in terms of magma plumbing systems resembles the other province derived from the LLSVP—Paraná-Etendeka

Supporting Information:
- Supporting Information S1
- Data Set S1
- Data Set S2
- Data Set S3
- Data Set S4

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Constraining the Magmatic Plumbing System in a Zoned Continental Flood Basalt Province

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Abstract The geographic heterogeneities in lava composition observed in continental flood basalt provinces could provide a probe of material upwelling from the deep mantle and their length scales, but their utility is limited by uncertainties in the locus of magmatism. We examine the magma plumbing system for the Oligocene Ethiopian flood basalts. The province, which exhibits domains defined by the eruption of low-Ti (LT) and high-Ti (HT) lavas, requires a magmatic plumbing system that facilitates the transit of compositionally distinct magmas through the crust without mixing. Here we present a geochemical and geochronological study of a suite of 43 dikes from western Ethiopia. We find that the dikes were dominantly emplaced contemporaneously with the Oligocene flood basalt phase of activity. The composition of the dikes is overwhelmingly LT in character, typified by an overall flat rare earth element pattern (median value of $La/Lu_{CN} = 2.6$), and a lack of enrichment in incompatible trace elements in comparison to the HT lavas. These observations confirm the western Ethiopian dike swarm as a source for the LT flood basalts in the Ethiopian flood basalt province. We also present tentative evidence for an eastward migration in the LT dike system over time. These observations are consistent with the terminal stages of the LT magmatism being centered on the Simien shield volcano. We conclude that the apparent separation of ~400 km between the LT and HT magma plumbing systems allowed for the development of a strongly geochemically zoned continental flood basalt province.

1. Introduction

The most significant mantle structures on the planet are considered the African and Pacific large low shear velocity provinces (LLSVPs; Garnero & McNamara, 2008). Seismic tomography and geodynamic modeling methods have placed constraints on the intensive parameters of material within these provinces (e.g., Garnero et al., 2016; Garnero & McNamara, 2008; Lekic et al., 2012). Similarly, geochemical analysis of melts derived from materials upwelled from these LLSVPs has placed further constraints on their compositional structure (Jackson et al., 2010; Konter et al., 2008; Weis et al., 2011). However, the primary focus of these prior geochemical studies have been on materials upwelling from Pacific LLSVP; relatively little attention has been focused on the antipodal African LLSVP.

Geochemically defined zonation of ocean islands adjacent to the African continent has been previously observed (Schwindrofska et al., 2016); however, the most volumetrically significant volcanism that is associated with the African LLSVP occurs in East Africa (Rooney, 2017). Here prior studies have suggested that a broad thermochemical upwelling has influenced the upper mantle (Kieffer et al., 2004) and resulted in the Oligocene Traps phase of the Ethiopian-Arabian Large Igneous Province (LIP; Figure 1). This continental flood basalt is thus thought to represent the surface manifestation of a deep thermochemical upwelling derived from the African LLSVP. The geochemical characteristics of basalts erupted during the Oligocene Traps phase of magmatism define a strong zonation from west to east (e.g., Pik et al., 1998). It is, however, unclear how this zonation may be influenced by materials upwelling from the African LLSVP.

A barrier to our understanding of the relationship between the geochemically defined spatial zonation of continental flood basalts and any potential parallel zonation in their mantle source(s) revolves around the eruption mechanisms of continental flood basalts. Unlike the shield volcanoes that comprise most oceanic

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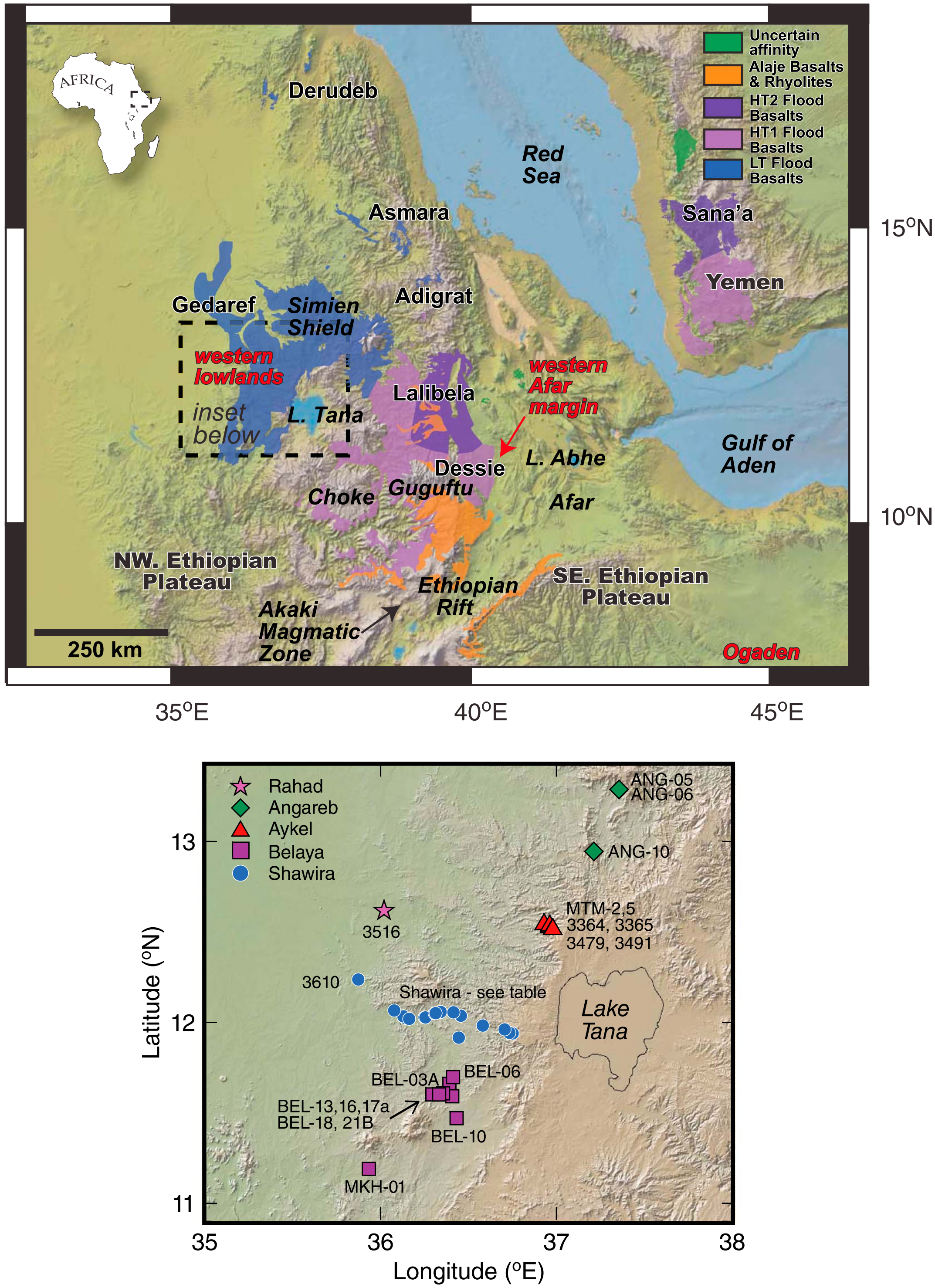

Figure 1. (a) Regional distribution of flood basalts within the Ethiopian-Arabian LIP (Rooney, 2017). The main flood basalt episode has been divided into a low Ti (LT) and two high Ti (HT1 and HT2) magma subtypes. The overlying Alaje series is younger and dominated by felsic activity. The focus area is approximately outlined within the inset and is located in the LT province. Note that the three major dike swarms identified in the region: Ogaden (Mège et al., 2015), Western Afar Margin (Rooney et al., 2013), and Western Lowlands (this contribution), are colored red. (b) Distribution of dikes within the study area overlain on a digital elevation model. The dikes have been coded by locality, and these symbols are used in subsequent plots. For Shawira, the quantity of dikes within a small aerial footprint prevents labeling of individual dikes and the reader is referred to latitude and longitude in Supporting Information S2. The background image is an image rendered from GeoMapApp.

islands, continental flood basalts do not exhibit central edifices during their main eruptive phase and are instead dominated by fissural eruptions that are fed from dikes. The potential for these basalts to flow hundreds of kilometers from their fissural source (Self et al., 1997) presents difficulties in linking the observed surface zonation of the flood basalts with their source. Placing spatial constraints on the magmatic plumbing system of these continental flood basalts thus requires an analysis of the locus of magmatism—that is, the feeder dikes to the flood basalt volcanism.

Here we present a study of a swarm of dikes located along the western margin of the Ethiopian flood basalt province (Figure 1). Through a major and trace element geochemical analysis of 43 intrusive bodies, we show that these dikes represent a feeder system for the low Ti (LT) variety of flood basalt magmatism that dominates this region. We show that the lava flows that constitute the geochemically zoned Ethiopian Traps are fed from at least two distinct clusters of dike swarms—one along the current Western Afar margin at Dessie (Rooney et al., 2013), the other to the west of the current western Plateau escarpment (Mège & Korme, 2004a, 2004b). Similar to other continental flood basalt provinces, the orientation of the dikes in this region appears strongly controlled by basement fabrics (Mège & Korme, 2004a; Schultz et al., 2008). We show that the locus of magmatism for the LT flood basalts migrated eastward over time, consistent with the terminal stages of magmatism for the LT subprovince being located beneath the Simien shield volcano (Kieffer et al., 2004). We suggest that the migration in the locus of LT magmatism is related to lithospheric thinning associated with incipient extension along the western margin of the province. The implications of this work are that while the lateral separation between the hypothesized loci of magmatism for both geochemically defined subprovinces may have been up to 400 km, lithospheric thinning may have added complexity to attempts to translate these surface separations in magmatism to the scale of mantle heterogeneities preserved within the upwelling that formed the province.

2. Background

2.1. Cenozoic Magmatism in East Africa: Eocene to Present

Cenozoic magmatic activity in East Africa consists of at least 720,000 km^3 of dominantly basaltic lavas and subordinate rhyolites/tuffs (Rooney, 2017). Magmatic activity commenced with significant basaltic volcanism and intercalated felsic rocks centered on southern Ethiopia ca. 45 Ma (Davidson, 1983; George et al., 1998; Rooney, 2017). These Amaro/Gamo flows terminated ca. 34 Ma and were followed by a renewed pulse of dominantly basaltic volcanism defining the Ethiopian flood basalt province to the north (Rooney, 2017). The initiation of the flood basalt phase is constrained by the earliest reliably dated basalt within the Ethiopian flood basalt province at 31.2 Ma (Hofmann et al., 1997). The Ethiopian flood basalts erupted over a compressed period from ca. 31 to 29 Ma; however, less volumetrically significant bimodal activity continued to ca. 27 Ma (Rooney, 2017).

Following the flood basalt phase, magmatic activity in East Africa manifested during the Miocene as a resurgence in volcanism centered on shield volcanoes and widely distributed small volume flows over paleosols or basement (e.g., Abbate et al., 2014; Kieffer et al., 2004). The origin of this resurgence remains unclear, but it may relate to an extensional event ca. 24–22 Ma (Rooney, 2017). With the development of the East African rift (Purcell, 2018), magmatism not only became dominantly centered on the evolving rift but also expanded along the length of the rift as far south as Rungwe in Tanzania (Thiéblemont, 2016). Within Ethiopia, magmatism migrated from zones of diking and magmatism along the rift margin (Chiasera et al., 2018; Rooney et al., 2014) into zones of focused magmatic intrusion within the rift: the Wonji Fault Belt (Furman et al., 2006; Mohr, 1967; Rooney et al., 2007; Rooney et al., 2012) and Silti Debre Zeyit Fault zone (Gasparon et al., 1993; Rooney, 2010; Rooney et al., 2005; Rooney et al., 2011; WoldeGabriel et al., 1990). While most magmatic activity is now focused within the rift, limited Pliocene-recent volcanism is also evident on both plateaus (Mège et al., 2016; Purcell, 2018).

2.2. Ethiopian Flood Basalt Province

The Oligocene period of magmatic activity (31.2–27 Ma: Hofmann et al., 1997; Ukstins et al., 2002; Ukstins Peate et al., 2005, 2008), which extended from Ethiopia to Yemen, has been divided spatially into two regions defined by their characteristic magma chemistry (Figure 1; Pik et al., 1998, 1999). The high Ti (HT) subprovince is located in the eastern portion of the flood basalt province and extends into Yemen. Within this province

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two subdivisions are evident—HT1 and HT2 lava types (groups III and IIa, respectively, of East African Magma types: Rooney, 2017). The HT2 lava type (group IIa) is centered on Lalibela in Ethiopia and Sana'a in Yemen. The extremely porphyritic alkaline character of HT2 flood basalts (Beccaluva et al., 2009; Natali et al., 2011; Pik et al., 1998, 1999) is unlike those seen in this study and not considered further. The HT1 (group III) lava type is more transitional in composition and occupies the rest of the HT subprovince (Figure 1). The second of the two subprovinces is defined by the presence of LT flood basalts (East African Magma type Ia: Rooney, 2017). This subprovince occupies the western portion of the NW Ethiopian plateau and extends into Sudan at Gedaref (Figure 1). There is no clear temporal relationship between HT1 lavas and LT lavas due to the spatial separation of the flows; however, on the basis of stratigraphic constraints from the northeastern Ethiopian plateau, HT2 lavas commenced eruptions subsequent to HT1 (Kieffer et al., 2004; Pik et al., 1999). Late stage basalts and rhyolites overlie the flood basalts along the western Afar margin (Alaje basalts/rhyolites).

The origin of the Ethiopian flood basalt province is considered related to the impact of a deep thermochemical upwelling (mantle plume) with the overlying continental lithosphere (e.g., Beccaluva et al., 2009; Pik et al., 1999). An origin for the flood basalt magmatism via a deep thermochemical anomaly is consistent with geophysical data showing anomalously low *P* wave velocities in the upper mantle (Bastow et al., 2008; Benoit et al., 2006) that may connect to a lower mantle anomaly (Hansen et al., 2012; Mulibo & Nyblade, 2013). A lower mantle origin for material erupted in the flood basalt province is required considering the existing evidence of elevated mantle potential temperatures (up to 1,520 °C: Rooney et al., 2012) and helium isotopes that extend beyond those found in the upper mantle (Pik et al., 2006).

The specific mode of origin for the LT and HT basalts remains a topic of active debate. HT2 lavas may derive from either an enriched eclogite component within the upwelling plume (Natali et al., 2016) or destabilization of a recently formed metasomatic component within the lithospheric mantle (Beccaluva et al., 2009). HT1 lavas have a broad array of compositions that have undergone variable degrees of crustal contamination (Baker et al., 1996) but may derive from a mixture of plume, depleted mantle, and Pan-African lithosphere (Rooney et al., 2013). The origin of the LT group is considered related to either melting of plume-metasomatized mantle material (lacking Ti-rich phases: Beccaluva et al., 2009), a depleted component within the plume head or entrained by it (Pik et al., 1999), or from a part of a broad upwelling that was thermochemically heterogeneous (Kieffer et al., 2004). This contribution does not seek to assess the origin of these magma groups but instead to use their spatial distribution in order to evaluate the magma plumbing system to the Ethiopian flood basalt province.

3. Samples and Methods

Here we focus on dikes associated with the Ethiopian flood basalts in order to examine the magmatic plumbing system of the province. In particular, this study examines dikes associated with the LT flood basalts erupted in western Ethiopia (Figure 1). We define dike swarms first on the basis of orientation, and second on the basis of age (where available). The agreement between geometrical and temporal criterion can confirm a homogenous swarm or alternately show that the swarm is temporally heterogeneous and thus should be split into two new, smaller swarms. Coeval with the main flood basalt eruptive event (ca. 31–29 Ma) we define three dikes swarms in western Ethiopia: God Serpent (NE-SW), Doka (NNW-SSE), and Angareb (radial) dike swarms (Figure 2a). Temporally less well constrained are the Ayama (N-S), Dinder (WNW-ESE), and unnamed (E-W) dike swarms (Figures 2b and 2c). Observations from the Dinder swarm that structures continue onto the Tana plateau surface may be evidence that the swarm was emplaced prior to the termination of flood basalt magmatism. Finally, two major diking events postdate the main flood basalts: the Dangur dike swarm and the circum-Tana dike swarm (Figures 2d and 2e). The samples collected as part of this project could not, in all cases, be assigned to specific dike swarms (e.g., Figure 2a), and for many swarms, there is insufficient sample density to assess potential intraswarm geochemical variability. It has thus proved more useful from a geochemical perspective to combine dikes in a more simplistic fashion on the basis of composition and location (Figure 1b). We have therefore clustered the geochemical data into five composite groups that broadly accommodate the variation observed: Shawira, Angareb, Rahad, Belaya, and Aykel. There is utility in future studies that more completely resolve the potential geochemical heterogeneities between the structurally established dike swarms, but this is beyond the scope of this contribution. The majority of mafic dikes are petrographically consistent with LT lavas of the NW Ethiopian plateau, and we therefore adopt the

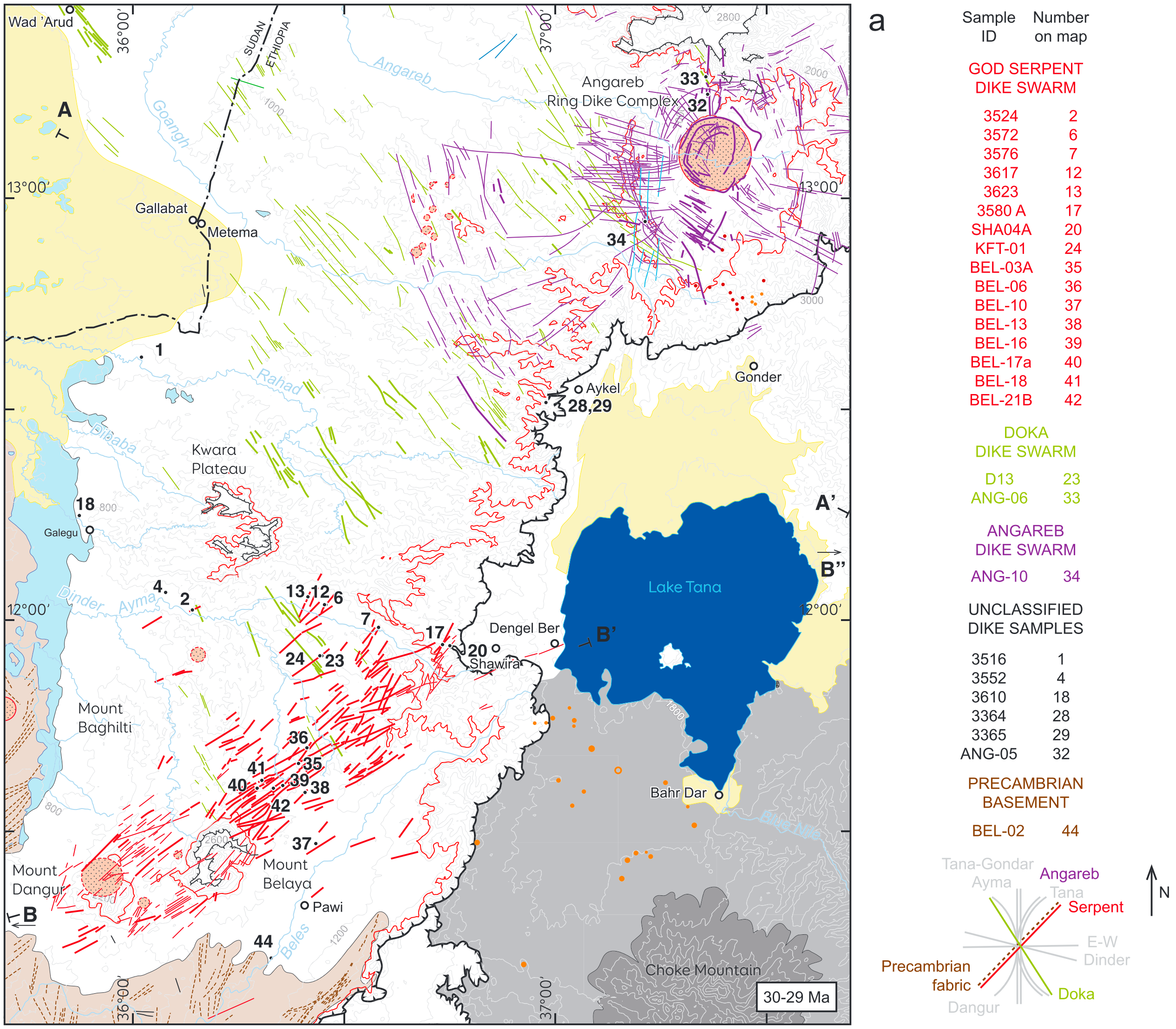
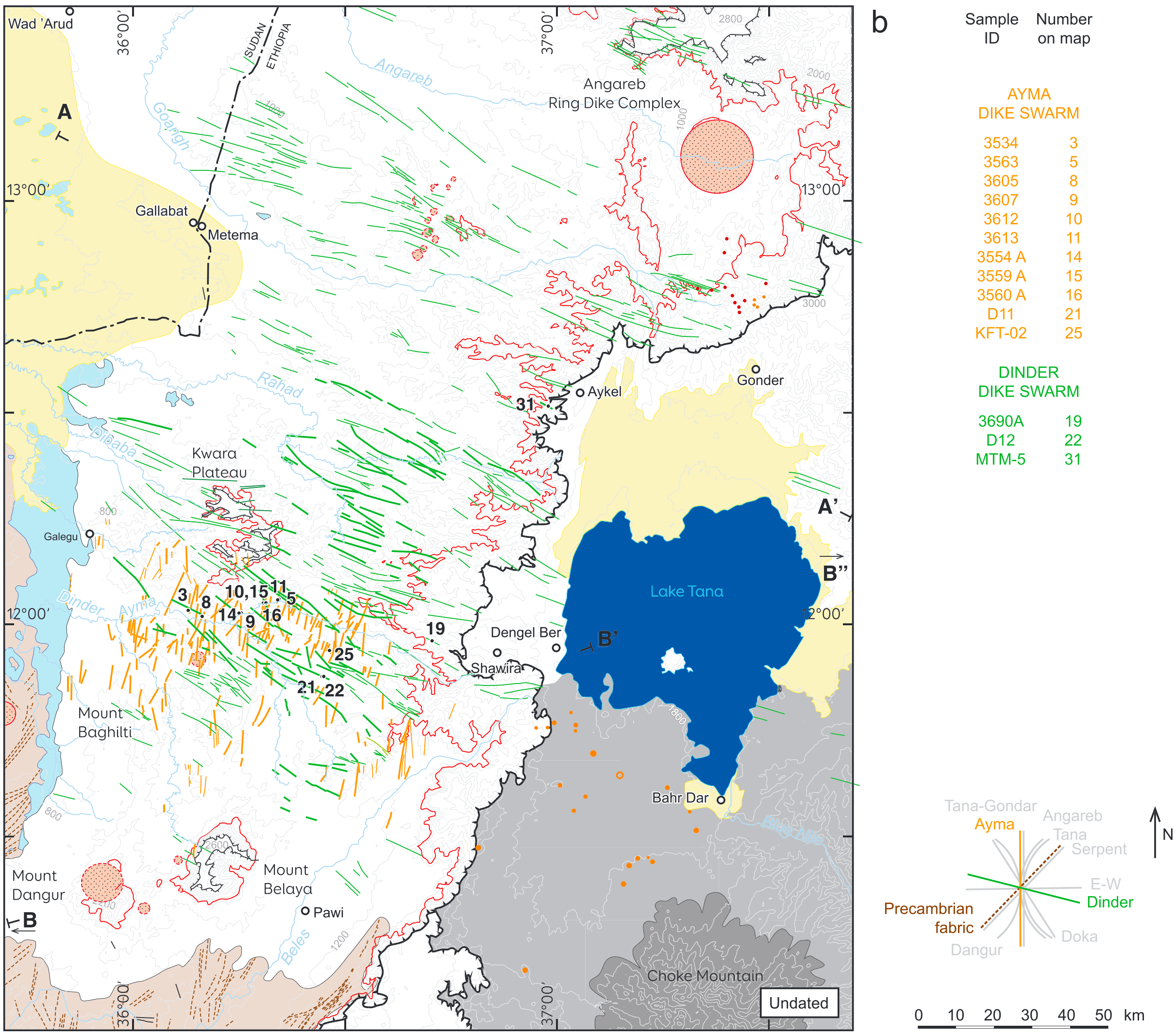


Figure 2. (a) Structures coeval with the main flood basalt eruption event, dated 31–29 Ma: God Serpent, Doka, Angareb, and unclassified dikes. The God Serpent Dike Swarm (Mège & Korme, 2004a) is dated by samples BEl-03a, BEL06, BEL-10, BEL-13, BEL-16, BEL-17a, and BEL-21b. The Doka dike swarm was dated 33 Ma by Grasty et al. (1963); the ANG-06 sample gives a consistent age, 30.2 Ma. The Angareb dike swarm, circumferential about the Angareb ring dike complex, is thought to be coeval with the end of the main flood basalt injection event (Hahn et al., 1976), at 29 Ma. The trend of Precambrian foliation, in a gneiss cooled at ~560 Ma (BEL-02), is reported. The Precambrian fabric is thought to have guided the God Serpent dyke swarm orientation (Mège & Korme, 2004a; Schultz et al., 2008). The 1,500-m elevation contour line marks the elevation corresponding to a change in Oligocene dike chemical composition discussed in the text. All the structures mapped on Figures 2a–2e are reported on a single figure as Figure S1, with additional discussion. (b) Undated structures related to the Ayma and Dinder dike swarms. The NW-SE-oriented Dinder dike swarm is aligned with the Blue Nile and Atbara rifts (GMRD-Sudan, 1981; Jorgensen & Bosworth, 1989). Note that some Dinder-related structures are traced on the Tana plateau surface. However, their density is much lower than in the eroded flood basalt sequence, suggested that they were formed prior to the end of the main flood basalt event, with some limited reactivation. The Precambrian fabric, locally N-S oriented, may have guided the Ayma dyke swarm orientation. (c) Structures associated with the E-W dike swarm. Although the difference in trend with the WNW-oriented Dinder dyke swarm may not be significant, comparison with Figure 2b shows that based on orientation, two distinct fracture populations do exist, pointing to possible two different magmatic-structural events. (d) Structures postdating the main flood basalt eruption event: Tana-Gondar structures, circum-Tana structures and dense fracture network, and Dangur. The Tana-Gondar structures are parallel to the Tana plateau edge and Gondar graben (Chorowicz et al., 1998) and include many normal faults that cut across the entire flood basalt pile, which it therefore needs to postdate. A dike from the Dangur dike swarm is dated 25.8 Ma (MKH-01), significantly more recent than the main flood basalt event, making plausible that the Dangur ring dike complex is not coeval with the Angareb ring dike complex. The orientation of the Precambrian foliation, locally N-S, may have guided dikes erupted from the Dangur ring dike complex and is displayed as well. The 1,500-m elevation contour line marks the elevation corresponding to a change in Oligocene dike chemical composition discussed in the text. (e) Structures postdating the main flood basalt eruption event: circum-Tana structures and dense fracture network. The circum-Tana structures are suggested to testify to gravitational postflood basalt plateau subsidence in response to a decreasing crust or lithosphere temperature and/or magmatic underplating, therefore postdating the main flood basalt event. Fracture orientation in the dense fracture network is consistent with the orientation of the circum-Tana fractures and may be coeval.



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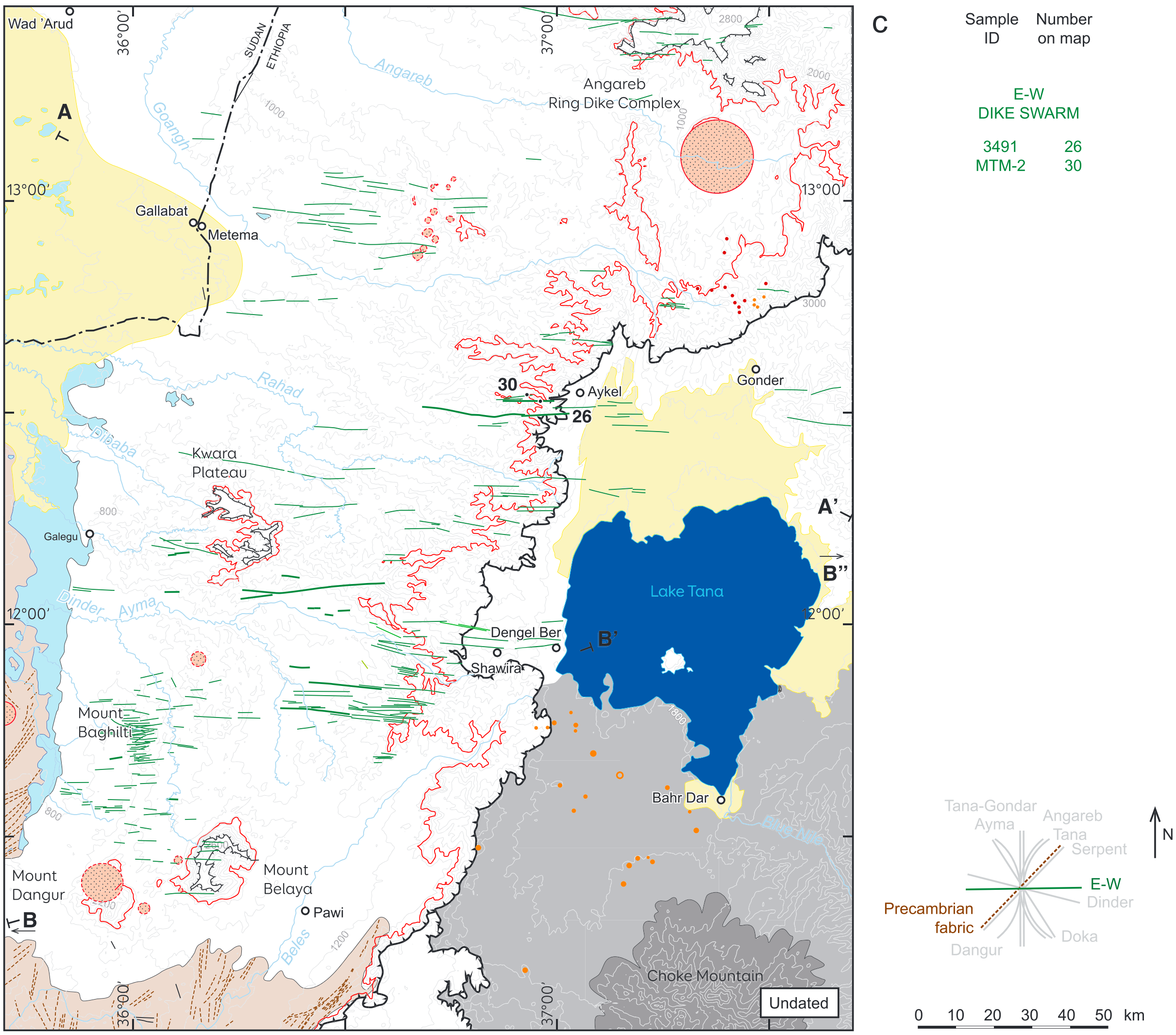
nomenclature described in Krans et al. (2018). The dikes are mostly aphyric-microcrystalline to aphyric-intergranular and occasionally porphyritic with plagioclase ± olivine as the dominant phenocryst phase. Porphyritic dikes have between 7–18% phenocrysts with microcrystalline to intergranular groundmass. Plagioclase is more commonly the dominant phenocryst phase and is typically euhedral to subhedral, blocky to tabular lathes ranging from 1 to 7 mm in length with rare oscillatory zoning and sieve texture. Olivine, when present, is smaller (0.5–1 mm) euhedral to subhedral crystals occurring with or without plagioclase. One dike from Rahad differs from typical LT characteristics in that it is dominantly ol-phyric with abundant interstitial titaniferous-augite (pinkish-brown in PPL) and Fe-Ti oxides in the groundmass, consistent with more transitional lava types found at this locality (Krans et al., 2018).

Forty-three dike/sill samples and one basement sample collected from the western portion of the Ethiopian plateau (Figure 1) were prepared for geochemical analysis. Billets of approximately 30 g were cut from the rock samples, polished to remove saw marks, and then crushed in a steel jaw crusher. The resulting gravel was powdered in a Bico disk pulverizer, fitted with ceramic contamination control plates. Glass disks were prepared from the powder using a lithium tetraborate flux that followed procedures detailed elsewhere (Rooney et al., 2012). Major element data were obtained using a Bruker S4 Pioneer XRF (Supporting Information S2). A series of standards were analyzed as unknowns over the period of data collection and



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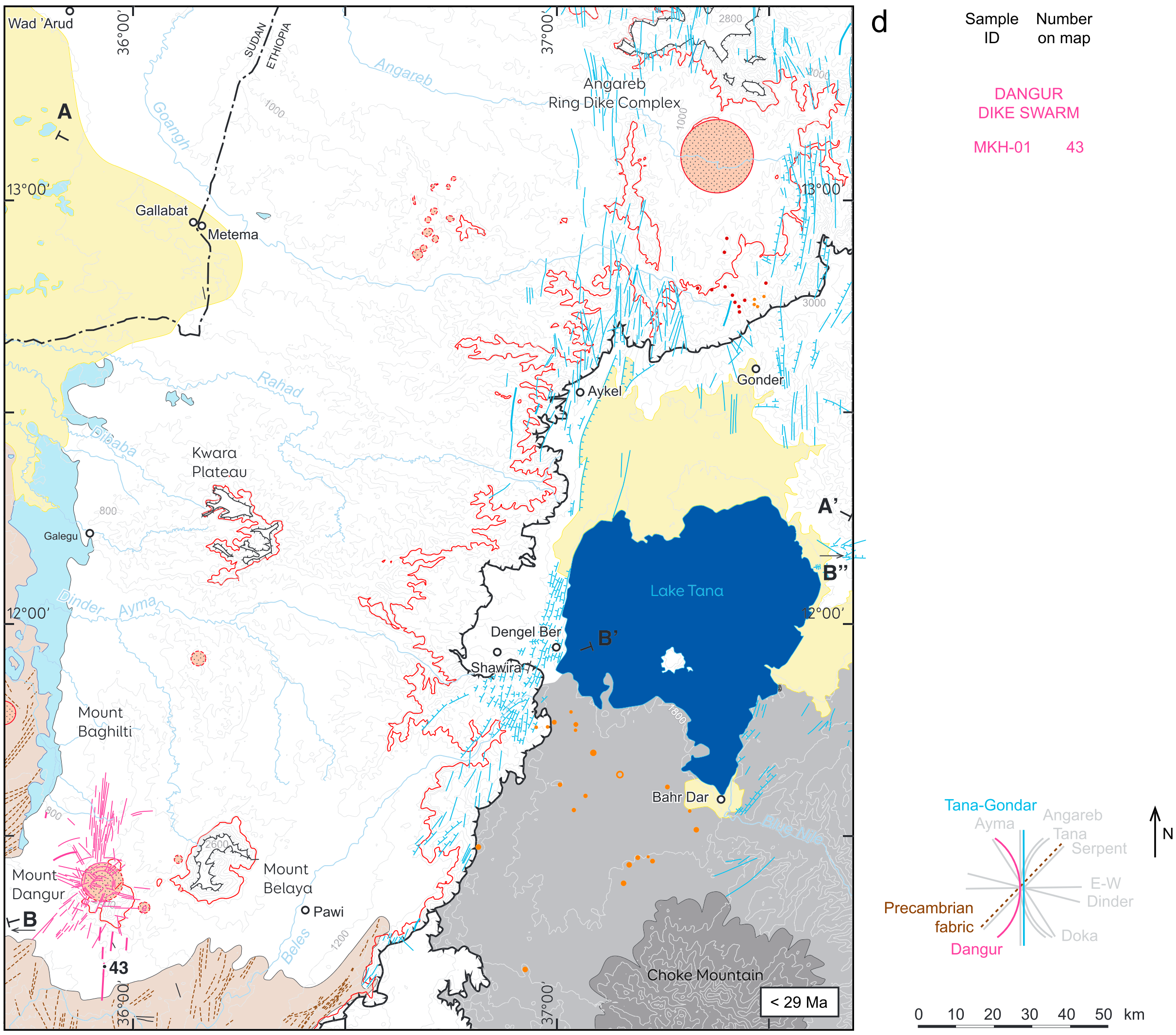
are presented in a supplemental table. Each disk was then analyzed in triplicate for trace elements using a Photon Machines G2 excimer laser coupled to a Thermo iCap ICP-MS following procedures detailed elsewhere (Rooney et al., 2015). Full procedural replicates, denoted with an "X" suffix, are presented in the supplemental table along with standard information and the relative standard deviation of the triplicate sample analysis. Of these dikes, 17 were selected for $^{40}Ar/^{39}Ar$ age dating. Ten dikes yielded interpretable matrix ages. The J factor was estimated by the use of duplicates of the Fish Canyon sanidine standard with an age of 28.02 ± 0.16 Ma (Renne et al., 1998), with reproductive values within 0.6%. The full protocol is described in Supporting Information S1.

4. Results

4.1. Argon Dating

Argon dating (Supporting Information S1 and S2) indicates that all the dated dikes were emplaced during Oligocene. Three rhyolite dykes from the God Serpent Dike Swarm (GSDS; Mège & Korme, 2004a, 2004b), north of Mt. Belaya, are dated 30–31 Ma (BEL03a, BEL17a, and BEL21b) and slightly predate the mafic component of the swarm, dated 29–30 Ma (BEL06, BEL13, and BEL16).



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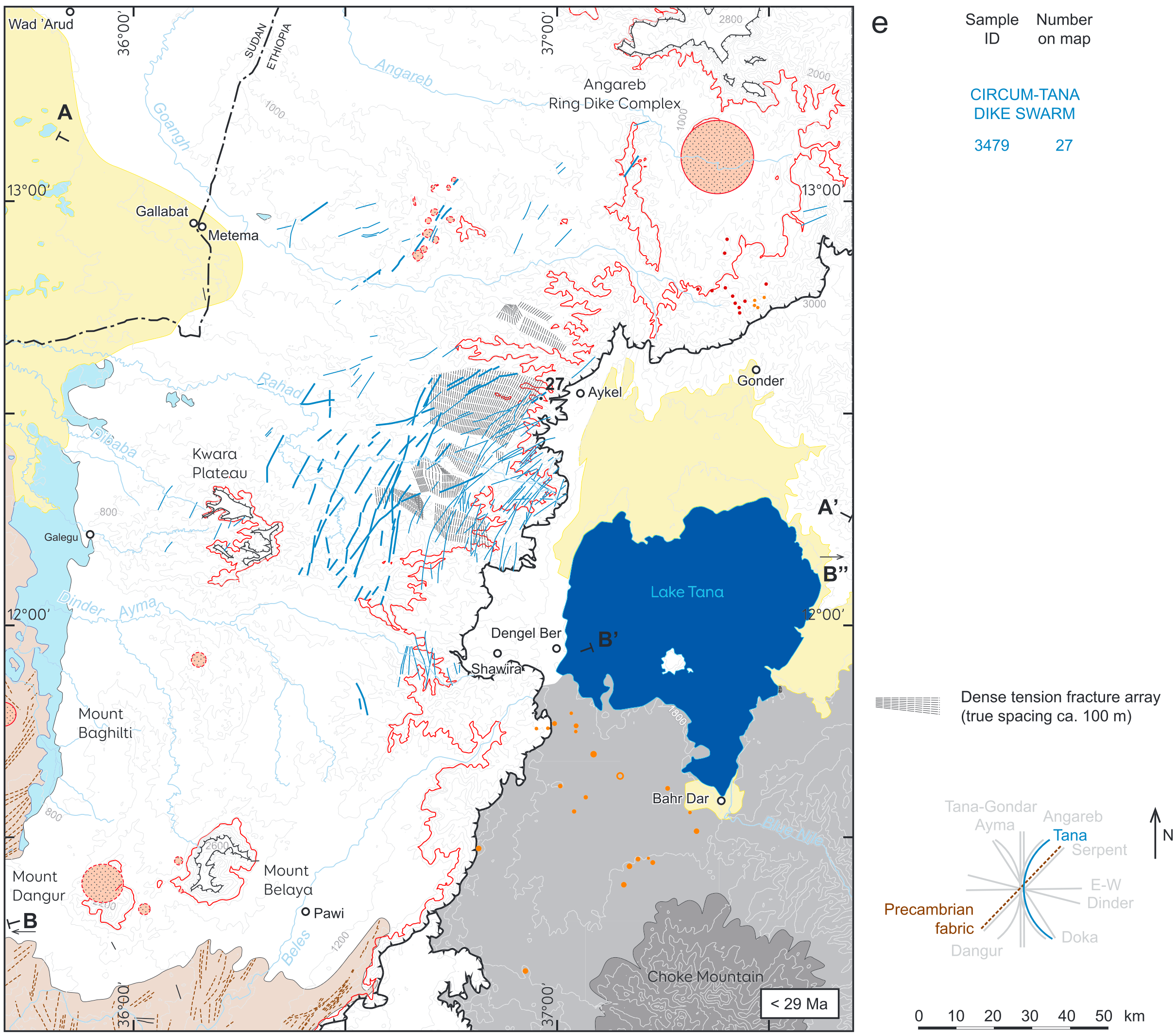
The 30.7 ± 0.4 Ma age of the ANG06 rhyolite dike, though 150 km north of the GSDS, is similar to the age of the rhyolitic component of the swarm. Dikes are abundant between the GSDS swarm and the ANG06 dike; however, no clear continuation of the GSDS northward toward the Angareb area has been demonstrated. The ANG06 dike, located north of the Angareb Ring Dike Complex, ascribed a post-early Miocene age (Hahn et al., 1976), appears older than the latter.

The MKH-01 trachyte sample, south of Mt Belaya, is distinctly younger (25.8 ± 0.3 Ma) than the GSDS. The last dated sample, KFT-01 (probably $<$24 Ma), did not yield a very precise age but indicates that basaltic dyke emplacement continued, or resumed, significantly later than the GSDS and more generally, after the main episode of flood basalt eruption. This date is consistent with the Miocene resurgent phase noted throughout the region (Rooney, 2017).

4.2. Major and Trace Element Analysis

The complete geochemical results are presented in Supporting Information S2 and are divided on the basis of locality. The dike compositions are dominantly subalkaline basalts with some transitional compositions and rhyolites also evident. To a first order the most significant difference between the samples was the relative abundance of felsic dikes in the Mt. Belaya area (Figure 3). Excepting these samples, the remainder of the



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dikes exhibit strong affinity with the LT Ethiopian flood basalts in terms of major element (Figure 4) and trace element variation as a function of magma evolution (Figure 5). Chondrite normalized rare earth element patterns are relatively flat, with a median value of $(La/Lu)_{CN}$ = 2.6 for the mafic samples (Figure 6). Rare earth element patterns are broadly parallel, suggesting similar parental magmas (Figure 6), which is consistent with the affinity with LT flood basalts evident in the Fenner plots (Figures 4 and 5). The extended trace element spidergram shows a typically flat profile that follows a line equivalent to a 10× primitive mantle enrichment, with the exception of Ba, Pb, and Sr, which show markedly higher concentrations (Figure 7). This pattern is consistent with the characteristics East African magma types classified as group Ia (Rooney, 2017).

Despite the typically similar geochemical characteristics of the dikes presented herein, some variation is evident. In particular, the mafic dike samples from Mt. Belaya exhibit consistently higher concentrations in P, Fe, Ti, Ba, and alkalis but are depleted in Ca and Si. No differences are evident in high field strength elements between Mt. Belaya and the other dikes samples. These variations result in alkaline character for these lavas (Figure 3). The origin of this variation may relate to cumulate assimilation given the slightly positive Eu anomaly of ~1.1 ($Eu^* = Eu_N/[Sm_N{*}Gd_N]^{0.5}$) evident in the Mt. Belaya samples (Figure 6). A single intrusion evident at Rahad (3516) exhibits trace element characteristics that are distinct from the other LT basalts and manifests

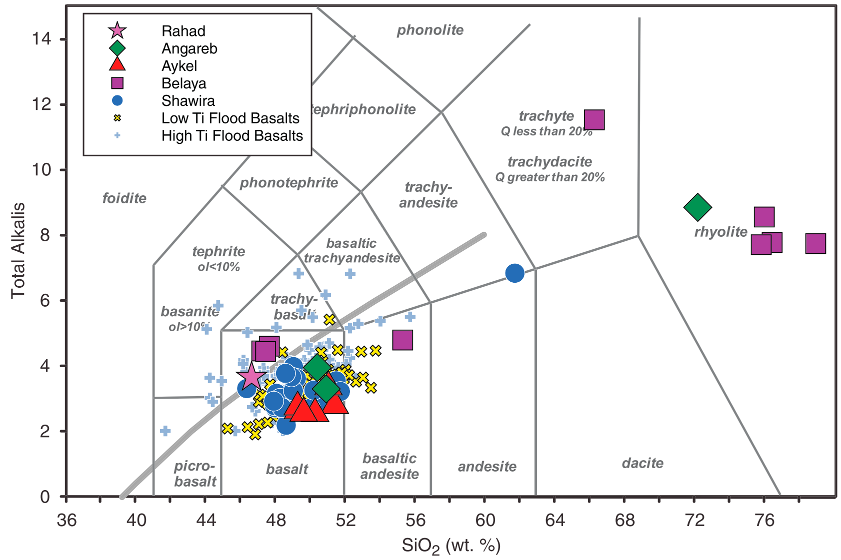

Figure 3. Total alkali ($Na_2O + K_2O$)—silica classification diagram for samples used in this study and for low Ti (LT) and HT1 flood basalts. The samples are plotted on a volatile-free basis, calculated by distributing the measured total Fe_2O_3 as 85% FeO and 15% Fe_2O_3 and performing a normalization to 100%. Data sources: Supporting Information S2 for our data; LT flood basalts—Kieffer et al. (2004), Teklay et al. (2005), Rooney et al. (2013), Lucassen et al. (2008), Pik et al. (1999), and Beccaluva et al. (2009). High Ti flood basalts (HT1 only)—Pik et al. (1999) and Beccaluva et al. (2009).

as enrichments in Nb, Ta, and P, combined with a negative Pb anomaly (Figure 7). The Rahad intrusion plots at elevated Ce/Pb (~40), higher than any other LT flood basalt (Figure 8). These characteristics may superficially resemble those of HT1 flood basalts; however, this intrusion lacks the Ti enrichment and fractionation of the heavy rare earth elements that are typical for such HT1 lavas. The source and relationship of this sill with the other flood basalts in this region remains unclear.

The most significant heterogeneity within the data set is evident in terms of elements sensitive to variation in the ratio of plagioclase to clinopyroxene that are fractionating from a magma (i.e., CaO/Al_2O_3, Sc, and Sr). These variations transgress the regional groupings and are instead coincident with the elevation at which a dike was sampled. Above 1,500 m in elevation, all Oligocene dikes exhibit elevated CaO/Al_2O_3, Sc, and lower Sr at a given value of MgO when compared to dikes sampled below this horizon (Supporting Information S2). Given the lack of variation in other elements, this is characteristic of more enhanced fractionation of plagioclase (in comparison to clinopyroxene) in the upper dike samples. Petrographic observations (as reported above) suggest that phases are in equilibrium with the groundmass with no evidence of crystal accumulation. Therefore, major and trace element chemistry is representative of liquid compositions. It is important to note that these samples are both spatially and temporally constrained: (A) these dikes are limited to the eastern portion of the study area. (B) The dikes cross cut the lower and middle flood basalt sequences, suggesting that they are coincident with the upper flood basalt sequences (or younger).

Intermediate composition dikes (basaltic andesite, trachy-andesite, and trachyte) parallel the chondrite and primitive mantle normalized patterns exhibited by the mafic dikes but at higher concentrations, consistent with an evolutionary relationship between the mafic and intermediate dikes. The most evolved samples typical classify as metaluminous in composition (Figure 9) and fall along lines of evolution consistent with fractionation of a typically gabbroic assemblage. Strongly negative Eu anomalies (Eu* as low as 0.2) are evident in these felsic dikes (72–79 wt. % SiO_2 on a volatile free basis) but sample ANG-06 exhibits a positive Eu* (Figure 6), suggesting cumulate assimilation, consistent with a significant positive Ba anomaly in the sample (Figure 10). A depletion in the middle rare earth elements (e.g., Dy and Ho) in comparison to heavy rare earth elements (e.g., Yb) results in a spoon shaped pattern in some samples (e.g., BEL-03a and BEL-017a) suggestive of amphibole/titantite fractionation (Figure 6). We have included a single sample of the Pan-African basement granite for comparison to the felsic samples within our study. Unsurprisingly,

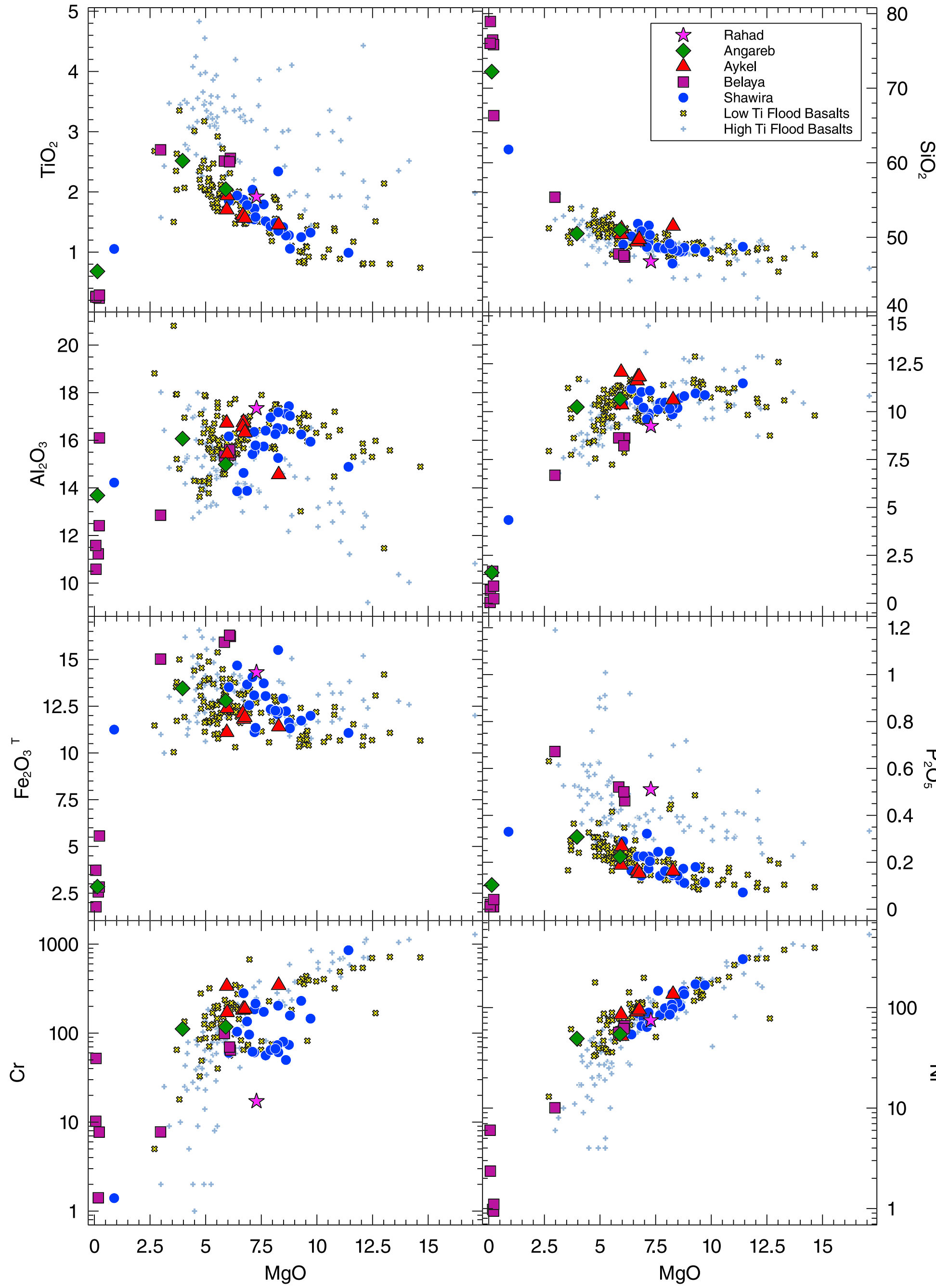

Figure 4. Variation of select major elements (normalized as per the method noted for Figure 2) and compatible trace elements versus an index of differentiation (MgO). Data from this study are presented in Supporting Information S2. Note that major element oxides are presented as weight percent, and the trace elements as parts per million. Data sources from the low Ti and high Ti flood basalts are the same as Figure 3.

this granite is distinct from all the samples studied, in particular the pronounced Nb-Ta anomaly, relative enrichment in Sr, depletion in rare earth elements, and steep slope in the middle and heavy rare earth elements (Figure 10).

Within the flood basalt province, there is a strong linkage between the composition of basalt and rhyolite end-members in the LT and HT provinces (Rooney, 2017). Previous studies have shown that the rhyolites in the Ethiopian Traps are largely derived from fractional crystallization processes, consistent with the lack

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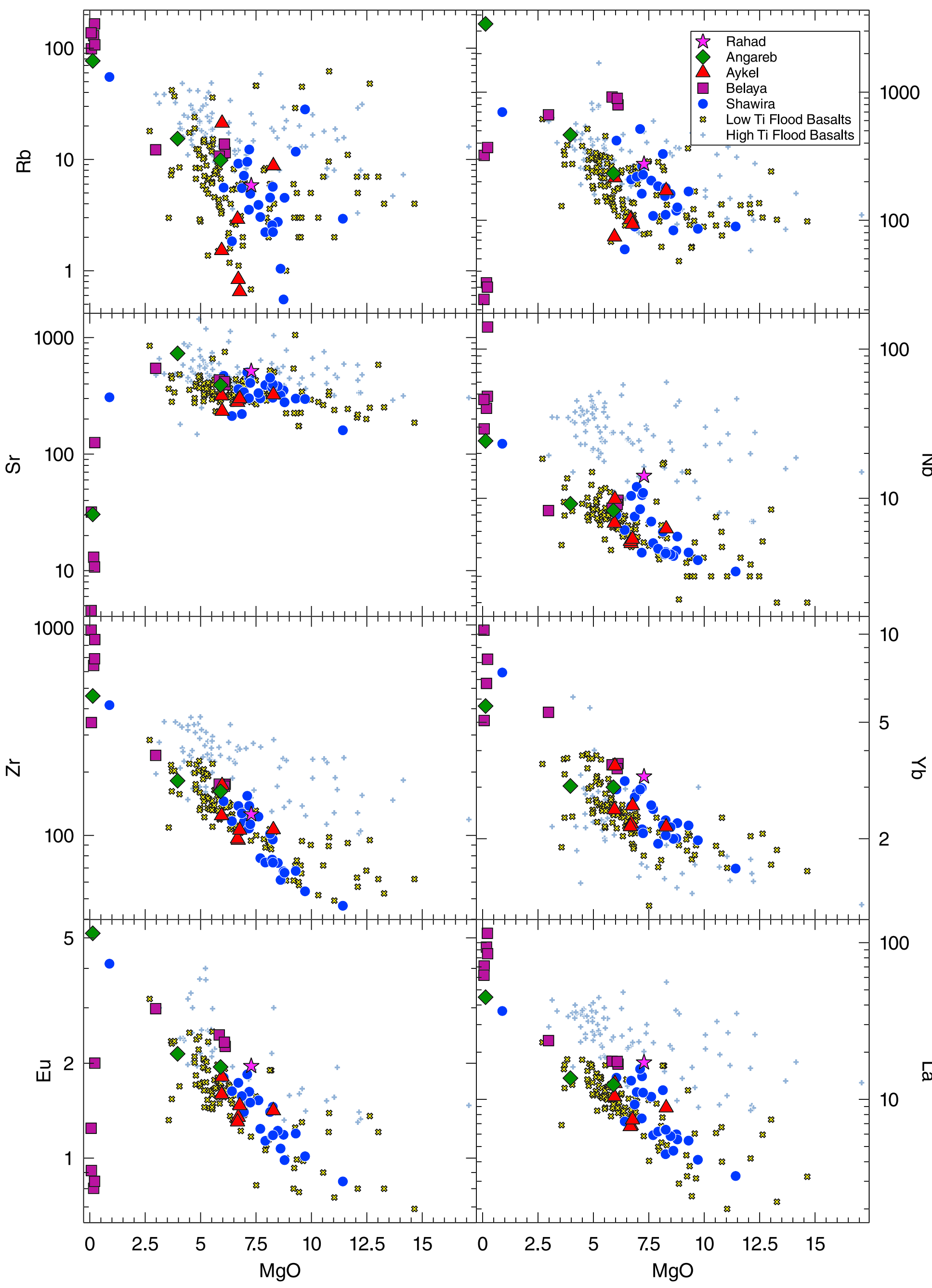

Figure 5. Variation of select trace elements versus an index of differentiation (MgO as weight percent). Data from this study are presented in Supporting Information S2. Note that the trace elements are presented as parts per million. Data sources from the low Ti and high Ti flood basalts are the same as Figure 3.

of intermediate rocks in the region (Ayalew et al., 2002; Ayalew & Yirgu, 2003; Natali et al., 2011). There is some evidence, however, of crustal assimilation processes within the LT-derived rhyolites from Lima Limo, where previously published $^{143}Nd/^{144}Nd$ values exhibit evidence of crustal assimilation (Ayalew et al., 2002).

Felsic magmas within the Ethiopian flood basalt province exhibit a convergence in geochemical characteristics with increasing differentiation. At lower silica contents, elements such as Ti and Sr effectively separate the HT and LT magma series; however, as compositions converge on 75% SiO_2, these differences are lost due to

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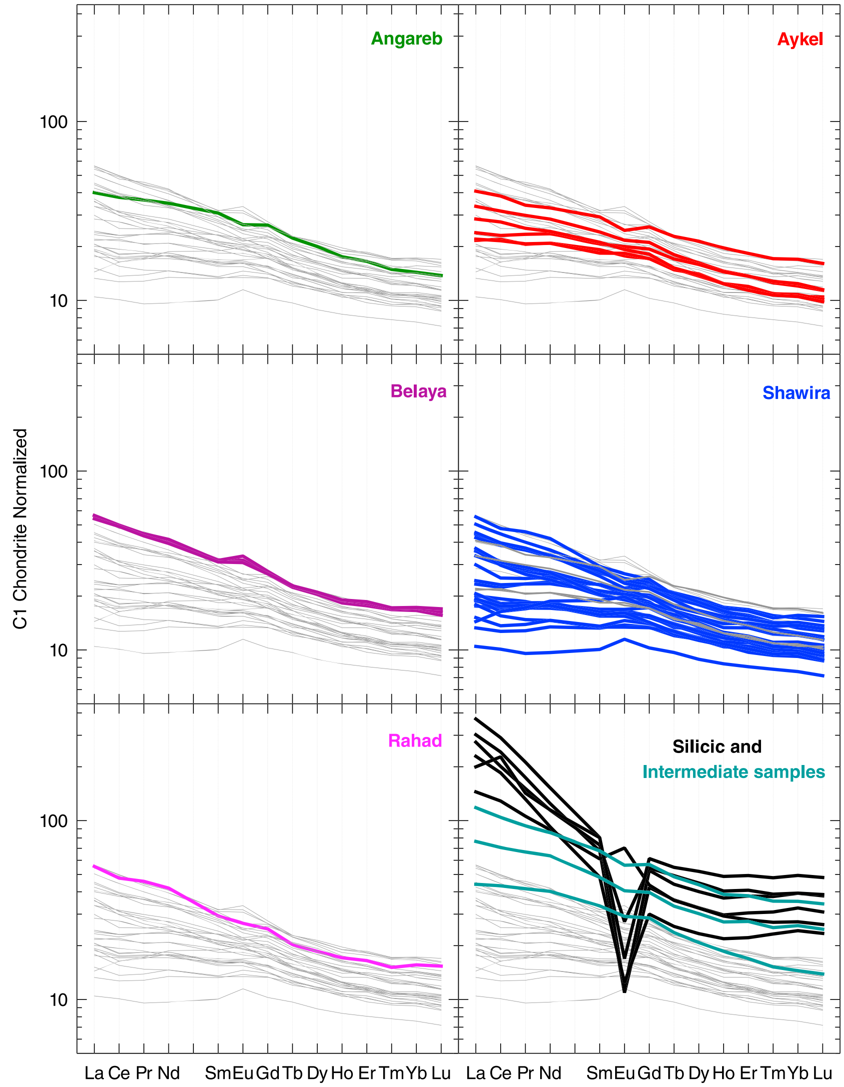

Figure 6. Chondrite normalized (Boynton, 1984) variation diagram showing the behavior of the rare earth elements for our data set. The gray lines denote the entire data set repeated in each panel within the exclusion of the intermediate and felsic samples.

the increasingly important role of fractional crystallization/assimilation processes (Figure 9). Despite the apparent convergence in the LT and HT magma series, distinctive differences remain in terms of the lower concentrations of Nb and Ta in the LT basalt-derived rhyolites (Figure 9). This differential may be expressed as the ratio of Nb to La (Figure 9) where rhyolites derived from LT basalts plot around ~0.5 Nb/La, in contrast to rhyolites derived from HT magmas (Nb/La ~1). The felsic dikes from within our study area are consistent with a derivation from an LT basalt (Figure 9), strengthening existing models of an evolutionary relationship between basalt and rhyolite within the province (Ayalew et al., 2002; Ayalew & Yirgu, 2003; Natali et al., 2011; Peccerillo et al., 2003; Trua et al., 1999). It is notable, however, that sample MKH-01 is anomalous and is unlikely to be derived from the same source as the other felsic dikes. Indeed, this sample shows commonalities with rhyolites derived from the HT flood basalts and later shield volcanoes at Choke and Guguftu (Figure 9). An origin by differentiation from basalts with a different geochemical signature for this magma is consistent with the age of this dike, which is younger by a few million years than most dykes dated in the area—that is, falling within the Miocene resurgent phase of activity in the province that is dominated by basalts with a greater enrichment in trace elements (Rooney, 2017).

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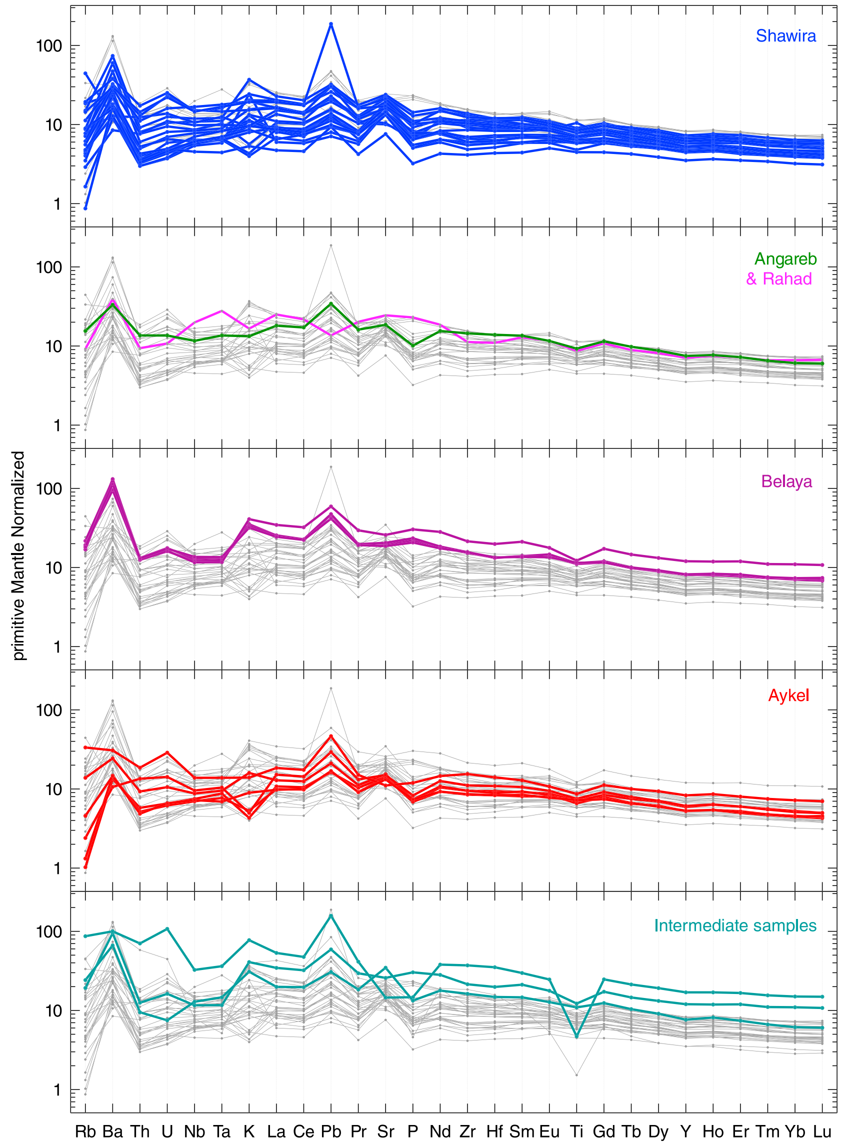

Figure 7. Primitive mantle normalized (Sun & McDonough, 1989) variation diagram showing the behavior of incompatible trace elements for our data set. The gray lines denote the entire data set repeated in each panel within the exclusion of the intermediate and felsic samples.

5. Discussion

5.1. Relationship of Dike Orientation With Basement Fabric

Large Igneous Provinces were initially linked with the concept of radial dike swarms based on well-exposed systems in Canada and work on Venus and Mars (e.g., Ernst et al., 2001; Ernst & Buchan, 1997). The expansion of this concept to other LIPs (Ernst & Buchan, 1997) proved challenging as pseudo-radial diking patterns also resulted from the intersection of structural lineaments that may even contain multiple generations of (much older) dikes (Jourdan et al., 2006; Le Gall et al., 2002). There is growing evidence that dike swarms associated with LIPs may largely follow preexisting structural features or rock fabrics in addition to, or instead of, regional stress fields (Almeida et al., 2013; Hastie et al., 2014; Jourdan et al., 2006; Mège & Korme, 2004a; Schultz et al., 2008; Will & Frimmel, 2013).

The intrusion of magma into the continental lithosphere requires conditions such as enhanced magmatic flux, shear, or other processes such as melt channeling along topography in the lithosphere asthenosphere

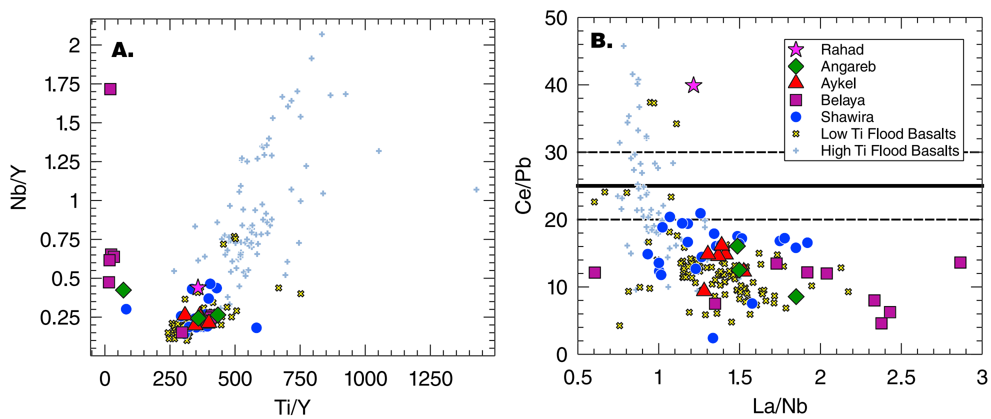

Figure 8. Ratio plots used to classify and assess the origin of magmas in the Ethiopian-Arabian LIP. (a) Nb/Y versus Ti/Y is used to classify high Ti (HT) and low Ti (LT) basalt in Ethiopia (Pik et al., 1998,1999). Our samples plotting at low Ti/Y are felsic samples. Our samples plot with the LT lavas consistent with an origin in the LT domain of the Ethiopian-Arabian LIP. (b) Ce/Pb versus La/Nb is used to examine potential crustal influence on magmatic rocks (Hofmann et al., 1986). The bounds of mantle rocks have been suggested to be ~25 (±5) by Hofmann et al. (1986) and are drawn on the figure. The dikes from this study overlap existing LT lava flows.

boundary (Ebinger & Sleep, 1998; Havlin et al., 2013). Within the Ethiopian rift, dike swarms, whose current surface manifestation are cinder cone fields (Chiasera et al., 2018), display clustering characteristics consistent with a control of the magmatic plumbing system by the crustal strain state (Mazzarini et al., 2013). Similarly, for the Akaki magmatic field, adjacent to the western rift margin, magma is channeled into the lithosphere aligned in an E-W orientation consistent with the preexisting structural fabric within the Ethiopian lithosphere (Abebe, 2014; Abebe et al., 1998) but erupts in a NE-SW alignment that mirrors extensional structures associated with rifting (Rooney et al., 2014). These observations suggest that magma intrusion into the lithosphere in Ethiopia is a function of both preexisting fabrics and the lithospheric stress state.

Along the western margin of the Ethiopian flood basalt province, it has been shown that the NE-striking dikes of the GSDS are aligned with the Precambrian fabric of the Tulu Dimtu Ophiolite Belt (Figure 2a, brown and red colored dikes; Mège & Korme, 2004a). A granitic portion of this belt, located at the southern end of the GSDS, is here dated ca. 600 Ma (Supporting Information S1 and S2). Mège and Korme (2004a) reported on evidence of strike-slip motion at the contact between the wall of one of the main felsic dikes and the host rock, as well as shear structures localized within the margin of a basaltic dike. Magnetic imbrications in dikes close to the dike margins, which are expected to signify dike flow a short time before magma freezing (Callot et al., 2001), indicate dike shearing during emplacement (Schultz et al., 2008). Samples having ID starting with BEL are representative of the composition of such dikes having a NE-SW trend. Mège and Korme (2004a) also noted that the Dinder dike swarm itself (Figure 2b, intermediate green) is parallel to a secondary trend of the Blue Nile rift, suggesting structural control of this swarm as well—the strike of the dike from which MTM-05 was sampled is representative of this ESE swarm and rift trend. On Figure 2b, this trend corresponds to the ESE orientation of the Dinder, Dibaba, Rahad, and Angareb rivers. The Blue Nile rift itself, of orientation N150°E, may have influenced the orientation of the Doka dike swarm (Figure 2a, light green), which the dikes D13 and ANG-06 may belong to. The Doka dike swarm (Medani, 1973; Whiteman, 1971) is mainly exposed in Sudan between Doka and Wad' Arud.

5.2. Location of the Initial Plumbing System

The influence of the basement fabric on the plumbing system is noticeable early in the plumbing system, with the GSDS dikes dated 31–29 Ma (Supporting Information S1 and S2). The ANG-06 dike is dated ca. 30.2 Ma too, which is consistent with the 33-Ma age for the Doka dike swarm in Sudan, obtained using the K-Ar method (Grasty et al., 1963). More recent dating of the swarm in Sudan would be desirable. Emplacement of the dikes from the Angareb ring dike complex (Figure 10, violet) is suggested to have

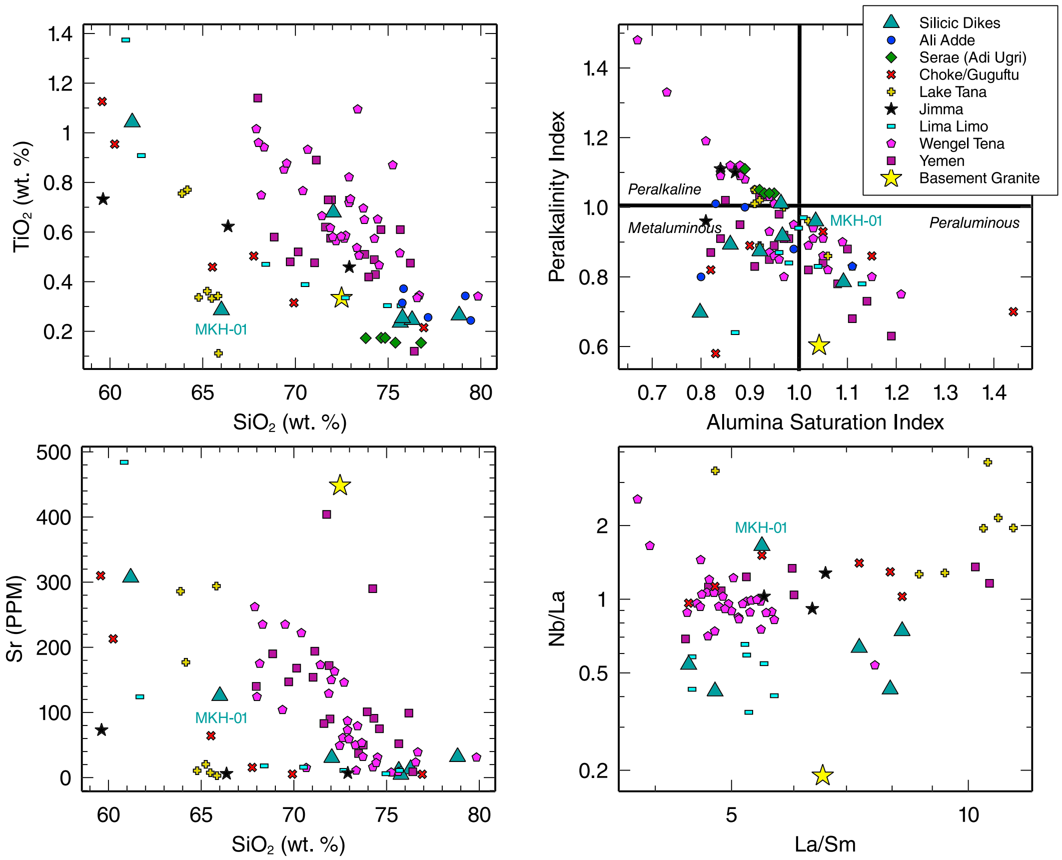

Figure 9. Variation of felsic samples in comparison to other regional data sets. Felsic samples from this study plot with eruptive low Ti (LT) felsic samples, typically plotting at low Sr, TiO_2, and Nb/La. Data sources: Ali Adde—Deniel et al. (1994): Serae—Zanettin et al. (1999): Choke/Guguftu (note that sample 274 within the data set from these authors is excluded as its strong positive Eu anomaly seem to point toward a cumulate origin)—Kieffer et al. (2004): Lake Tana—Dercq et al. (2001): Jimma—Ayalew et al. (2002): Wengel Tena—Ayalew et al. (2002); Ayalew and Yirgu (2003); Natali et al. (2011): Lima Limo—Ayalew et al. (2002); Ayalew and Yirgu (2003): Yemen—Ukstins Peate et al. (2005); Baker et al. (2000); Chazot and Bertrand (1993,1995); Manetti et al. (1991); Chiesa et al. (1989); Capaldi et al. (1983). Note that Choke/Guguftu, Serae, and Ali Adde are considered part of the Early Miocene resurgence phase, while the rest are regarded as part of the tail end of the Oligocene Traps phase. The Lake Tana samples are of unclear temporal affinity but seem to plot with the Miocene samples. We have highlighted sample MKH-01 given its unusual trace element composition relative to other samples.

been coeval with the eruption of the Alaje/upper flood basalts (Hahn et al., 1976), which is now dated at the end of the main flood basalt event at ca. 29 Ma (Abbate et al., 2014; Baker et al., 1996; Hofmann et al., 1997).

5.3. Migration of the Magma Plumbing System

To a first order, the spatial and temporal variation of magmatic activity in East Africa during the Cenozoic era can best be described as a progressive localization of magmatism upon the evolving rift system. However, prior to the large-scale surface manifestation of the rift, volumetrically significant and spatially widespread pulses of magmatism dominated the landscape during the Eocene and Oligocene. The initial Eocene pulse was centered on Southern Ethiopia and extended into Northern Kenya. During the Oligocene, the locus of magmatism became centered beneath the footprint of the Ethiopian flood basalt province. Thus, a broad northward migration of magmatic activity has already been identified in the region. Prior studies of flood basalt stratigraphy have revealed stratigraphic evidence that may also suggest a west to east migration of magmatism. Kieffer et al. (2004) noted that LT flood basalts, which are dominant in the northwestern part of the flood basalt province, are also found in the basal few hundred meters of section in regions where HT flood basalt magmatism is dominant (HT flood basalts are restricted to the eastern portion of the

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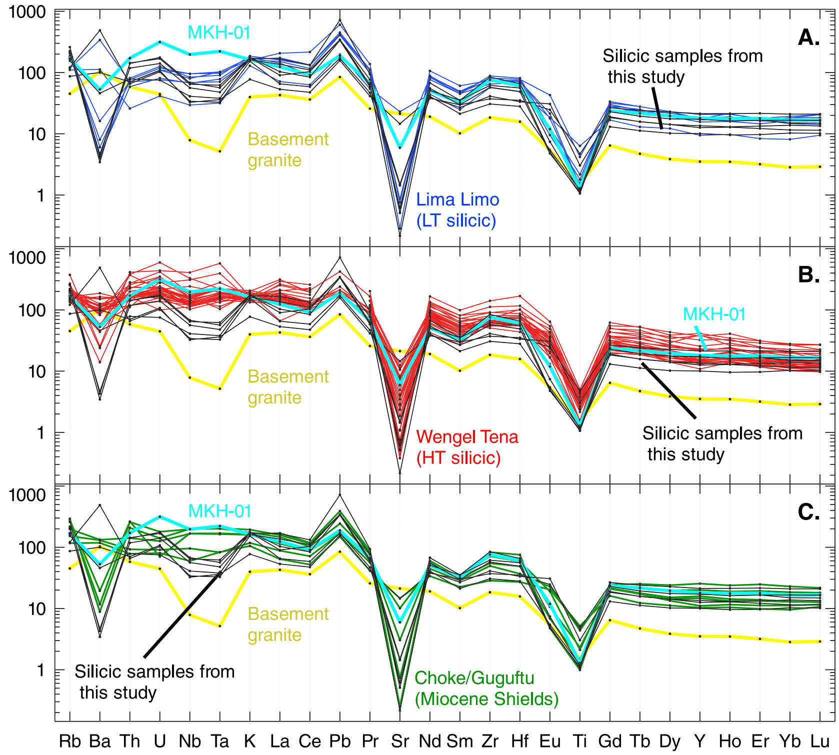

Figure 10. Primitive mantle normalized (Sun & McDonough, 1989) variation diagram showing the behavior of incompatible trace elements for felsic samples from our data set. We also show the composition of a basement granite (yellow) of Pan-African origin (BEL-02), which displays a distinctively depleted trace element composition with the exception of Sr in comparison to samples from this study. On this figure, all felsic samples with the exception of MKH-01 (which is shown in cyan) are colored as black lines. We compare these data with the trace element values of (a) felsic samples erupted in the low Ti portion of the flood basalt province (Lima limo), (b) HT1 portion of the province (Wengel Tena), and (c) the Miocene shield volcanoes of Choke and Guguftu. Data are the same as for Figure 8.

province). However, it has been difficult to establish the general trend in volcanic activity. A key constraint is examining how the locus of magmatism for the LT flood basalts may have migrated through time (Figure 11).

The basal portion of the lower flood basalts in the study region have transitional to alkaline characteristics and do not appear to have been derived from the dikes presented in this study (Krans et al., 2018). The locus of magmatism for these flows remains unknown and could lie further west in Sudan where significant magmatic activity is recorded in Gedaref (e.g., Lucassen et al., 2008) or elsewhere. Above these lower basaltic flows, the dominantly transitional to tholeiitic lower and middle flood basalts dominate the basaltic stratigraphy in this region (Figure 12). The majority of dikes presented within this study have geochemical characteristics consistent with most LT flood basalts and are thus plausible conduits for these magmas. However, given the cyclic nature of the magmatic system during this period (Krans et al., 2018), it is not possible to further constrain dikes to particular stratigraphic horizons. It is thus apparent that the dike swarms of western Ethiopia represent an important portion of the magmatic plumbing system of the LT flood basalts.

Toward the top of the flood basalt stratigraphy, there exist a series of dikes with similar geochemical characteristics that are typified by elevated CaO/Al_2O_3 and Sc, and more depleted Sr at a given value of MgO in comparison to the other dikes lower in the stratigraphy (Figure 13). These characteristics require a more significant role for plagioclase fractionation at shallow crustal levels in the evolution of these magmas and are consistent with the evolution of the upper flood basalts, where the magmatic plumbing system was more focused at shallow crustal levels in comparison to the lower and middle flood basalt sequence (Krans et al., 2018). The link between these dikes and the upper flood basalts is further supported by the observation that these dikes are restricted to elevations above 1,500 m (Figure 10, red contour line) and thus date, at a minimum, to post-middle flood basalt times. Critically, these dikes are also restricted to the eastern portion of the

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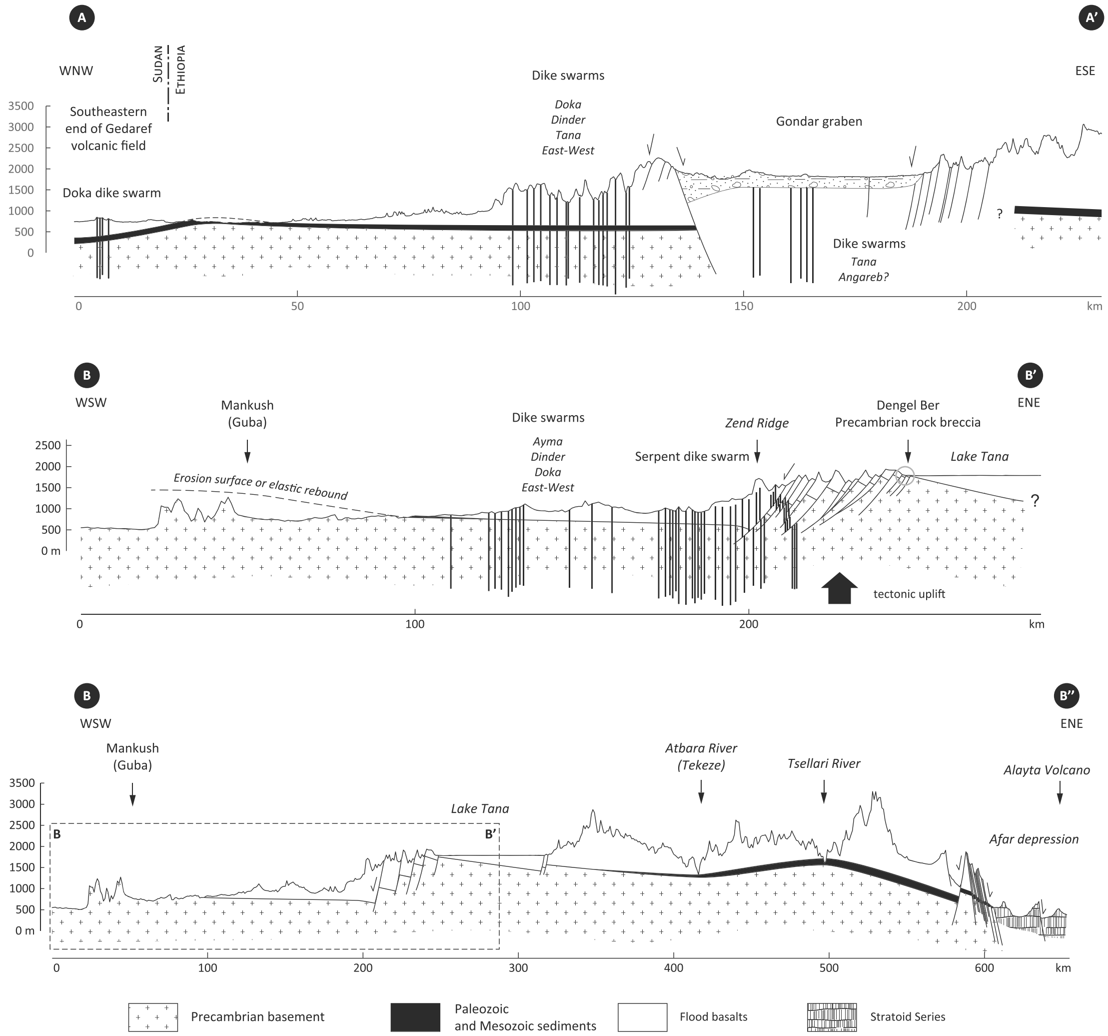

Figure 11. Geological cross sections (located on Figure 2a).

study area, occurring near to the escarpment at Shawira and Aykel. While the upper flood basalts have been removed through erosion in regions west of the escarpment, the absence of dikes displaying this characteristic composition is evidence of an eastward migration of the locus of magmatism for the LT flood basalts.

We have undertaken thermodynamic modeling of the equilibrium crystallization sequence in the region using the Excel MELTS formulation (Gualda et al., 2012). Our starting material was sample 3607—the most primitive dike in our series, which also lies along geochemical trends within the MgO variation plots (Figures 3 and 4). Assigning relatively anhydrous conditions for the LT flood basalts (Kieffer et al., 2004), we initially set the MELTS model to the QFM buffer but allowed the oxygen fugacity to vary with crystallization. We then examined the sensitivity of the model to depth of crystallization during magma evolution. Deep crystallization conditions ($<$0.3 GPa) resulted in evolution models that increased alkalis at a relatively constant SiO_2 content and are not consistent with the observed trends, in particular for Al_2O_3. The majority of the data are better matched to models that start out relatively deep (0.4 to 0.6 GPa) and progressively shallow with ongoing crystallization to 0.05 GPa. Assuming 1 GPa is about 35 km of depth, the data are consistent with crystallization shallowing from 15–20 km depth in the crust to ~2 km during the main sequence. However, the interpretation of such results must be viewed with caution given the potential complexities in such magmatic systems (e.g., O'Hara & Herzberg, 2002)

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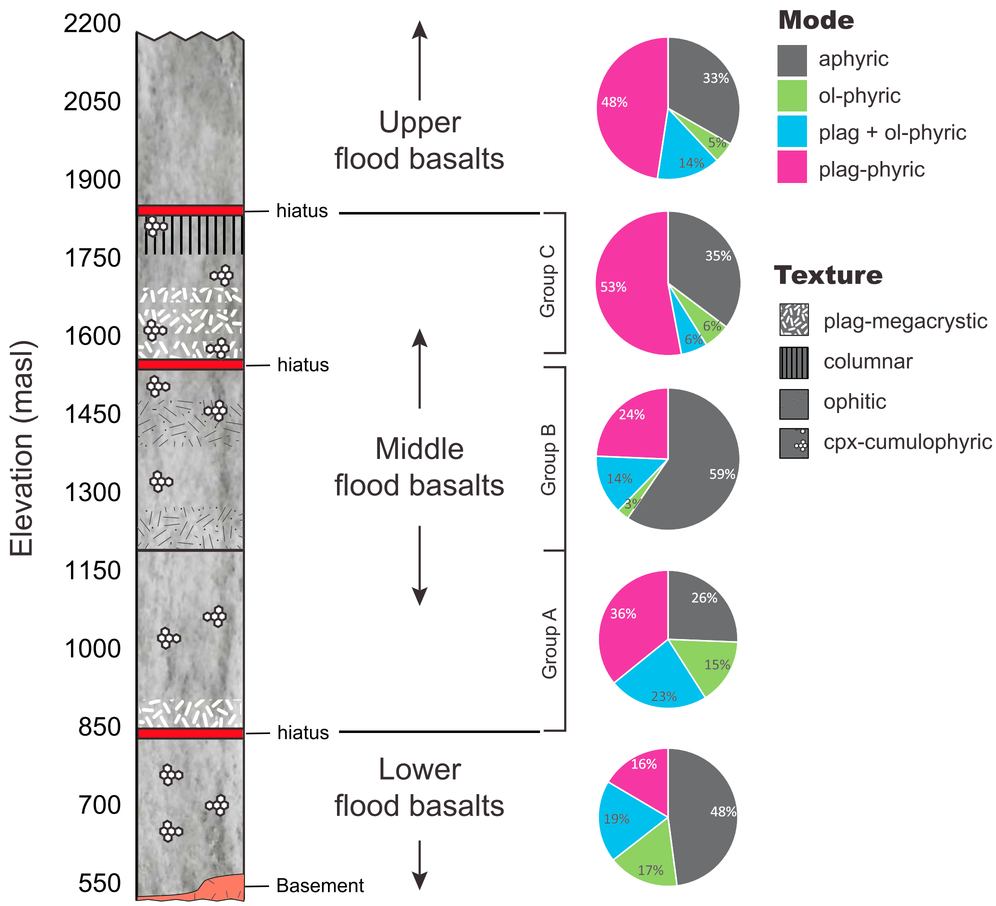

Figure 12. Stratigraphic column derived from petrographic investigation of the Ethiopian flood basalt province from Galegu to Aykel (Krans et al., 2018). Divisions between lower, middle, and upper flood basalts are defined by the presence/absence of two cumulate textures (plagioclase-megacrystic and clinopyroxene-glomerocrystic) that illustrate changes in depth of magma storage (shallow vs. deep, respectively). Mode refers to the dominant phenocryst phase in a given flow. If no phenocryst phase is present, flows are aphyric. Relative percentages of modal phases for each flood basalt division, and groups within divisions, are shown to the right of the stratigraphic column. Krans et al. (2018) note that flows above 1,500 masl (group C portion of the middle flood basalts and the upper flood basalts) are dominated by plagioclase as a phenocryst phase.

Despite the apparent coherency of the MELTS model in addressing the magmatic evolution for the majority of the data, the younger dikes at higher elevations cannot be replicated with this model (Figure 13). Given the geochemical characteristics of these dikes, which suggest a more pronounced role for the crystallization of plagioclase over clinopyroxene in their evolution, we adjusted the overall crystallization sequence to induce plagioclase crystallization much earlier (i.e., assigning a constant 0.05-GPa pressure). Even with this adjustment, the resulting trends are unable to replicate the observed data. In particular, the high values of Al_2O_3, when combined with elevated CaO, present difficulties in permitting either clinopyroxene or plagioclase crystallization and maintaining an appropriate liquid line of descent (Figure 13). Either these outcomes require a different composition as the parent in crystallization models, or the complexity of the magma plumbing system does not allow for such a model to effectively capture the differentiation trend. Specifically, the effects of recharge, evacuation, assimilation, and fractional crystallization are known to impact the geochemical evolution of magmas (Bohrson et al., 2014; Bohrson & Spera, 2001; Lee et al., 2014; Nielsen, 1988; O'Hara & Herzberg, 2002; Spera & Bohrson, 2001) including continental flood basalt provinces (Yu et al., 2015). Capturing such recharge, evacuation, assimilation, and fractional crystallization processes within the magmatic plumbing system requires compositional data on the flows themselves and cannot be effectively modeled with the current data set. These model results are suggestive of a more complex magmatic system for the Ethiopian flood basalts and warrant further investigation.

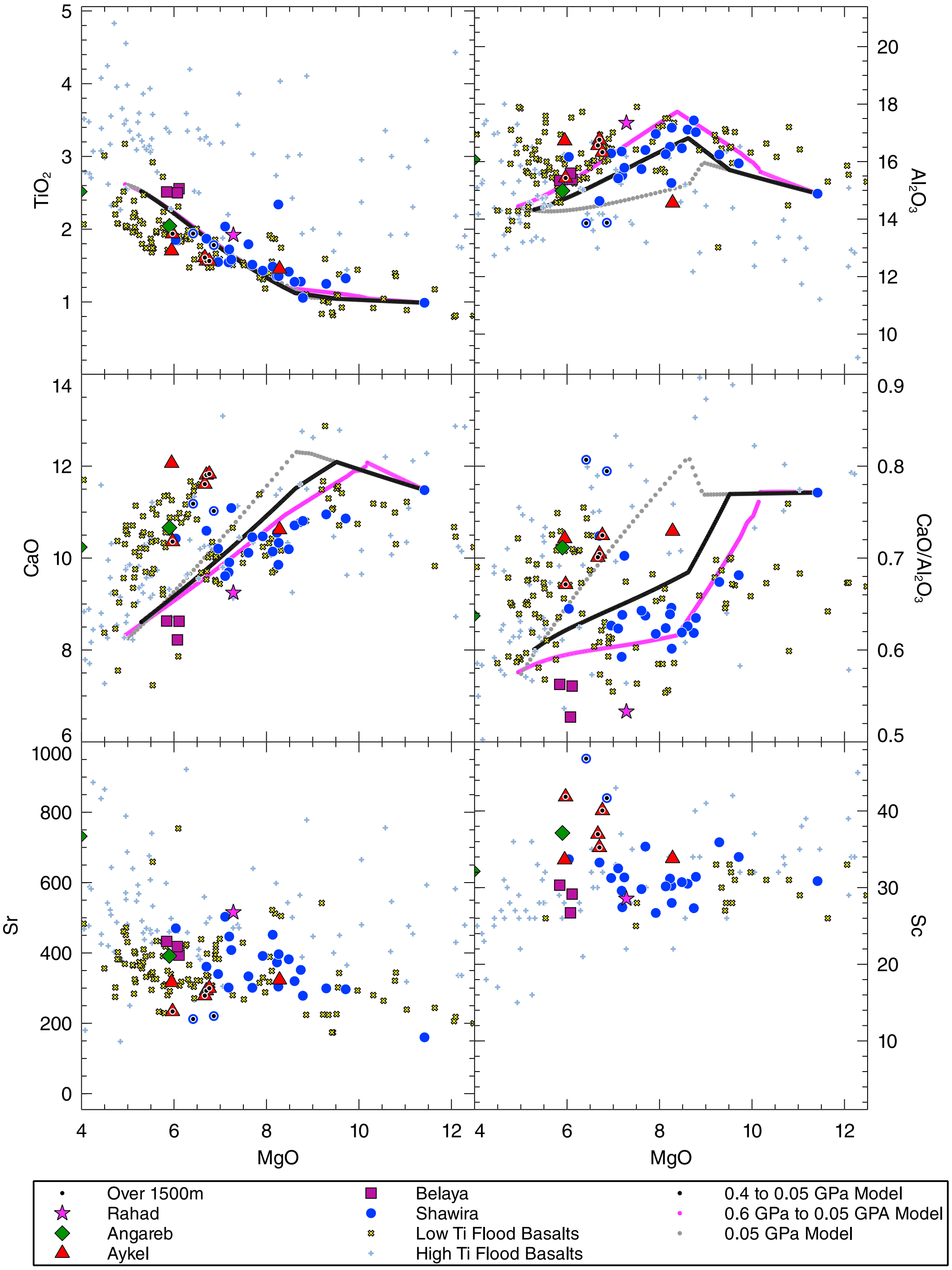

Figure 13. Thermodynamic modeling of sample 3607 using the MELTS model (Ghiorso & Sack, 1995). We utilized the MELTS for Excel formulation using rhyolite-MELTS_v1.0.x (Gualda et al., 2012). Initial conditions were set at 0.25 wt. % water, and initial fO_2 set to the QFM + 0 buffer (but unbuffered during melt evolution). The solution space was explored from 0.1 to 0.5 wt. % water, buffered evolution, and from 0.8 to 0.05 GPa. Solutions at a single pressure failed to adequately describe the data, and the best match was for models that commenced crystallization at deep levels and shallowed progressively toward the terminal pressure of 0.05 GPa. We also show Sr and Sc plots versus MgO and highlight Oligocene samples that are from elevations above 1,500 m (symbols with a black dot in the center). These samples clearly occupy the highest Sc and lowest Sr portions of the figures, requiring a strong role for plagioclase crystallization in the origin of these dikes. See text for detailed narrative.

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Despite the inability to model the crystallization sequence, the geochemical characteristics of these younger dikes (i.e., low Sr and elevated Sc) still requires an important role for plagioclase in their petrogenesis, consistent with the upper flood basalts (Krans et al., 2018). Our assertion of an eastward migration in the locus of LT flood basalt activity during the Oligocene is consistent with existing stratigraphic constraints. Specifically, the terminal stages of LT magmatism during the Oligocene were centered on the Simien Shield Volcano (Figure 1). Here flows of LT composition overlie the upper LT flood basalts and extend from 29.9 to 29.1 Ma (Kieffer et al., 2004). The dikes presented herein expand upon existing data and thus require an eastward migration of magmatism in the LT component of flood basalt magmatism in Ethiopian flood basalt province during the Oligocene from ~36–36.5°E at the lower to middle flood basalt stage, to 36.75–37°E in the upper flood basalt stage to 38°E during the terminal Simien Shield volcano event.

It is not immediately clear what mechanism resulted in the migration of magmatism from west to east in the LT portion of the Ethiopian flood basalt region. However, such temporal migrations in the magmatic plumbing system of flood basalt provinces had been noted elsewhere. Notably, the Deccan Traps exhibit a zoning whereby magmatism migrates from an existing zone of lithospheric weakness (Narmadi-Tapi grabens) toward the Coastal Swarm that is associated with the breakup of India and the Seychelles (Vanderkluysen et al., 2011). Equally, a northward migration of volcanism in the Paraná-Etendeka province has been linked with rifting of the South Atlantic (Peate et al., 1990). Our suggestion of an eastward motion in the locus of LT magmatism in the Ethiopian LIP toward the future rift margin is suggestive of a potential linkage between magmatism and lithospheric deformation. Previous studies have noted that flood basalt magmatism in the eastern portion of the Ethiopian flood basalt province was synchronous with crustal deformation, manifesting as the tilting of the lowest members of the HT flood basalt magmas around Lake Ashenge (Mohr & Zanettin, 1988; Zanettin et al., 1980), and in the regions of Lalibela, Dessie, and Bora (Kieffer et al., 2004; Pik et al., 1999). The relationship between deformation and magmatism in this region has resulted in prior studies, suggesting that the emplacement of the HT series in portions of the province was facilitated by "fractures in the underlying lithosphere" (Kieffer et al., 2004). These assertions are consistent with HT flood basalt dikes evident along the current rift margin (Rooney et al., 2013), suggesting a relationship between the development of the rift and HT magmatism.

Support for a linkage between crustal deformation and diking in the Ethiopian flood basalt province comes from the proposed mechanisms for the formation of the Tana-Gonder dike swarm (Figure 2d, light blue) east of the Aykel and Shawira, which is thought to be contemporaneous with Neogene normal faulting (Chorowicz et al., 1998). The Gonder graben testifies to crustal thinning in the study area associated with eastward migration of the diking activity. Evidence of continuing crustal uplift in this area (near Chagni) is documented until after 8 Ma (Yemane et al., 1985). Precambrian breccia, mainly crush breccia, observed along normal faults that separate some of the tilted blocks west of Lake Tana (Figure 11) at an elevation of 1,800 m, indicate that this uplift, hence thinning, has been extreme at Lake Tana. It has been more limited at the latitude of Aykel (Figure 11; cross sections BB′ and AA′, respectively). Extension not only has taken the form of N-S trending normal faulting and diking but also, as noted by Chorowicz et al. (1998), circumferential diking around Lake Tana (Figure 2e, dark blue). The meridian trend might correspond to early rifting of the African plate (the Main Ethiopian Rift did not significantly open at that latitude until after 11 Ma (Wolfenden et al., 2004), whereas circumferential diking could be related to additional uplift at Lake Tana, to such a point that in addition to generating the Tana tilted blocks, Precambrian rocks were brought to the elevation of the lake (Figure 11). The age and origin of the dense tension fracture arrays (Figure 2e, dashed lines) is not well constrained but might be related to the same event. While speculative at present, it is possible that the migration of the locus of LT flood basalt magmatism is coincident with progressive lithospheric thinning that would be necessary for the eventual development of the rift margin.

5.4. A Feeder System for the LT Flood Basalts

The Ethiopian flood basalt province is unusual in that it exhibits a strongly zoned spatial pattern of magmatism. Both HT and LT basalts were erupted simultaneously but only occur within their respective regions. This characteristic of the Ethiopian flood basalt province has been explained in terms of different mantle sources (see summary in background). However, to preserve these distinctive compositions given the synchronous nature of the eruptions, independent magma plumbing systems are also required. It is thus critical to establish the identity of the feeder dikes to these flows and assess the magnitude of the spatial separation to provide constraints on the wavelength of the mantle heterogeneity in this continental flood basalt province.

Establishing relationships between surface lava flows and contemporaneous dikes in continental flood basalt provinces would seem a logical progression; however, the relationship between dikes, LIPs, and mantle plumes has proven to be controversial (e.g., Baragar et al., 1996; Ernst & Buchan, 1997; Hastie et al., 2014; Jourdan et al., 2006; Le Gall et al., 2002; McHone et al., 2005; Vanderkluysen et al., 2011). Initial focus was on the concept of radial dike swarms, such as those in northern Canada (McKenzie Dike Swarm: Baragar et al., 1996; Ernst & Buchan, 1997), where dikes that are 20–30 m thick (average values) extend some 2,100 km in a radial pattern out from the proposed plume source (Ernst & Baragar, 1992). Given the distance "giant" dike swarms extend from their mantle source and associated eruptive continental flood basalts (e.g., McKenzie and Okavango dyke swarms), such features are of limited utility in probing the magmatic plumbing system of the eruptive lava flows within continental flood basalt provinces.

In regions where substantial denudation of a LIP has yet to occur, exposed dikes are typically more proximal to the paleo-surface (e.g., Columbia River Basalts, Deccan Traps, and Ethiopian-Arabian Traps). Dike widths are on average, markedly thinner than distal giant dike swarms (Mège & Korme, 2004b; Petcovic & Dufek, 2005; Ray et al., 2007), likely a result of dike sampling above the zone of neutral buoyancy, where dikes thin toward zero thickness (Mège & Korme, 2004b). For our study area, Mège and Korme (2004b) showed that ~1 km of erosion has occurred, exposing dikes relatively close to the original surface during dike emplacement and above the zone of neutral buoyancy. Moreover, an anomalous power-law distribution for dikes more than 9–10 km long was suggested to reflect the eruption of these dikes. Taken together, there is strong evidence that the dike swarms in this region of Ethiopia were feeders to the flood basalt lava flows.

The data we present suggest that while the existence of at least three major dike swarms have long been recognized in Ethiopia (western Afar margin, Ogaden, and the western lowlands; Figure 1) as candidates for feeders of flood basalt magmatism (Mohr, 1971), it is only with recent geochronological and geochemical constraints that the relationship between the dikes and flood basalts is being established. For the Ogaden dikes in eastern Ethiopia, geochronologic studies have shown the majority of these intrusions date to the Miocene resurgence phase (27 to 24 Ma) and are thus unrelated to the Ethiopian flood basalt event (Mège et al., 2015; Mège et al., 2016). In contrast, a study of dikes along the western Afar margin exhibited a wide array of ages that extend from ~31 to 8 Ma (Rooney et al., 2013). Among this data set, the dikes related to the Ethiopian flood basalts were classified as HT, consistent with the surface flows in this region, which are also HT in character. The younger dikes in this region are related to magmatic activity from the nearby Guguftu shield volcano and developing rift (Rooney et al., 2013).

The magmatic plumbing system that fed the LT flood basalt flows has heretofore been unconstrained. The data we present shows that the dike swarm previously identified in the western Ethiopian lowlands contain dikes that classify as LT in composition (i.e., group Ia: Rooney, 2017). It is therefore apparent that the LT flood basalt flows were fed from conduits located within this dike swarm. The implication of this observation is that flood basalts in Ethiopia were fed from two independent fissure systems located ~400 km apart, in western Ethiopia and along the Afar margin. These dikes permitted the creation of the strongly zoned Ethiopian flood basalt province. Such observations are important in evaluating the magmatic plumbing system of continental LIPs given the heterogeneities in the spatial and temporal distribution of magma types apparent in many flood basalt provinces.

5.5. Comparisons and Contrasts Among Young Continental Flood Basalt Provinces

The Ethiopian Traps, Columbia River flood basalts, Deccan Traps, and Paraná-Etendeka flood basalts are among the youngest continental flood basalt provinces on the planet. Examination of these provinces and comparing how magmatism manifested within them furthers our understanding of how flood basalt eruptions proceed. It is instructive to compare observations within these other provinces with the results of this work to assess commonalities or differences between the regions. As with the Ethiopian Traps, dike swarms have been linked with lava flows within the Deccan LIP (Vanderkluysen et al., 2011). In that region, however, the dominant heterogeneity in the magma plumbing system is the apparent temporal migration of magmatism. Here the initial stages of magmatic activity within the Deccan LIP were fed from dikes that were controlled by a zone of lithospheric extension (Narmada-Tapi swarm, orientated broadly E-W) that is located in the north of the province. The upper flood basalts within the Deccan traps were, in contrast, erupted from the Nasik-Pune swarm to the south. A third period of diking (Coastal Swarm) is linked to subsequent rifting events (Vanderkluysen et al., 2011). The pattern of magmatism in this region thus shows a relatively strong relationship between magmatism and preexisting lithospheric structures/extension, though there is no evidence of contemporaneous magmatism being fed from multiple feeder zones.

For the Columbia River Basalts, there are a series of well-mapped dike swarms (Steens, Monument, Chief Joseph dike swarms: Camp, 1995) that are interpreted to have fed the flood basalt magmatism (e.g., Hooper et al., 2007; Reidel et al., 2013). Observations in this region have shown that the Chief Joseph dike swarm broadly parallels the North American craton boundary, and the orientation of the swarm is also consistent with structural evidence of E-W extension within the accreted terranes that constitute the crust through which the Chief Joseph dike swarms was emplaced (Hooper et al., 2007). In contrast to the Deccan Traps, there were no changes in the locus of magmatism in terms of abandonment of individual dike swarms within the Columbia River Basalt province. However, for the Monument and Chief Joseph swarms, younger dikes are found predominantly in the northern end of the swarms (Camp & Ross, 2004); this observation is consistent with the northward migration of surface magmatism in the province (Camp, 1995; Camp et al., 2013). The reason for this northward migration in magmatism remains highly controversial and may relate to a rapidly spreading plume head (Reidel et al., 2013), propagating slab tear (Liu & Stegman, 2012), mantle flow induced by slab roll-back (Long et al., 2012), or the outward migration of magmas from a common magma chamber (Coble & Mahood, 2012; Wolff et al., 2008). While the Columbia River Flood Basalts thus exhibit contemporaneous magmatism from two dike systems, the lack of clarity as to the linkage between the locus of melt in the mantle and the lithospheric plumbing system makes it difficult to compare with the Ethiopian example.

The Paraná-Etendeka system might provide the closest analog to the Ethiopian LIP. Within the Paraná portion of the province, the flood basalts have a strong spatial zonation—HT lavas to the north, and LT lavas to the south (Peate et al., 1992; Peate & Hawkesworth, 1996). While this spatial separation is evident at the extremities of the province, a significant region in the center of the province and along the coastal margin displays intercalation of LT and HT flows (e.g., De Min et al., 2018; Peate et al., 1999). This intercalation can also result in the mixing of HT and LT magmas, though the current understanding in this region is that the magmatic plumbing system of the LT and HT systems remained largely distinct with two simultaneously active plumbing systems erupting distinct compositions (De Min et al., 2018; Peate et al., 1999). This assertion is consistent with the composition of the dike swarm considered to have been the feeders of the Paraná-Etendeka system that appear to be largely composed of one type of magma (e.g., Peate, 1997). The Asuncion-Sapucai and Ponta Grossa dike swarms, in which dike orientation is controlled by preexisting structures and faults (e.g., Comin-Chiaramonti et al., 2013; Strugale et al., 2007), both contain dikes of HT composition equivalent to the dominant HT compositions in the lava pile (Pitanga and Paranapanema; Peate, 1997). HT lavas are also fed from the Florianopolis dike swarm (Florisbal et al., 2014), though these lavas are compositionally distinct from the HT dykes of the Ponta Grossa and Ascuncion-Sapucai dyke swarms and instead appear linked to the volumetrically subordinate HT composition (Urubici). LT dikes are found in the Florianoplois, but they are younger than the HT dikes, cross cutting them (Florisbal et al., 2014), and are compositionally consistent with younger LT lavas (Esmeralda). The magmatic plumbing system of the main LT flood basalts in this region (Gramado) appears to be sourced on the conjugate African margin and is represented by the False Bay and Henties Bay-Outjo dike swarms (Trumbull et al., 2007). The magmatic plumbing system and magma distribution of the Paraná-Etendeka system (i.e., spatially distributed LT and HT magmas and distinct magma plumbing systems) thus share much in common with the Ethiopian system. Given the Paraná-Etendeka flood basalt province is also considered to be derived from the African LLSVP (Hoernle et al., 2015), future examination of the commonalities between the two provinces may reveal the characteristics of material upwelling from the African LLSVP if the confounding factors associated with the continental lithosphere can be resolved (Luttinen, 2018).

5.6. Felsic Magmatism and the Plumbing System of Flood Basalt Provinces

As flood basalt magmas transit the continental lithosphere, the transfer of heat associated with the flux of vast volumes of basaltic magma needed to construct a flood basalt province may result in the anatexis of adjacent crustal rocks. On the basis of this model, felsic magmas were hypothesized to represent melts of the continental crust, facilitated by continued flux of basaltic magma through conduits (Coble & Mahood, 2012; Petcovic & Dufek, 2005). During high-flux events, felsic magmas are absent due to the mixing of relatively small volumes of crustal melts within the vast volumes of flood basalts (e.g., Coble & Mahood, 2012; Wolff et al., 2008). By contrast, during lower flux events, felsic magmas may be present. Garland et al. (1995) showed that the unusually elevated eruption temperatures of the Paraná rhyolites, combined with the spatial association of geochemical characteristics between basalts and rhyolites, required assimilation and fractional crystallization processes or melting of underplated flood basalt magmas (Peate, 1997). In this case rhyolites are typically late stage events that occur where magmatic flux is decreasing (Peate, 1997).

Felsic activity within the Ethiopian flood basalt province is not currently recorded at the earliest stages of volcanism and is instead more pronounced toward the final stages of the flood basalt sequence (Ayalew et al., 2002; Kieffer et al., 2004; Mohr & Zanettin, 1988; Pik et al., 1998; Rooney, 2017). Despite this, tuffs are found intercalated with the flood basalt sequence, suggesting contemporaneous felsic eruptions (Krans et al., 2018). The presence of Oligocene dikes of rhyolitic affinity in the Mt. Belaya area might hint at a source in this region for the tuffs. However, rhyolite domes dated from 31.11 to 30.86 Ma have been reported from the Lake Tana region and might also serve as a locus for these rhyolite dikes (Prave et al., 2016). There is no current evidence within the Ethiopian LIP for felsic magmas generated through crustal anatextis (e.g., Ayalew et al., 2002). Further work on magma flux and depth of fractionation is needed to assess the relationship between the spatial distribution of felsic lavas and processes of magma-lithosphere interaction.

6. Conclusions

We have shown that

(A) the western Ethiopian dike swarm was largely contemporaneous with the eruption of the Oligocene flood basalts;
(B) the composition of the dikes is identical to the LT magma type identified in the province;
(C) the Oligocene felsic dikes from within our study area are consistent with a derivation from an LT basalt;
(D) the western Ethiopian dike swarm is a locus of magmatism for the LT flood basalt lavas and is separated from the HT feeder system by ~400 km;
(E) the locus of magmatism for the LT flood basalts migrates eastward overtime, terminating at the Simien shield volcano; and
(F) similarities between the magmatic plumbing system of the Paraná-Etendeka and Ethiopian flood basalt provinces may provide future avenues for understanding the length scale of material upwelling within the African LLSVP.

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