



Draft Manuscript for Review

### Transition from plume-driven to plate-driven magmatism in the evolution of Main Ethiopian Rift

Journal:	<i>Journal of Petrology</i>
Manuscript ID	JPET-Sep-18-0118.R2
Manuscript Type:	Original Manuscript
Date Submitted by the Author:	28-Jun-2019
Complete List of Authors:	Feyissa, Dejene; Institute for Planetary Materials, Okayama University Kitagawa, Hiroshi; Institute for Planetary Matetials, Okayama University, Bizuneh, Tesfaye; Ethiopian Space Science and Technology Institute Tanaka, Ryoji; Okayama University, Institute for Study of the Earth's Interior Kabeto, Kurkura; Addis Ababa Science and Technology University Nakamura, Eizo; Okayama University, Institute for Study of the Earth's Interior
Keyword:	Ethiopian Plateau, Ethiopian Rift, Afar Depression, mantle source, mantle melting

SCHOLARONE™  
Manuscripts

1  
2  
3  
4  
5  
6  
7 1 *Transition from plume-driven to plate-driven magmatism in the*  
8  
9 2 *evolution of the Main Ethiopian Rift*  
10  
11  
12  
13 3

14  
15 4 **Dejene Hailemariam Feyissa<sup>1</sup>, Hiroshi Kitagawa<sup>1\*</sup>, Tesfaye Demissie**

16  
17  
18 5 **Bizuneh<sup>1,2</sup>, Ryoji Tanaka<sup>1</sup>, Kurkura Kabeto<sup>1,3†</sup> and Eizo Nakamura<sup>1</sup>**  
19  
20  
21 6

22  
23  
24 7 <sup>1</sup>Pheasant Memorial Laboratory, Institute for Planetary Materials, Okayama University,  
25  
26  
27 8 Yamada 827, Misasa, Tottori 682-0193, Japan  
28  
29

30 9 <sup>2</sup>Ethiopian Space Science and Technology Institute, Addis Ababa (5 kilo)  
31  
32

33 10 <sup>3</sup>Addis Ababa Science and Technology University, Addis Ababa, Ethiopia, P.O Box 1647  
34  
35

36 11 †Deceased  
37  
38  
39 12

40  
41  
42 13 \*Corresponding author. Email: kitaga-h@okayama-u.ac.jp  
43  
44  
45 14  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

## 16 **ABSTRACT**

17 New K-Ar ages, major and trace element concentrations, and Sr-Nd-Pb isotope data are  
18 presented for Oligocene to recent mafic volcanic rocks from the Ethiopian Plateau, the Main  
19 Ethiopian Rift (MER), and the Afar depression. Chronological and geochemical data from  
20 this study are combined with previously published data sets to reveal secular variations in  
21 magmatism throughout the entire Ethiopian volcanic region. The mafic lavas in these regions  
22 show variability in terms of silica-saturation (i.e., alkaline and sub-alkaline series) and extent  
23 of differentiation (mafic through intermediate to felsic). The *P-T* conditions of melting,  
24 estimated using the least differentiated basalts, reveal a secular decrease in the mantle  
25 potential temperature, from when the flood basalt magmas erupted (up to 1550 °C) to the time  
26 of the rift-related magmatism (<1500 °C). Variations in the Sr-Nd-Pb isotopic compositions  
27 of the mafic lavas can account for the involvement of multiple end-member components. The  
28 relative contributions of these end-member components vary in space and time owing to  
29 changes in the thermal condition of the asthenosphere and the thickness of the lithosphere.  
30 The evolution of the Ethiopian rift is caused by a transition from plume-driven to plate-driven  
31 mantle upwelling, although the present-day mantle beneath the MER and the Afar depression  
32 is still warmer than normal asthenosphere.

33 **KEY WORDS:** Ethiopian Plateau, Ethiopian Rift; Afar Depression; mantle source; mantle  
34 melting

## 36 **INTRODUCTION**

37 Understanding of the genesis of basaltic magmas in relation to tectonic setting is fundamental  
38 in the petrologic and geochemical disciplines. It is generally accepted that basaltic magmas

1  
2  
3  
4  
5  
6  
7 39 are derived, to a first order, by melting of asthenospheric mantle that adiabatically upwells to  
8  
9  
10 40 the base of the lithosphere (McKenzie, 1984). Magma productivity is primarily controlled by  
11  
12  
13 41 the temperature of the melting region; thus voluminous emplacement of basalt, as in Large  
14  
15  
16 42 Igneous Provinces (LIPs), is generally attributed to melting of anomalously hot mantle  
17  
18  
19 43 (White & McKenzie, 1989; White *et al.*, 2008). Compositional heterogeneity is also  
20  
21  
22 44 considered to be an important factor in enhancing magma productivity and diminishing the  
23  
24  
25 45 need for extremely high temperatures in the mantle (Korenaga, 2004; Kitagawa *et al.*, 2008).  
26  
27  
28 46 The LIP basalts in intra-continental plate settings show geochemical evidence for interaction  
29  
30  
31 47 with sub-continental lithosphere, which could result in high magma production through  
32  
33  
34 48 enrichment of volatiles in the melting regions (Arndt & Christensen, 1992; Furman *et al.*,  
35  
36  
37 49 2016).

38  
39 50 The Afar province in eastern Africa and adjacent regions is one example of a recent  
40  
41  
42 51 terrestrial LIP (Fig. 1; White & McKenzie, 1989). Magmatism in the region began with  
43  
44  
45 52 Oligocene trap formation at about 30 Ma (Jones & Rex, 1974; Hofmann *et al.*, 1997;  
46  
47  
48 53 Rochette *et al.*, 1998; Ukstins *et al.*, 2002; Coulié *et al.*, 2003; Kieffer *et al.*, 2004; Prave *et*  
49  
50  
51 54 *al.*, 2016). The ensuing rift-related magmatism has been active over the last *c.* 27–24 Myr in  
52  
53  
54 55 the Main Ethiopian Rift (MER) and Afar (WoldeGabriel *et al.*, 1990; Chernet *et al.*, 1998;  
55  
56  
57 56 Ukstins *et al.*, 2002; Bonini *et al.*, 2005; Wolfenden *et al.*, 2005; Feyissa *et al.*, 2017). Trap-  
58  
59  
60

1  
2  
3  
4  
5  
6  
7 57 phase magmatism is thought to be the surface manifestation of melting of actively upwelling  
8  
9 58 mantle (i.e., a plume; Hart *et al.*, 1989; Marty *et al.*, 1996; Pik *et al.*, 1998, 1999; Furman *et*  
10  
11  
12 59 *al.*, 2006a; Beccaluva *et al.*, 2009; Natali *et al.*, 2016). The present-day rift magmatism is also  
13  
14  
15 60 considered to be influenced by the mantle plume (Afar mantle plume), and its  
16  
17  
18 61 thermochemical effect has been intensively discussed in petrologic, geochemical, and  
19  
20  
21 62 geophysical studies. For example, the excess temperature in the mantle has been estimated to  
22  
23  
24 63 be 100–200 °C by petrologic models (Ayalew & Gibson, 2009; Rooney *et al.*, 2012a;  
25  
26  
27 64 Ferguson *et al.*, 2013a; Pinzuti *et al.*, 2013; Armitage *et al.*, 2015), which are consistent with  
28  
29  
30 65 the estimates based upon seismic tomography and receiver function analysis, if the  
31  
32  
33 66 uncertainty of compositional effects is taken into account (e.g., Nyblade *et al.*, 2000; Rychert  
34  
35  
36 67 *et al.*, 2012; Hammond *et al.*, 2013). Persistent upwelling of a buoyant mantle plume is also  
37  
38  
39 68 suggested by the geochemistry of Oligocene to Recent mafic volcanic rocks, such as the  
40  
41  
42 69 occurrence of high  $^3\text{He}/^4\text{He}$  or high-*T* magmas throughout this period (Marty *et al.*, 1996;  
43  
44  
45 70 Scarsi & Craig, 1996; Pik *et al.*, 2006; Furman *et al.*, 2006a; Ayalew & Gibson, 2009;  
46  
47  
48 71 Rooney *et al.*, 2012a; Rogers *et al.*, 2010).

51 72 Magmatism related to rifting in Ethiopia is still ongoing, and young volcanic activity  
52  
53  
54 73 (early Pleistocene, <2 Ma) occurs in the axial sectors of the MER and Afar. Numerous  
55  
56  
57 74 studies have addressed the petrogenesis of mafic magmas in these sectors in conjunction with  
58  
59  
60

1  
2  
3  
4  
5  
6 75 Oligocene trap-phase magmatism (e.g., Hart *et al.*, 1989; Deniel *et al.*, 1994; Pik *et al.*, 1998,  
7  
8  
9 76 1999, 2006; Kieffer *et al.*, 2004; Furman *et al.*, 2004, 2006a, 2016; Furman, 2007; Rooney *et*  
10  
11  
12 77 *al.*, 2007, 2012a, 2012b, 2013, 2014a, 2014b; Ayalew & Gibson, 2009; Beccaluva *et al.*,  
13  
14  
15 78 2009; Shinjo *et al.*, 2011; Natali *et al.*, 2011, 2016; Nelson *et al.*, 2012; Feyissa *et al.*, 2017).  
16  
17  
18 79 However, although temporal variation may provide important constraints on the evolution of  
19  
20  
21 80 magmatism in continental rift regions, it remains uncertain how magmatic activity varied  
22  
23  
24 81 with time. In particular, the relationship between the compositions of erupted magmas and  
25  
26  
27 82 thermal conditions of melting regions beneath this volcanic province needs to be evaluated in  
28  
29  
30 83 more detail. Recent advances in thermobarometry, calibrated using numerous data sets from  
31  
32  
33 84 melting experiments, allows us to estimate the thermal condition of the melting region in the  
34  
35  
36 85 mantle (e.g., Putirka *et al.*, 2007; Putirka, 2008; Lee *et al.*, 2009; Herzberg & Asimow, 2015).  
37  
38  
39 86 Rooney *et al.* (2012a) applied this approach, and demonstrated that the upwelling of hotter-  
40  
41  
42 87 than-normal mantle has been persistent beneath the Afar and MER regions since 30 Ma.  
43  
44  
45 88 However, the temporal variations in the entire Ethiopian and in adjacent volcanic fields were  
46  
47  
48 89 not fully examined, suggesting the need for further evaluation using data sets including  
49  
50  
51 90 recently published studies (e.g., Ayalew *et al.*, 2016, 2018; Rooney *et al.*, 2014b; Natali *et*  
52  
53  
54 91 *al.*, 2016).

55  
56  
57 92 In this study, we present new K-Ar ages, whole-rock major and trace element  
58  
59  
60

1  
2  
3  
4  
5  
6 93 analyses, and Sr-Nd-Pb isotope data for mafic volcanic rocks from the Ethiopian volcanic  
7  
8  
9 94 province. Our samples include Oligocene mafic rocks from the Maychew area in the  
10  
11  
12 95 northwestern (NW) Ethiopian Plateau and Oligocene to Recent mafic rocks from the rift  
13  
14  
15 96 zones in the southern and northern MER and Afar (Fig. 1). The Maychew rocks include a  
16  
17  
18 97 peculiar type of basalt not yet reported in the NW Plateau (Rooney, 2017), that is strongly  
19  
20  
21 98 alkaline (basanite) and occurs in the basal unit of a lava succession. Such a strongly alkaline  
22  
23  
24 99 basalt provides important constraints on melting conditions and source composition during  
25  
26  
27 100 the onset of Oligocene trap magmatism. We apply thermobarometric calculations to the  
28  
29  
30 101 samples of this study and those presented in previous studies, with careful screening to select  
31  
32  
33 102 the least differentiated magma types, and attempt to constrain the thermal conditions in  
34  
35  
36 103 relation to the chemical variability of the magma source.  
37  
38  
39 104

## 105 **GEOLOGICAL BACKGROUND**

106  
107 Eocene to Quaternary volcanic fields are distributed in three different geological domains in  
108 Ethiopia (Fig. 1; Kazmin, 1979; Berhe *et al.*, 1987; Hart *et al.*, 1989; Ebinger & Sleep, 1998;  
109 GSE, 2005): (1) the rift-bounding plateaus (northwestern, southwestern, and southeastern),  
110 (2) the rift zones (MER) and (3) the rift junction with an associated geological depression

1  
2  
3  
4  
5  
6 111 (Afar). The MER is subdivided into northern, central, and southern sectors, each sector is  
7  
8  
9 112 denoted as Northern MER (NMER), Central MER (CMER), and Southern MER (SMER),  
10  
11  
12 113 respectively (Hayward & Ebinger, 1996; Bonini *et al.*, 2005; Corti, 2009). The Afar is also  
13  
14  
15 114 subdivided three sectors, Northern Afar, Eastern Central Afar, and Southern Afar (Hayward  
16  
17  
18 115 & Ebinger, 1996; Stab *et al.*, 2015). The geological and geochronological features of each  
19  
20  
21 116 volcanic region are briefly described below.  
22  
23  
24  
25  
26

117

### 118 **Rift-bounding plateaus (45 Ma to 10 Ma)**

119 Magmatism related to the formation of basalt plateaus occurred during the period from 45–10  
120 Ma (Rooney, 2017). In the initial phase, the volcanism occurred at 45–34 Ma in southern  
121 Ethiopia and northern Kenya (Davidson & Rex, 1980; Ebinger *et al.*, 1993; George *et al.*,  
122 1998). This volcanism was characterized by bimodal eruptions of basalt and rhyolite  
123 producing intercalated piles of lavas in the Yabello and Amaro areas located in the southeast  
124 of the southwestern (SW) plateau (Figs 1 and Supplementary Data S1; Amaro-Gamo  
125 sequence following Ebinger *et al.*, 1993). The lowest unit of the Amaro-Gamo sequence is  
126 composed mainly of subalkaline basalts (Amaro basalts; Fig. 2b) with ages of 45–40 Ma  
127 (Ebinger *et al.*, 1993, George *et al.*, 1998; Yemane *et al.*, 1999). The upper unit of the  
128 Amaro-Gamo sequence consists of alkaline basalts (Fig. 2b), termed Gamo basalts, which



1  
2  
3  
4  
5  
6 129 conformably overlie the Amaro basalts and have been dated at 40–34 Ma (Ebinger *et al.*,  
7  
8  
9 130 1993; George *et al.*, 1998; Yemane *et al.*, 1999). The Eocene-Oligocene rhyolitic tuff, termed  
10  
11  
12 131 the Amaro tuff (37.0–35.5 Ma; Ebinger *et al.*, 1993; George *et al.*, 1998), is distributed  
13  
14  
15 132 widely in the Amaro-Kele and Gedeb areas (Supplementary Data Fig. S1) and composed of  
16  
17  
18 133 welded ignimbrites, commonly interbedded or overlain by pyroclastic breccias and ash-fall  
19  
20  
21 134 tephra. The second period of flood-basaltic eruptions occurred at 15–7 Ma, and produced lava  
22  
23  
24 135 piles of 200–400 m thickness overlying the Amaro-Gamo sequence in the SW plateau. These  
25  
26  
27 136 mafic rocks are termed Wollega basalts in reference to their type locality (Fig. 1) and consist  
28  
29  
30 137 of subalkaline and alkaline mafic rocks (Ayalew *et al.*, 1999; Conticelli *et al.*, 1999; Bonini *et*  
31  
32  
33 138 *al.*, 2005).

36 139 In the early Oligocene (*c.* 31–25 Ma), intense eruptions of basalt (i.e., flood basalt  
37  
38  
39 140 volcanism) occurred in northwest and southeast Ethiopia and western Yemen (Fig. 1; Baker  
40  
41  
42 141 *et al.*, 1996a, b; Hofmann *et al.*, 1997; Rochette *et al.*, 1998; Ukstins *et al.*, 2002; Coulié *et*  
43  
44  
45 142 *al.*, 2003; Kieffer *et al.*, 2004; Wolfenden *et al.*, 2005; Prave *et al.*, 2016; Rooney *et al.*,  
46  
47  
48 143 2018), referred to as the “Oligocene Traps phase” (Rooney, 2017). In Ethiopia, the lava piles  
49  
50  
51 144 produced during this phase have thicknesses of 500–3000 m and cover an area of 600,000  
52  
53  
54 145 km<sup>2</sup> (Mohr & Zanettin, 1988; Rooney, 2017). Voluminous magma production in this region  
55  
56  
57 146 is generally attributed to melting of anomalously hot mantle delivered by the Afar plume  
58  
59  
60

1  
2  
3  
4  
5  
6 147 (e.g., Ebinger & Sleep, 1998; Pik *et al.*, 2006; Beccaluva *et al.*, 2009; Natali *et al.*, 2016).  
7  
8  
9 148 Several studies have also pointed out the role of volatiles in the magma source region. These  
10  
11  
12 149 components could have enhanced magma production, and been derived either by deep  
13  
14  
15 150 devolatilization in the plume stem (e.g., Beccaluva *et al.*, 2009) or by delamination of sub-  
16  
17  
18 151 continental lithosphere into the plume (e.g., Furman *et al.*, 2016). The majority of Oligocene  
19  
20  
21 152 plateau basalts in Ethiopia are classified as transitional or tholeiitic series (Fig. 2), and are  
22  
23  
24 153 associated with felsic volcanic and pyroclastic rocks (30–22 Ma) in the upper part of the lava  
25  
26  
27 154 successions (Ayalew *et al.*, 2002; Ukstins *et al.*, 2002; Coulié *et al.*, 2003; Kieffer *et al.*,  
28  
29  
30 155 2004; Prave *et al.*, 2016; Rooney *et al.*, 2018). The type locality of Oligocene flood basalts is  
31  
32  
33 156 the NW Ethiopian plateau, divided from the SW plateau by the Yerer-Tullu Wellel volcano-  
34  
35  
36 157 tectonic lineament (YTVL in Fig. 1; Abebe *et al.*, 1998). Previous studies provide details  
37  
38  
39 158 about its stratigraphy in some regions (e.g., Adigrat, Lalibela; Hofmann *et al.*, 1997; Kieffer  
40  
41  
42 159 *et al.*, 2004; Fig. 1). Based on spatiotemporal relationships of the distribution and  
43  
44  
45 160 composition, Pik *et al.* (1998) sub-divided the Oligocene Trap phase basalts into: (1) low-Ti  
46  
47  
48 161 basalts (LT, with  $Ti/Y = 288\text{--}437$  and  $Nb/Y = 0.1\text{--}0.41$ ); (2) high-Ti1 basalts (HT1, with  
49  
50  
51 162  $Ti/Y = 352\text{--}814$  or  $Nb/Y = 0.52\text{--}1.1$ ); and (3) high-Ti2 basalts (HT2, with  $Ti/Y = 670\text{--}885$   
52  
53  
54 163 and  $Nb/Y = 0.9\text{--}1.44$ ). The LT basalts mainly occur in the western periphery of the NW  
55  
56  
57 164 Ethiopian and northern Yemen plateaus, whereas the HT1 and HT2 basalts are distributed in  
58  
59  
60

1  
2  
3  
4  
5  
6 165 the eastern part of the NW plateau (e.g., Lalibela and Maychew) and the southern Yemen  
7  
8  
9 166 plateau (Fig 1; Baker *et al.*, 1996a, b; Pik *et al.*, 1998; Beccaluva *et al.*, 2009). The samples  
10  
11  
12 167 from Maychew described here include the HT1 and HT2 varieties (Supplementary Data Text  
13  
14  
15 168 S1, Table S2 and Figs S2 and S3).

16  
17  
18 169 Following the emplacement of the flood basalts, a number of shield volcanoes were  
19  
20  
21 170 formed during Oligocene to Miocene times, locally creating an additional 1000 to 2000 m of  
22  
23  
24 171 relief (Berhe *et al.*, 1987). The shield volcanoes show a range of eruption ages, 30–19 Ma for  
25  
26  
27 172 the northernmost Simien volcano (Coulié *et al.*, 2003; Kieffer *et al.*, 2004), 23–22 Ma for the  
28  
29  
30 173 Choke and Guguftu volcanoes and 11 Ma for the Guna volcano on the central NW Ethiopian  
31  
32  
33 174 plateau (Kieffer *et al.*, 2004), and 25–24 Ma for the Gerba Guracha volcano in the southern  
34  
35  
36 175 part of the NW plateau (Rooney *et al.*, 2014a, 2017a). Miocene volcanoes also occur on the  
37  
38  
39 176 plateau margins (i.e., rift shoulders), e.g., the 16–10 Ma old volcanic rocks in the Tarmaber-  
40  
41  
42 177 Megezez Formation at the southeastern margin of the NW plateau (e.g., Zanettin & Justin-  
43  
44  
45 178 Visentin, 1974; Zanettin *et al.*, 1978; Chernet *et al.*, 1998; Wolfenden *et al.*, 2004).

46  
47  
48 179

### 50 51 180 **Main Ethiopian rift (30 Ma to present)**

52  
53  
54 181 The Getra-Kele basalts in the SMER are syn-rift alkaline rocks, distributed in the  
55  
56  
57 182 northwestern and southwestern parts of the Amaro-Yabello areas and unconformably  
58  
59  
60

1  
2  
3  
4  
5  
6  
7 183 overlying the Amaro-Gamo sequence (Supplementary Data Fig. S1). These basalts have been  
8  
9 184 dated at 20–11 Ma by the K-Ar method (this study; Ebinger *et al.*, 1993, 2000; George *et al.*,  
10  
11  
12 185 1998; Shinjo *et al.*, 2011) and 19.8–11.9 Ma by the  $^{40}\text{Ar}/^{39}\text{Ar}$  method (Yemane *et al.*, 1999;  
13  
14  
15 186 Rooney, 2010). The Quaternary volcanic rocks, termed the Nech Sar basalts and Bobem  
16  
17  
18 187 trachybasalts (Ebinger *et al.*, 1993) or Tosa-Sucha volcanics (George, 1999), overlie the  
19  
20  
21 188 Getra-Kele basalts. The ages of Getra-Kele basalts indicate that the volcanism followed a  
22  
23  
24 189 period of marked extension in the SMER from 19–18 Ma (Ebinger *et al.*, 2000). The K-Ar  
25  
26  
27 190 ages of the Tosa-Sucha basalts range from 1.94 to 0.29 Ma (Ebinger *et al.*, 1993, Shinjo *et*  
28  
29  
30 191 *al.*, 2011; this study), and indicate Quaternary volcanic activity. This mafic volcanism  
31  
32  
33 192 produced basanite flows and accompanied eruptions of widespread ignimbrites from 1.6–0.5  
34  
35  
36 193 Ma (Ebinger *et al.*, 1993; Bonini *et al.*, 2005; Corti, 2009; Rooney, 2010; Shinjo *et al.*, 2011).  
37  
38  
39 194 The basanites contain mantle xenoliths consisting of anhydrous and hydrous (amphibole- and  
40  
41  
42 195 mica-bearing) spinel lherzolites (Meshesha *et al.*, 2011).  
43  
44

45 196 Volcanic activity in the CMER and NMER has been active since 16–10 Ma,  
46  
47  
48 197 coincident with the onset of rifting (Supplementary Data Fig. S4; WoldeGabriel *et al.*, 1990;  
49  
50  
51 198 Chernet *et al.*, 1998; Ukstins *et al.*, 2002; Wolfenden *et al.*, 2004; Bonini *et al.*, 2005). The  
52  
53  
54 199 Miocene volcanism is characterized by voluminous felsic rocks (e.g., 9–6 Ma Nazret Group  
55  
56  
57 200 and 4–3 Ma Butajira ignimbrite) with associated mafic volcanic rocks (e.g., Justin-Visentin *et*  
58  
59  
60

1  
2  
3  
4  
5  
6 201 *al.*, 1974; WoldeGabriel *et al.*, 1990; Wolfenden *et al.*, 2004). A riftward-younging trend of  
7  
8  
9 202 the ages of volcanic rocks has been well documented in the NMER and CMER (e.g., Morton  
10  
11  
12 203 *et al.*, 1979). The rift-margin volcanic rocks yield K-Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of *c.* 30–10 Ma;  
13  
14  
15 204 they are variably named in reference to their type localities (WoldeGabriel *et al.*, 1990;  
16  
17  
18 205 Chernet *et al.*, 1998; Ukistins *et al.*, 2002; Wolfenden *et al.*, 2004; Bonini *et al.*, 2005; GSE,  
19  
20  
21 206 2005; Feyissa *et al.*, 2017; see Supplementary Data Fig. S5). In ascending stratigraphic order,  
22  
23  
24 207 the mafic rock series are termed Alaje (or Alage) and Kella (Oligocene–Miocene), Tarmaber-  
25  
26  
27 208 Megezez (middle Miocene), Anchar or Guraghe (middle–late Miocene), Kessem or Nazret  
28  
29  
30 209 (late Miocene), Mursi, Bofa, and Mathabila (or Metehbila, early Pliocene). The late Miocene  
31  
32  
33 210 to Pliocene mafic volcanic rocks occur in the transition of marginal regions to axial regions in  
34  
35  
36 211 the rift, commonly associated with widespread ignimbrites. In CMER, the late Miocene to  
37  
38  
39 212 Pliocene volcanic activity also occurred in the rift embayment (Bishoftu embayment;  
40  
41  
42 213 Supplementary Data Fig. S4); e.g., Miocene Addis Ababa basalts (Morton *et al.*, 1979;  
43  
44  
45 214 Chernet *et al.*, 1998) and Miocene Guraghe basalts (Bonini *et al.*, 2005).

46  
47  
48 215 Pliocene-Quaternary volcanic activity mainly occurred at monogenetic vents located  
49  
50  
51 216 in the fault belts in the MER (Figs 1, S4 and S5), e.g., Wonji Fault Belt (WFB; Mohr, 1967)  
52  
53  
54 217 and Silti-Debre Zeyit Fault Zone (SDFZ; WoldeGabriel *et al.*, 1990). Off-axis vents parallel  
55  
56  
57 218 to the rift axis also occur locally, e.g., Akaki magmatic zone and Galema range in the CMER  
58  
59  
60

1  
2  
3  
4  
5  
6 219 (Rooney *et al.*, 2014b; Chiasera *et al.*, 2018). The WFB is a 20 km wide system of bounding  
7  
8  
9 220 faults that developed since 2 Ma and forms a structural link between the MER and Afar  
10  
11  
12 221 (Mohr, 1967; Bonini *et al.*, 2005; Kier *et al.*, 2015; Mazzarini *et al.*, 2016). *En-echelon*  
13  
14  
15 222 segments in the WFB form individual magmatic plumbing systems, e.g., Fantale, Dofan,  
16  
17  
18 223 Boset, and Kone (Supplementary Data Fig. S4, WoldeGabriel *et al.*, 1990, 1992a, b; Ebinger  
19  
20  
21 224 & Casey, 2001; Rooney *et al.*, 2007, 2011). These volcanic complexes are characterized by  
22  
23  
24 225 the occurrence of mafic to felsic lavas (e.g., Boccaletti *et al.*, 1999; Peccerillo *et al.*, 2003;  
25  
26  
27 226 Abebe *et al.*, 2007; Rooney *et al.*, 2012c; Rooney *et al.*, 2007, 2011, 2012c, 2014b; Corti,  
28  
29  
30 227 2009; Giordano *et al.*, 2014), resulting from the development of shallow and mature magma  
31  
32  
33 228 reservoirs (Rooney *et al.*, 2007). In contrast, the SDFZ lacks the development of intense  
34  
35  
36 229 faulting and has less evolved magmatic plumbing systems (Rooney *et al.*, 2007).

230

### 231 **Afar depression (5 Ma to present)**

232 The Afar depression is a down-faulted lowland plain bounded by uplifted basement (Danakil  
233 Range) in the north, Oligocene flood basalt plateaus in the southeast and west, and the Red  
234 Sea in the northeast (Figs. 1, S6 and S7). At its margin, rift-parallel basins are imposed on the  
235 Oligocene flood basalt piles (Wolfenden *et al.*, 2005; Rooney *et al.*, 2013; Corti *et al.*, 2015).  
236 The Afar depression is divided into three rift systems, the Southern, Central, and Northern

1  
2  
3  
4  
5  
6 237 Afar sectors (Hayward & Ebinger, 1996). The Central and Southern Afar are divided by a  
7  
8  
9 238 Quaternary fault zone known as Tendaho-Goba'ad Discontinuity (TGD), whereas the Central  
10  
11  
12 239 and Northern Afar are divided at 12–13 °N, corresponding to the landward extension of the  
13  
14  
15 240 Red Sea Rift through the Gulf of Zula. Crustal thickness varies from 16 km in Northern Afar  
16  
17  
18 241 through 25 km in Central Afar to 26 km in Southern Afar (Hayward & Ebinger, 1996). The  
19  
20  
21 242 TGD also marks an abrupt change in the rate and direction of extension. Rifting is faster in  
22  
23  
24 243 the north of the TGD (20 mm/yr) and NNE-SSW directed, whereas rifting is slower (3–8  
25  
26  
27 244 mm/yr) and NW-SE directed in the south of the TGD, similar to that in the NMER.

28  
29  
30 245 The stratigraphy of the Afar depression consists of six units in the ascending order  
31  
32  
33 246 (Bosworth *et al.*, 2005) of: (1) Neoproterozoic metamorphic rocks; (2) Mesozoic strata and  
34  
35  
36 247 *Early* Tertiary volcanic rocks; (3) Oligocene trap basalts (Aiba and Alaje basalts); (4)  
37  
38  
39 248 Miocene volcanic rocks; (5) Plio-Pleistocene volcanic rocks; and (6) Quaternary volcanic  
40  
41  
42 249 rocks. The Miocene volcanic units (Mabla rhyolites and Adolei-Dalha basalts) are distributed  
43  
44  
45 250 in the margin of the depression, and are dated to 23–5 Ma (e.g., Barberi *et al.*, 1975; Zumbo  
46  
47  
48 251 *et al.*, 1995; Audin *et al.*, 2004; Stab *et al.*, 2015). The Pliocene-Pleistocene mafic volcanic  
49  
50  
51 252 rocks are widely distributed in the Afar depression, and termed the Afar stratoid series  
52  
53  
54 253 (Supplementary Data Fig. S6; Barberi *et al.*, 1974; Barberi & Varet, 1975; Varet, 1978;  
55  
56  
57 254 Berhe, 1986). The Quaternary volcanic rocks occur in internal grabens and marginal zones  
58  
59  
60

1  
2  
3  
4  
5  
6 255 (Chernet *et al.*, 1998; Deniel *et al.*, 1994; Pinzuti *et al.*, 2013; Stab *et al.*, 2015). They consist  
7  
8  
9 256 of basalt lava flows [Gulf basalts (Kidane *et al.*, 2003) and axial range basalts, e.g., Erta’Ale  
10  
11  
12 257 and Manda Inakir], scoria cones, and some felsic rocks (Varet, 1978). According to the  
13  
14  
15 258 geological map of Stab *et al.* (2015), our samples consist of mafic rocks corresponding to the  
16  
17  
18 259 Afar stratoid basalts, Gulf basalts, and axial range basalts (Supplementary Data Fig. S6).  
19  
20

21  
22 260

## 23 24 261 **GEOPHYSICAL PROPERTIES**

25  
26  
27 262 Seismic and gravity data provide constraints on the properties of the lithosphere and  
28  
29  
30 263 asthenosphere beneath the volcanic regions in this area. The lithosphere-asthenosphere  
31  
32  
33 264 boundary (LAB) lies at *c.* 60–80 km depth beneath the plateaus, and at *c.* 50 km depth  
34  
35  
36 265 beneath the MER and Afar (Dugda *et al.*, 2007; Rychert *et al.*, 2012; Hammond *et al.*, 2013).  
37  
38  
39 266 The LAB boundary is well-defined beneath the plateau regions, whereas it is obscured  
40  
41  
42 267 beneath the rift axes due to thermal erosion of the base of the lithosphere (Rychert *et al.*,  
43  
44  
45 268 2012; Armitage *et al.*, 2015). The crustal thickness beneath the eastern and western Ethiopian  
46  
47  
48 269 plateaus is estimated at 30–45 km, whereas beneath the rift it shows lateral variation, from 35  
49  
50  
51 270 km in the SMER, through 25–30 km in the CMER, and 25 km in the NMER to 16–26 km  
52  
53  
54 271 beneath the Afar depression (Dugda *et al.*, 2005; MacKenzie *et al.*, 2005; Maguire *et al.*,  
55  
56  
57 272 2006; Hammond *et al.*, 2011; Lavayssière *et al.*, 2018).  
58  
59  
60



1  
2  
3  
4  
5  
6 273 Seismic tomography detects broad low-velocity anomalies in the upper mantle  
7  
8  
9 274 beneath Ethiopia, extending from the base of lithosphere to the mantle Transition Zone (e.g.,  
10  
11  
12 275 Hammond *et al.*, 2013; Civiero *et al.*, 2015). The pronounced low-velocity zone at 75–150  
13  
14  
15 276 km depth, aligned along the Afar and MER axial zones, is interpreted to reflect the presence  
16  
17  
18 277 of partially molten mantle (Bastow *et al.*, 2008), whereas the low-velocity anomaly at greater  
19  
20  
21 278 depth is thought to be due to a weak thermal anomaly (<150 K) and hydrated mantle  
22  
23  
24 279 materials (Thompson *et al.*, 2015).  
25  
26  
27  
28  
29

## 30 281 **SAMPLES AND ANALYTICAL METHODS**

31  
32  
33  
34 282 Samples analyzed in this study were collected from several volcanic fields in the Ethiopian  
35  
36  
37 283 volcanic provinces including the MER (NMER and SMER), Afar, and the NW Plateau  
38  
39  
40 284 (Supplementary Data Figs S1, S2, S4–S7). These fields are the same or close to the fields  
41  
42  
43 285 investigated in previous studies [e.g., Plateau region by Beccaluva *et al.* (2009), Afar by  
44  
45  
46 286 Barrat *et al.* (1998), NMER by Furman *et al.* (2006a), and SMER by George & Rogers  
47  
48  
49 287 (2002)]. We therefore integrate our new data sets with the existing data and provide an update  
50  
51  
52 288 of geochemical information about Ethiopian volcanism. The geodetic coordinates and altitude  
53  
54  
55 289 of sampling locations were obtained using GPS (Global Positioning System), or estimated  
56  
57  
58 290 from maps. Efforts were made to sample the least altered rocks for geochemical and  
59  
60

1  
2  
3  
4  
5  
6 291 geochronological analyses. The geochronological and other geochemical work was  
7  
8  
9 292 performed at the Pheasant Memorial Laboratory, Institute for Planetary Materials, Okayama  
10  
11  
12 293 University at Misasa, Japan (see Nakamura *et al.*, 2003). Details of analytical methods are  
13  
14  
15 294 given in the Supplementary Data Text S2.  
16  
17

18 295  
19

## 20 21 296 **RESULTS**

### 22 23 24 297 **K-Ar ages and petrography**

25  
26  
27 298 K-Ar dating was used to constrain the age of mafic volcanic rocks from the NW Plateau ( $n =$   
28  
29  
30 299 11), SMER ( $n = 10$ ), NMER ( $n = 13$ ), and the Afar Depression ( $n = 19$ ); the results of these  
31  
32  
33 300 analyses are summarized in Table 2. Samples were selected to represent the spatial,  
34  
35  
36 301 stratigraphic, and chemical diversities in each region (Supplementary Data Figs S1, S2, S4  
37  
38  
39 302 and S7). Our data are combined with previously published ages to reconstruct the volcanic  
40  
41  
42 303 history of these regions. Careful comparison was also made between our ages and published  
43  
44  
45 304 ones, in particular  $^{40}\text{Ar}/^{39}\text{Ar}$  dates to confirm the reliability of our dates. Below, we  
46  
47  
48 305 summarize the geochronological data, together with petrographic features (Supplementary  
49  
50  
51 306 Data Table S1), of basaltic rocks from the individual volcanic regions.  
52  
53

54 307  
55  
56  
57  
58  
59  
60

1  
2  
3  
4  
5  
6 308 *Rift-bounding plateau basalts from Maychew*  
7  
8

9 309 Eleven K-Ar ages were determined for mafic rocks from the lava successions in the Maychew  
10  
11 310 area (Figs 1 and S2). We defined six volcanic units, referred to as the sequences 1, 2, 3, 4, 5  
12  
13  
14  
15 311 and 6 in ascending stratigraphic order (see details in Supplementary Data Text S1). The  
16  
17  
18 312 majority of them yield K-Ar ages of 28 Ma, irrespective of stratigraphic unit (Table 2 and  
19  
20  
21 313 Supplementary Data Fig. S2). The younger ages (25–21 Ma) for some samples are  
22  
23  
24 314 inconsistent with their stratigraphic positions (BK06, TS12, TS35, TS43 and TS45). Although  
25  
26  
27 315 there are no systematic differences in the extents of alteration between samples showing two  
28  
29  
30 316 age populations (28 and 25–21 Ma), including loss on ignition and petrographic texture, the  
31  
32  
33 317 younger ages are considered to be inaccurate as a result of post-eruptive processes. Recent  
34  
35  
36 318 precise and more reliable  $^{40}\text{Ar}/^{39}\text{Ar}$  ages for basalts in the other regions on the NW Ethiopian  
37  
38  
39 319 Plateau suggest that the trap-phase magmatism occurred between 31–25 Ma (e.g., Hofmann *et*  
40  
41  
42 320 *al.*, 1997; Ukstins *et al.*, 2002; Coulié *et al.*, 2003). We therefore consider that the volcanism  
43  
44  
45 321 in Maychew likely occurred at 28 Ma or older (*c.* 30 Ma).  
46  
47

48 322 The HT2 basanites (sequence 1) are aphyric with microphenocrysts of clinopyroxene.  
49  
50  
51 323 The HT2 and HT1 alkaline basalts (sequences 2–6) are porphyritic with clinopyroxene and  
52  
53  
54 324 olivine as major phenocryst phases. Occasionally, they show sub-ophitic to doleritic textures.  
55  
56  
57 325 In the upper stratigraphic units (sequences 4–6), mafic rocks include plagioclase-phyric  
58  
59  
60

1  
2  
3  
4  
5  
6 326 basalts (HT1 type). The relationship among magma types, petrographic features and  
7  
8  
9 327 stratigraphic positions is similar to that observed in the other regions of the NW Ethiopian  
10  
11  
12 328 Plateau (Pik *et al.*, 1998; Beccaluva *et al.*, 2009; Natali *et al.*, 2016; Krans *et al.*, 2018;  
13  
14  
15 329 Rooney *et al.*, 2018).

16  
17  
18 330

19  
20  
21 331 *Getra-Kele basalts in SMER*

22  
23  
24 332 Six basaltic samples from Getra-Kele yield ages of 16.4–10.8 Ma (Table 2 and  
25  
26  
27 333 Supplementary Data Fig. S1). With the published K-Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$  ages (WoldeGabriel *et*  
28  
29  
30 334 *al.*, 1991; Ebinger *et al.*, 1993, 2000; George *et al.*, 1998; Rooney, 2010; Shinjo *et al.*, 2011),  
31  
32  
33 335 the eruptions of Getra-Kele mafic rocks are likely to have occurred from 20–11 Ma,  
34  
35  
36 336 coinciding with the northward propagation of the SMER (Ebinger *et al.*, 1993, 2000; George  
37  
38  
39 337 *et al.*, 1998; Bonini *et al.*, 2005). The Getra-Kele mafic rocks are commonly porphyritic,  
40  
41  
42 338 consisting of euhedral to subhedral phenocrysts of olivine, plagioclase, augite, and opaque  
43  
44  
45 339 minerals (Supplementary Data Table S1). The groundmass shows a pilotaxitic texture  
46  
47  
48 340 consisting of plagioclase, olivine, clinopyroxene, and Fe-Ti-oxides.

49  
50  
51 341

52  
53  
54 342 *Tosa-Sucha basalts in SMER*

55  
56  
57 343 Four basalts from lavas or volcanic cones in the Arba Minch area yield ages of 1.26–0.56 Ma  
58  
59  
60

1  
2  
3  
4  
5  
6 344 (Table 2 and Supplementary Data Fig. S1), consistent with K-Ar dates of 1.34–0.68 Ma by  
7  
8  
9 345 Ebinger *et al.* (1993). Shinjo *et al.* (2011) also obtained comparable K-Ar ages of 1.94–0.29  
10  
11  
12 346 Ma for mafic volcanic rocks in the south of Yabello. The Quaternary age is consistent with  
13  
14  
15 347 the volcanic morphology and occurrence of these mafic rocks overlying the Amaro and  
16  
17  
18 348 Gamo basalts (Ebinger *et al.*, 1993). The Tosa-Sucha mafic rocks are porphyritic with  
19  
20  
21 349 phenocrysts mostly of plagioclase (20–42 vol.%), olivine (2–11 vol.%), and augite (up to 4  
22  
23  
24 350 vol.%) (Supplementary Data Table S1). Plagioclase crystals are euhedral and 0.5–3 mm in  
25  
26  
27 351 size. Olivine and augite exhibit subhedral, rounded shapes (0.5–1.5 mm). Abundant  
28  
29  
30 352 plagioclase crystals are considered to be xenocrysts, based on their zoning patterns and  
31  
32  
33 353 resorption textures (Rooney, 2010). The groundmass is composed of feldspars, olivine,  
34  
35  
36 354 clinopyroxene, and Fe-Ti oxides.  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

#### 356 *Syn-rift basalts from NMER*

357 Feyissa *et al.* (2017) referred to the late Oligocene to early Pliocene mafic volcanic rocks  
358 from the NMER as Mathabila basalts. These mafic rocks are commonly subdivided into six  
359 major formations: Alage, Tarmaber-Megezez, Nazret-Afar, Cholalo-Bishoftu, and the  
360 Quaternary Formations (GSE, 2005; Supplementary Data Fig. S5). The oldest rocks are  
361 distributed in the western escarpment of the NMER, and dated at 27–25 Ma (DBZ-22 and

1  
2  
3  
4  
5  
6 362 DBZ-30; Table 2). Considering their localities (Supplementary Data Fig. S5), these basalts  
7  
8  
9 363 are equivalent to the Alage basalts. The ages obtained in this study is consistent with the  
10  
11  
12 364 existing K-Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$  ages for Alage basalts or intercalated pyroclastic rocks (Chernet  
13  
14  
15 365 *et al.*, 1998; Ukstins *et al.*, 2002; Supplementary Data Fig. S4). Two samples, DBZ-8 and  
16  
17  
18 366 DH-429, collected in the east of Debre Birhan (Supplementary Data Figs S4 and S5), yield  
19  
20  
21 367 ages of 20–15 Ma. Based on the ages and localities, they are classified as Tarmaber-Megezez  
22  
23  
24 368 basalts (GSE, 2005). Similar ages (19.8–10.0 Ma) were obtained by the  $^{40}\text{Ar}/^{39}\text{Ar}$  method for  
25  
26  
27 369 this formation (basalt and associated ignimbrites: Ukstins *et al.*, 2002; Wolfenden *et al.*,  
28  
29  
30 370 2004).

31  
32  
33 371 The K-Ar ages of mafic rocks from the rift floors ( $n = 7$ ) fall within the range 6.5–2.7  
34  
35  
36 372 Ma, consistent with the eruptive products of the Miocene-Pliocene Nazret Series and the  
37  
38  
39 373 overlying Pliocene Formations, i.e., the Bofa and Bishoftu basalts (Chernet *et al.*, 1998).  
40  
41  
42 374 These samples were collected in regions surrounding the Fantale-Dofan magmatic segment  
43  
44  
45 375 (Supplementary Data Figs S4 and S5), and the ages obtained here are consistent with the  
46  
47  
48 376  $^{40}\text{Ar}/^{39}\text{Ar}$  ages (7–2 Ma) for intercalated ignimbrites (WoldeGabriel *et al.*, 1992a; Chernet *et*  
49  
50  
51 377 *al.*, 1998; Wolfenden *et al.*, 2004). We refer to these basalts as Nazret series.

52  
53  
54 378 Two basalts from Fantale volcano yield ages of 0.24 and 0.20 Ma (DHDH-4 and  
55  
56  
57 379 DBAG-115). These ages are consistent with a fission-track age of  $0.17 \pm 0.04$  Ma for a  
58  
59  
60

1  
2  
3  
4  
5  
6 380 welded tuff in the caldera of this volcano (Williams *et al.*, 2004) and also fall within the  
7  
8  
9 381 range of an explosive volcanic pulse (0.32–0.17 Ma) in the NMER and CMER (Peccerillo *et*  
10  
11  
12 382 *al.*, 2003; Hutchison *et al.*, 2016; Siegburg *et al.*, 2018). We refer to these basalts as  
13  
14  
15 383 Quaternary Fantale basalts.

16  
17  
18 384 Mafic rocks in the NMER show similar petrographic features, irrespective of eruption  
19  
20  
21 385 ages. They are porphyritic with a phenocryst assemblage of plagioclase (*c.* 14 vol%), olivine  
22  
23  
24 386 (2–12 vol%), and rare clinopyroxene (2–3 vol%). An exception are the mineral modes of the  
25  
26  
27 387 older mafic lavas with ages of 25 and 15 Ma (Alage and Tarmaber-Megezez series,  
28  
29  
30 388 respectively). These rocks are highly porphyritic with 20–25 vol% plagioclase phenocrysts  
31  
32  
33 389 (Supplementary Data Table S1). Groundmasses of all rocks are composed of olivine,  
34  
35  
36 390 clinopyroxene, feldspars, and Fe-Ti oxides, with dark interstitial glass.

37  
38  
39 391  
40  
41  
42 392 *Afar basalts*

43  
44  
45 393 The K-Ar ages of nineteen mafic samples range from 4.5 to 0.1 Ma (Table 2 and  
46  
47  
48 394 Supplementary Data Fig. S7). Our results are consistent with existing K-Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$   
49  
50  
51 395 ages (5.4 to <0.1 Ma) for mafic volcanic rocks from the Pliocene and Quaternary formations  
52  
53  
54 396 in this region (Zumbo *et al.*, 1995; Manighetti *et al.*, 1998; Kidane *et al.*, 2003; Lahitte *et al.*,  
55  
56  
57 397 2003; Audin *et al.*, 2004; Daoud *et al.*, 2010; Ferguson *et al.*, 2013b; Stab *et al.*, 2015).

1  
2  
3  
4  
5  
6 398 Following Stab *et al.* (2015), our samples are subdivided into stratoid basalts, Gulf basalts,  
7  
8  
9 399 and Afar axial range basalts in ascending stratigraphic order (Supplementary Data Fig. S6).

10  
11  
12 400 Our K-Ar ages for the Afar stratoid basalts range from 4.50 to 1.18 Ma ( $n = 17$ ).

13  
14  
15 401 Combined with previous geochronological studies (Supplementary Data Fig. S7), the  
16  
17  
18 402 majority of ages for the stratoid series fall within the range 4.0–1.1 Ma, as suggested by Stab  
19  
20  
21 403 *et al.* (2015). Among the stratoid series, the rocks in the west and southwest of the TGD tend  
22  
23  
24 404 to have older ages (4.5–2.7 Ma) than those in the east and northeast of the TGD (2.3–1 Ma).

25  
26  
27 405 The ages of the stratoid series also show different spatial variations within these two regions.

28  
29  
30 406 In the north of the TGD, ages become older from the axial range towards the northeast or  
31  
32  
33 407 southwest, consistent with NNE-SSW directed rifting (Hayward & Ebinger, 1996). In the  
34  
35  
36 408 south of the TGD, ages become older towards the northwest of the rift axis, consistent with  
37  
38  
39 409 NW-SE directed extension.

40  
41  
42 410 The K-Ar age of 0.79 Ma obtained for a basalt (DHA-17) from the Tendaho Graben  
43  
44  
45 411 corresponds to that of Gulf basalts (1.1–0.6 Ma) of Lahitte *et al.* (2003), Kidane *et al.* (2003)  
46  
47  
48 412 and Daoud *et al.* (2010), whereas the age of 0.12 Ma for basalt DHA-1 is consistent with the  
49  
50  
51 413 existing K-Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$  dates for the axial range basalts ( $< 0.6$  Ma; Manighetti *et al.*,  
52  
53  
54 414 1998; Kidane *et al.*, 2003; Lahitte *et al.*, 2003; Audin *et al.*, 2004; Ferguson *et al.*, 2013b).

55  
56  
57 415 The Afar mafic rocks are mostly aphyric and vesicular (up to 30 vol. % vesicles). A  
58  
59  
60



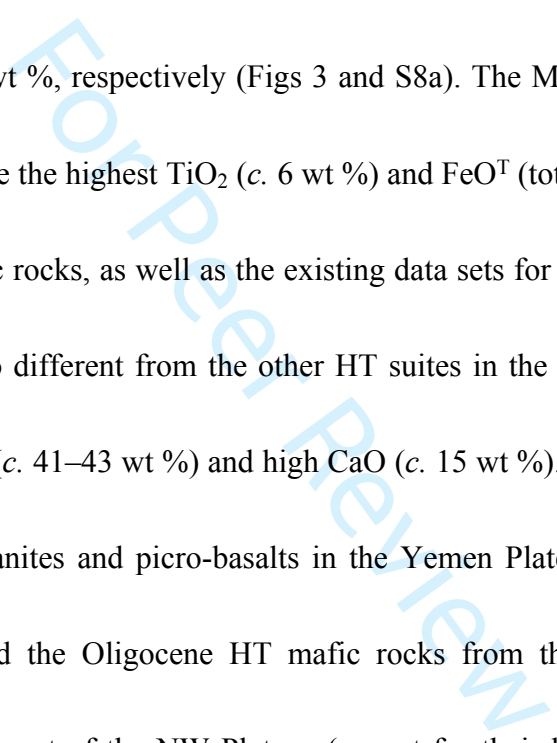
1  
2  
3  
4  
5  
6 416 few samples are porphyritic, consisting of phenocrysts of plagioclase (28 vol. %), olivine (up  
7  
8  
9 417 to 11 vol. %) and clinopyroxene (5 vol. %, except one sample with 31 vol. %; Supplementary  
10  
11  
12 418 Data Table S1). Some olivines are altered to iddingsite. Rocks without olivine phenocrysts  
13  
14  
15 419 tend to have relatively fine-grained groundmasses composed of olivine, clinopyroxene,  
16  
17  
18 420 plagioclase, and Fe-Ti oxides. Zeolites, silica, and carbonate are also found in some vesicles  
19  
20  
21 421 and interstitial parts of the groundmass in some rocks.  
22  
23  
24  
25 422

### 26 27 423 **Major element compositions**

28  
29  
30 424 The Ethiopian volcanic rocks studied here are classified as basanite, picro-basalt, basalt,  
31  
32  
33 425 basaltic andesite, trachybasalt or basaltic trachyandesite (Fig. 2; Le Bas *et al.*, 1986), and as  
34  
35  
36 426 belonging to either the alkaline or the sub-alkaline rock series (Irvine & Baragar, 1971). The  
37  
38  
39 427 Oligocene mafic rocks in Maychew include basanites (classified into HT2) from the lowest  
40  
41  
42 428 sequence (Figs 2a and S3). These basanites show a strong deficiency of SiO<sub>2</sub>, quite different  
43  
44  
45 429 from the other HT2 mafic rocks from the NW Plateau which have a sub-alkaline affinity  
46  
47  
48 430 (Figs 2a and S3; Pik *et al.*, 1998, 1999; Kieffer *et al.*, 2004; Beccaluva *et al.*, 2009; Natali *et*  
49  
50  
51 431 *al.*, 2011, 2016). To our knowledge, the silica-deficient HT suite is found only in Oligocene  
52  
53  
54 432 mafic rocks in the Yemen Plateau (Baker *et al.*, 1996a; Beccaluva *et al.*, 2009; Natali *et al.*,  
55  
56  
57 433 2016) and from a Miocene shield volcano, Gerba Guracha (25–24 Ma), in the western  
58  
59  
60

1  
2  
3  
4  
5  
6 434 Ethiopian Plateau (Rooney *et al.*, 2014a, 2017a). Compositions of the Maychew HT1 group  
7  
8  
9 435 largely overlap with the other HT1 rocks in the NW Ethiopian and Yemen Plateaus, and are  
10  
11  
12 436 more alkaline than the LT samples. Mafic volcanic rocks from Wollega in the SW Plateau  
13  
14  
15 437 (15–7 Ma; Ayalew *et al.*, 1999; Conticelli *et al.*, 1999) have higher Na<sub>2</sub>O + K<sub>2</sub>O abundances  
16  
17  
18 438 than the LT-type mafic rocks from the NW Plateau. Mafic rocks from the SMER (Miocene  
19  
20  
21 439 Getra-Kele and Quaternary Tosa-Sucha) are classified into alkaline series (Fig. 2b),  
22  
23  
24 440 consistent with data obtained in previous studies (Yemane *et al.*, 1999; George & Rogers,  
25  
26  
27 441 2002; Rooney, 2010; Shinjo *et al.*, 2011). These rocks have similar alkali enrichment to the  
28  
29  
30 442 Eocene Gamo basalts (Yemane *et al.*, 1999; George & Rogers, 2002). Mafic rocks from the  
31  
32  
33 443 NMER and Afar *province* include both alkaline and sub-alkaline series, irrespective of  
34  
35  
36 444 eruption ages (Figs 2d, e); sub-alkaline rocks are dominant in the Afar region. These features  
37  
38  
39 445 are consistent with those reported in previous studies (Deniel *et al.*, 1994; Wolde, 1996;  
40  
41  
42 446 Barrat *et al.*, 1998; Boccaletti *et al.*, 1999; Furman *et al.*, 2006a; Daoud *et al.*, 2010; Rooney  
43  
44  
45 447 *et al.*, 2012b; Pinzuti *et al.*, 2013; Giordana *et al.*, 2014; Ayalew *et al.*, 2016, 2018; Alene *et*  
46  
47  
48 448 *al.*, 2017). Quaternary mafic volcanic rocks in the CMER also show transitional compositions  
49  
50  
51 449 between the alkaline and sub-alkaline series (Fig. 2c; Boccaletti *et al.*, 1999; Rooney *et al.*,  
52  
53  
54 450 2007, 2011, 2014b; Rooney, 2010; Giordana *et al.*, 2014; Ayalew *et al.*, 2016; Tadesse *et al.*,  
55  
56  
57 451 2019). CMER mafic rocks from three Quaternary magmatic zones, the WFB, SDFZ, and  
58  
59  
60

1  
2  
3  
4  
5  
6 452 Akaki segments, have composition overlapping with each other (Gasparon *et al.*, 1993;  
7  
8  
9 453 Wolde, 1996; Rooney, 2010; Rooney *et al.*, 2005, 2007, 2014b; Ayalew *et al.*, 2016). The  
10  
11  
12 454 composition of Miocene Addis Ababa basalts from the Bishoftu embayment largely overlap  
13  
14  
15 455 with mafic rocks from the SDFZ and Akaki (Wolde, 1996; Furman *et al.*, 2006a).

16  
17  
18 456 In this study, we define mafic rocks as those with SiO<sub>2</sub> and MgO concentrations of  
19  
20  
21 457 42–54 wt % and 20–2 wt %, respectively (Figs 3 and S8a). The Maychew HT2 basanites in  
22  
23  
24 458 the lowest sequence have the highest TiO<sub>2</sub> (*c.* 6 wt %) and FeO<sup>T</sup> (total Fe as FeO; *c.* 19 wt %)   
25  
26  
27 459 among the studied mafic rocks, as well as the existing data sets for Ethiopian volcanic rocks.  
28  
29  
30 460 These basanites are also different from the other HT suites in the NW Ethiopian Plateau in  
31  
32  
33 461 terms of their low SiO<sub>2</sub> (*c.* 41–43 wt %) and high CaO (*c.* 15 wt %). Such features are similar  
34  
35  
36 462 to those of the HT basanites and picro-basalts in the Yemen Plateau (Baker *et al.*, 1996b;  
37  
38  
39 463 Natali *et al.*, 2016) and the Oligocene HT mafic rocks from the Gerba Guracha shield  
40  
41  
42 464 volcano in the southern part of the NW Plateau (except for their high P<sub>2</sub>O<sub>5</sub>; Rooney *et al.*,  
43  
44  
45 465 2014a, 2017a). Major element abundances of Maychew HT1 samples are similar to those of  
46  
47  
48 466 other HT1 mafic rocks from the NW Plateau (Pik *et al.*, 1998; Beccaluva *et al.*, 2009; Natali  
49  
50  
51 467 *et al.*, 2016) and the Yemen Plateau (Baker *et al.*, 1996b; Natali *et al.*, 2016). Miocene  
52  
53  
54 468 Wollega basalts from the SW Ethiopian Plateau have major element compositions that largely  
55  
56  
57 469 overlap with those of LT mafic rocks in the NW Plateau, except for their higher Na<sub>2</sub>O, K<sub>2</sub>O  
58  
59  
60

1  
2  
3  
4  
5  
6 470 and P<sub>2</sub>O<sub>5</sub> abundances.  
7  
8

9 471 Abundances of major elements in Miocene Getra-Kele and Quaternary Tosa-Sucha  
10  
11 mafic rocks largely overlap with each other, except for FeO<sup>T</sup> and MnO (Figs 3 and S8b).  
12 472  
13  
14 473 These oxides are more abundant in Miocene Getra-Kele mafic rocks than in Quaternary  
15  
16  
17  
18 474 Tosa-Sucha mafic rocks. Rooney (2010) also found a similar relationship for Miocene  
19  
20  
21 475 (Chencha, Fe-rich) and Quaternary (Arba Minch, Fe-poor) mafic rocks from the vicinity of  
22  
23  
24 476 the Amaro-Yabello area in the SMER. Eocene Gamo basalts show significant overlaps with  
25  
26  
27 477 Miocene Getra-Kele samples, except for TiO<sub>2</sub>, whereas Eocene Amaro basalts show the  
28  
29  
30 478 highest abundances of SiO<sub>2</sub> and the lowest abundances of TiO<sub>2</sub> and Na<sub>2</sub>O at a given MgO  
31  
32  
33 479 among the Eocene–recent mafic rocks in this region (Yemane *et al.*, 1999; George & Rogers,  
34  
35  
36 480 2002; Rooney, 2010; Shinjo *et al.*, 2011).  
37  
38

39 481 Major element abundances of Quaternary mafic rocks from the CMER (Rooney *et al.*,  
40  
41  
42 482 2007; 2014b) are similar to those of the SMER (Supplementary Data Fig. S8c). Abundances  
43  
44  
45 483 of Na<sub>2</sub>O for CMER rocks are slightly lower than those for Tosa-Sucha mafic rocks, and thus  
46  
47  
48 484 CMER rocks are classified as transitional rock series (Fig. 2). Rocks from the WFB and  
49  
50  
51 485 SDFZ show significant differences in abundances of CaO, Na<sub>2</sub>O and K<sub>2</sub>O at a given MgO,  
52  
53  
54 486 and Akaki mafic rocks exhibit intermediate compositions between those of the WFB and  
55  
56  
57 487 SDFZ. Compositions of Miocene Addis Ababa basalts largely overlap with these Quaternary  
58  
59  
60

1  
2  
3  
4  
5  
6 488 mafic rocks (Furman *et al.*, 2006a).  
7  
8

9 489 Mafic rocks in the NMER have major element compositions similar to those in the  
10  
11  
12 490 CMER (Figs 3 and S8d). Our data are consistent with the existing data sets for mafic rocks in  
13  
14  
15 491 adjacent regions (e.g., Boccaletti *et al.*, 1999; Furman *et al.*, 2006a; Giordana *et al.*, 2014).  
16  
17  
18 492 The older mafic rocks (*Oligocene* Alage and *Miocene* Tarmaber-Megezez series) have higher  
19  
20  
21 493  $\text{TiO}_2$  and  $\text{K}_2\text{O}$  at a given  $\text{MgO}$  than the younger mafic rocks (*Miocene-Quaternary*). Our data  
22  
23  
24 494 for the *Quaternary* Fantale magmatic segment falls within the ranges of the existing data sets  
25  
26  
27 495 for this segment and the other *Quaternary* magmatic segments in the NMER (Dofan, Kone,  
28  
29  
30 496 and Boset; Furman *et al.*, 2006a; Giordana *et al.*, 2014; Ayalew *et al.*, 2016).  
31  
32

33 497 Major element compositions of the stratoid, Gulf, and axial range series in the Afar  
34  
35  
36 498 region largely overlap with each other (Figs 3 and S8e). Our data are essentially consistent  
37  
38  
39 499 with the existing data for mafic rocks collected from the entire Afar province, including  
40  
41  
42 500 Djibouti (Deniel *et al.*, 1994; Barrat *et al.*, 1998, 2003; Daoud *et al.*, 2010; Pinzuti *et al.*,  
43  
44  
45 501 2013; Ayalew *et al.*, 2016; Alene *et al.*, 2017). The literature data for the Gulf basalt is that  
46  
47  
48 502 for mafic rocks in the vicinity of the Gulf of Tadjoura in Djibouti (Deniel *et al.*, 1994; Daoud  
49  
50  
51 503 *et al.*, 2010), which have a more mafic composition ( $\text{MgO} > 9 \text{ wt } \%$ ) than our samples from  
52  
53  
54 504 the Tendaho Graben ( $\text{MgO}$  of *c.* 7 wt %).  
55  
56  
57  
58  
59  
60

1  
2  
3  
4  
5  
6 505 **Trace element compositions**  
7

8  
9 506 Nickel and Cr concentrations in the studied volcanic rocks show wide variations ([Cr] to *c.*  
10  
11  
12 507 1700 ppm and [Ni] to *c.* 940 ppm), and a monotonous decrease with decreasing MgO (Figs 4  
13  
14  
15 508 and S9a). Variations of these elements in the Maychew HT1 and HT2 groups largely overlap  
16  
17  
18 509 with each other, as do HT1 and HT2 in the other regions on the NW Ethiopian Plateau (Pik *et*  
19  
20  
21 510 *al.*, 1998, 1999; Kieffer *et al.*, 2004; Beccaluva *et al.*, 2009; Natali *et al.*, 2016). Abundances  
22  
23  
24 511 of Sr, Zr, Nb and Ba in Maychew HT2 basanites are significantly higher than those of the  
25  
26  
27 512 other HT2 rocks in the NW Ethiopian Plateau. The high-Ti mafic rocks from the Gerba  
28  
29  
30 513 Guracha shield volcano also show similar enrichment patterns for these elements (Rooney *et*  
31  
32  
33 514 *al.*, 2014a, 2017a; see Supplementary Data Fig. S10). Abundances of moderately  
34  
35  
36 515 incompatible elements (e.g., Y and Yb) are similar between Maychew HT1 and HT2, as well  
37  
38  
39 516 as the other LT, HT1, and HT2 groups. The Wollega basalts from the SW Plateau (Ayalew *et*  
40  
41  
42 517 *al.*, 1999) display trace element compositions overlapping with HT1 and HT2 rocks.  
43  
44

45 518 The SMER mafic rocks show similar trace element compositions within different  
46  
47  
48 519 sequential units (Figs 4 and S9b), except for the sub-alkaline Amaro basalts (Yemane *et al.*,  
49  
50  
51 520 1999; George & Rogers, 2002). Our data for the Getra-Kele and Tosa-Sucha mafic rocks  
52  
53  
54 521 show variations consistent with the existing data for these rocks (Yemane *et al.*, 1999;  
55  
56  
57 522 George & Rogers, 2002; Rooney, 2010; Shinjo *et al.*, 2011). The NMER mafic rocks of this  
58  
59  
60

1  
2  
3  
4  
5  
6 523 study show smaller variations in trace element compositions, due to the lack of data for  
7  
8  
9 524 highly magnesian rocks. Our data for Quaternary rocks from the Fantale segment fall within  
10  
11  
12 525 the range of data sets for this and the other magmatic segments in the literature (Dofan, Kone,  
13  
14  
15 526 Boset; Boccaletti *et al.*, 1999; Furman *et al.*, 2006a; Giordana *et al.*, 2014; Ayalew *et al.*,  
16  
17  
18 527 2016). Afar mafic rocks also show trace element variations similar to those of NMER mafic  
19  
20  
21 528 rocks. Our data for three groups of Afar rocks, stratoid series, Gulf basalt, and axial range  
22  
23  
24 529 series, show greater overlap with each other, and fall within the range of literature data sets  
25  
26  
27 530 (Deniel *et al.*, 1994; Barrat *et al.*, 1998, 2003; Daoud *et al.*, 2010; Ayalew *et al.*, 2016; Alene  
28  
29  
30 531 *et al.*, 2017).

33 532 Mafic rocks with MgO > 6 wt % from different regions in Ethiopian volcanic fields  
34  
35  
36 533 show variable extents of incompatible trace element enrichment (Figs 5 and S10–S12). The  
37  
38  
39 534 Maychew HT2 plateau samples show higher Nb and Ta abundances relative to U and K (Fig.  
40  
41  
42 535 5a). The  $(La/Yb)_N$  ratios of Maychew HT2 samples are 7.7–24 (subscript N denotes  
43  
44  
45 536 chondrite-normalized abundance), comparable to the other HT2 rocks from the Ethiopian and  
46  
47  
48 537 Yemen Plateaus (8.7–24), and higher than those of the HT1 samples in this region (4.7–10)  
49  
50  
51 538 and the other HT1 (6.1–14) and LT (1.0–3.9) basalts from the NW Ethiopian Plateau  
52  
53  
54 539 (Supplementary Data Fig. S11a; data sources are the same as in Fig. 5). Strong enrichments  
55  
56  
57 540 of Nb, Ta, and LREE in Maychew HT2 samples are similar to high-Ti mafic rocks from the  
58  
59  
60

1  
2  
3  
4  
5  
6  
7 541 Gerba Guracha shield volcano [(La/Yb)<sub>N</sub> = 18–32; Rooney *et al.*, 2017a; Supplementary Data  
8  
9 542 Fig. S12a]. These two rock types show similar depletion of K (Fig. S10). The Wollega basalts  
10  
11  
12 543 from the SW Plateau (Ayalew *et al.*, 1999) display LREE abundance similar to HT1 rocks,  
13  
14  
15 544 but HREE abundance similar to LT samples from the NW Ethiopian Plateau [(La/Yb)<sub>N</sub> =  
16  
17  
18 545 6.0–10].  
19  
20

21 546 Among the mafic rocks from the SMER, the subalkaline Amaro basalts have the  
22  
23  
24 547 lowest abundances of incompatible elements and low LREE/HREE ratios [Figs 5b and S11b;  
25  
26  
27 548 (La/Yb)<sub>N</sub> = 1.9–6.0 (George & Rogers, 2002)]. Irrespective of eruption age, the other SMER  
28  
29  
30 549 mafic rocks (Eocene Gamo, Miocene Getra-Kele, and Quaternary Tosa-Sucha) show similar  
31  
32  
33 550 trace element patterns (George & Rogers, 2002; Shinjo *et al.*, 2011). The (La/Yb)<sub>N</sub> ratios of  
34  
35  
36 551 the Gamo, Getra-Kele, and Tosa-Sucha rocks are 7.2–7.6, 7.3–21, and 9.0–17, showing strong  
37  
38  
39 552 overlap with each other [Figs 5b and S11b; George & Rogers (2002); Shinjo *et al.* (2011);  
40  
41  
42 553 this study].  
43  
44

45 554 The NMER rocks show similar incompatible trace element and REE abundance  
46  
47  
48 555 patterns, irrespective of eruption age (Figs 5c and S11c). The older rocks (Alage and  
49  
50  
51 556 Tarmaber-Megezez series) have higher abundances of these elements, due to their  
52  
53  
54 557 differentiated nature (rocks with MgO 4–6 wt % are included in these plots). The younger  
55  
56  
57 558 mafic rocks analyzed in this study (Nazret series and Fantale segment) show trace element  
58  
59  
60



1  
2  
3  
4  
5  
6 559 abundance patterns consistent with previous studies (Wolde, 1996; Boccaletti *et al.*, 1999;  
7  
8  
9 560 Furman *et al.*, 2006a; Rooney *et al.*, 2012b; Ayalew *et al.*, 2018). The  $(La/Yb)_N$  ratios of  
10  
11  
12 561 NMER mafic rocks are 4.1-14. The existing data for mafic rocks from the CMER and the  
13  
14  
15 562 Addis Ababa region (Bishoftu embayment) show variations in  $(La/Yb)_N$  ratios of 5.1-14 (Fig.  
16  
17  
18 563 S12b; Gasparon *et al.*, 1993; Wolde, 1996; Furman *et al.*, 2006a; Rooney, 2010; Rooney *et*  
19  
20  
21 564 *al.*, 2005, 2007, 2014b; Giordana *et al.*, 2014; Ayalew *et al.*, 2016; Tadesse *et al.*, 2019),  
22  
23  
24 565 similar to the variations observed in NMER mafic rocks.  
25  
26

27 566 Trace element abundance patterns for Afar mafic rocks are similar to those of NMER  
28  
29  
30 567 mafic rocks (Fig. 5d). The  $(La/Yb)_N$  ratios of these rocks range from 3.4 to 6.8, consistent  
31  
32  
33 568 with the existing data sets (2.6–7.1; Deniel *et al.*, 1994; Barrat *et al.*, 2003). An exception are  
34  
35  
36 569 samples from axial-range series in Manda Hararo (Barrat *et al.*, 2003) and from Gulf basalts  
37  
38  
39 570 in the vicinity of the Gulf of Tadjoura in Djibouti (Deniel *et al.*, 1994; Daoud *et al.*, 2010, see  
40  
41  
42 571 localities in Supplementary Data Figs S6 and S7 and REE patterns in Fig. S11d). These mafic  
43  
44  
45 572 rocks have lower  $(La/Yb)_N$  ratios of 0.69-1.3, similar to those reported for submarine ridge-  
46  
47  
48 573 axis basalts in the Gulf of Tadjoura (Barrat *et al.*, 1990, 1993). Overall, our data confirm the  
49  
50  
51 574 northward decreasing trend of  $(La/Yb)_N$  ratios in mafic rocks from the MER and Afar axial  
52  
53  
54 575 regions, as pointed out by Furman *et al.* (2006a), Rooney *et al.* (2011), and Ayalew *et al.*  
55  
56  
57 576 (2016).  
58  
59  
60

1  
2  
3  
4  
5  
6 **577 Sr-Nd-Pb isotope compositions**  
7

8  
9 578 Maychew HT1 and HT2 samples have isotopic compositions largely overlapping with each  
10  
11  
12 579 other, and mostly fall within the range of the existing data for Oligocene HT mafic rocks in  
13  
14  
15 580 the NW Ethiopian and Yemen Plateaus (Figs 6a and S13; Baker *et al.*, 1996b; Pik *et al.*,  
16  
17  
18 581 1998, 1999; Kieffer *et al.*, 2004; Natali *et al.*, 2011, 2016). The Maychew HT2 basanites have  
19  
20  
21 582 the most radiogenic Pb isotopic compositions [ $(^{206}\text{Pb}/^{204}\text{Pb})_i = 19.20\text{-}19.26$ ] among the HT2  
22  
23  
24 583 rocks in the NW Ethiopian Plateau. Strongly alkaline rocks (basanites, foidites and tephrites)  
25  
26  
27 584 in the Gerba Guracha volcano in the NW Ethiopian Plateau have more radiogenic Pb isotopic  
28  
29  
30 585 compositions than the Maychew HT2 samples [ $(^{206}\text{Pb}/^{204}\text{Pb})_i$  of *c.* 20; Rooney *et al.* (2017)].  
31  
32  
33 586 The Wollega basalts from the SW Plateau (Ayalew *et al.*, 1999) have lower  $(^{87}\text{Sr}/^{86}\text{Sr})_i$  ratios  
34  
35  
36 587 and more radiogenic Pb isotope compositions than the Oligocene Plateau mafic rocks, and  
37  
38  
39 588 their isotopic features are similar to those of SMER mafic rocks (Getra-Kele and Tosa-  
40  
41  
42 589 Sucha).

43  
44  
45 590 The Sr-Nd-Pb isotopic compositions of the Getra-Kele and Tosa-Sucha mafic rocks  
46  
47  
48 591 from the SMER largely overlap with each other (this study; George & Rogers, 2002; Rooney,  
49  
50  
51 592 2010; Shinjo *et al.*, 2011), and significantly differ from those of the Eocene Amaro and Gamo  
52  
53  
54 593 basalts (George & Rogers, 2002). The Getra-Kele and Tosa-Sucha mafic rocks are  
55  
56  
57 594 characterized by radiogenic Pb isotopic compositions [ $(^{206}\text{Pb}/^{204}\text{Pb})_i > 19$ ] and lower  
58  
59  
60

1  
2  
3  
4  
5  
6 595 ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>i</sub> ratios (=0.703–0.704). Such features are akin to those of Miocene-Quaternary  
7  
8  
9 596 mafic rocks from the Turkana Depression, south of the SMER (Fig. 6b; Furman *et al.*, 2004,  
10  
11  
12 597 2006b). Among the NMER mafic lavas, the Oligocene Alage basalts and Miocene Tarmaber-  
13  
14  
15 598 Megezez mafic rocks have lower ( $^{143}\text{Nd}/^{144}\text{Nd}$ )<sub>i</sub> and higher ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>i</sub> ratios than those of the  
16  
17  
18 599 younger (Miocene to Quaternary) mafic rocks. In particular, two Alage (DBZ-22 and DBZ-  
19  
20  
21 600 30) and one Tarmaber-Megezez (DH-429) rock show highly radiogenic ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>i</sub> ratios of  
22  
23  
24 601 0.7051–0.7068 (Feyissa *et al.*, 2017). They are also characterized by higher SiO<sub>2</sub> abundances  
25  
26  
27 602 (> 50 wt %), lower ( $^{206}\text{Pb}/^{204}\text{Pb}$ )<sub>i</sub> ratios, and higher ( $^{207}\text{Pb}/^{204}\text{Pb}$ )<sub>i</sub> and ( $^{208}\text{Pb}/^{204}\text{Pb}$ )<sub>i</sub> ratios at a  
28  
29  
30 603 given ( $^{206}\text{Pb}/^{204}\text{Pb}$ )<sub>i</sub> (Figs 6c and S13). The Sr-Nd-Pb isotopic compositions of the Miocene–  
31  
32  
33 604 Quaternary CMER mafic rocks (Fig. S14) largely overlap with those of the Miocene–  
34  
35  
36 605 Quaternary NMER mafic rocks (Gasparon *et al.*, 1993; Furman *et al.*, 2006a; Rooney *et al.*,  
37  
38  
39 606 2012b; Giordana *et al.*, 2014; Ayalew *et al.*, 2016).

40  
41  
42 607 The Sr, Nd and Pb isotopic compositions of Afar mafic rocks partly overlap with  
43  
44  
45 608 those of NMER mafic rocks (except for Oligocene–Miocene rocks) and extend to more  
46  
47  
48 609 radiogenic Nd and less radiogenic Sr compositions (Figs 6d and S13). Overall, the Afar mafic  
49  
50  
51 610 rocks have lower  $^{207}\text{Pb}/^{204}\text{Pb}$  ratios at a given  $^{206}\text{Pb}/^{204}\text{Pb}$  than the NMER mafic rocks, and  
52  
53  
54 611 are thus similar to basalts from the Red Sea (Dupré *et al.*, 1988; Volker *et al.*, 1993, 1997).  
55  
56  
57 612 The axial range series in Djibouti and Etra ‘Ale (Deniel *et al.*, 1994; Barrat *et al.*, 1998) have  
58  
59  
60

1  
2  
3  
4  
5  
6 613 more radiogenic Pb isotope compositions [ $(^{206}\text{Pb}/^{204}\text{Pb})_i > 19$ ] than this series of mafic rocks  
7  
8  
9 614 in the western part of the central Afar region (this study). In contrast, Sr and Nd isotopic  
10  
11  
12 615 compositions do not show such lateral variations within the axial range series. The Sr-Nd-Pb  
13  
14  
15 616 isotopic compositions of the stratoid series and Gulf basalts largely overlap (this study;  
16  
17  
18 617 Deniel *et al.*, 1994; Barrat *et al.*, 1998; Daoud *et al.*, 2010; Alene *et al.*, 2017).  
19  
20

21 618

### 24 619 **Spatial and temporal variations in elemental and isotopic compositions**

26  
27 620 Previous studies have revealed spatial variations in the geochemical characteristics of mafic  
28  
29  
30 621 rocks in the Ethiopian volcanic province (e.g., Furman *et al.*, 2006a; Rooney, 2010; Rooney  
31  
32  
33 622 *et al.*, 2012b; Ayalew *et al.*, 2016). Here, we integrate our data sets with the existing data to  
34  
35  
36 623 provide an up-to-date the view of spatio-temporal variations in the volcanism of this region.  
37  
38

39 624 Latitudinal variations in  $(\text{K}/\text{Nb})_N$ ,  $(\text{La}/\text{Sm})_N$ ,  $(\text{Sm}/\text{Yb})_N$ ,  $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ,  $(^{143}\text{Nd}/^{144}\text{Nd})_i$  and  
40  
41  
42 625  $(^{206}\text{Pb}/^{204}\text{Pb})_i$  for the mafic volcanic rocks ( $\text{MgO} > 6$  wt %) from rift zones (MER and Afar)  
43  
44  
45 626 are shown in Fig. 7 (subscript N denotes primitive mantle normalized abundance). The  
46  
47  
48 627  $(\text{La}/\text{Sm})_N$  ratio broadly decreases from the SMER through CMER and NMER to the Afar  
49  
50  
51 628 province, whereas  $(\text{Sm}/\text{Yb})_N$  does not show any systematic change. A small positive peak in  
52  
53  
54 629  $(\text{La}/\text{Sm})_N$  is found at 9 °N, coincident with high  $(\text{K}/\text{Nb})_N$  and  $(^{87}\text{Sr}/^{86}\text{Sr})_i$  as well as a high  
55  
56  
57 630  $^3\text{He}/^4\text{He}$  peak on a northward increasing trend reported by Pik *et al.* (2006) and Rooney *et al.*  
58  
59  
60

1  
2  
3  
4  
5  
6  
7 631 (2012b). Our compilation also reveals that  $(^{143}\text{Nd}/^{144}\text{Nd})_i$  and  $(^{206}\text{Pb}/^{204}\text{Pb})_i$  show a concave  
8  
9 632 pattern with peaks or troughs at 9 °N. We note that the LAB boundary beneath the rift has a  
10  
11  
12 633 steep dip there (Kendall *et al.*, 2005; Keir *et al.*, 2015). In Afar,  $(\text{La}/\text{Sm})_N$  and  $(\text{Sm}/\text{Yb})_N$  are  
13  
14  
15 634 highly variable due to the occurrence of LREE- and MREE-depleted basalts (Barrat *et al.*,  
16  
17  
18 635 1993, 2003; Daoud *et al.*, 2010).

21 636 The NW Plateau mafic rocks show large variations in  $(\text{K}/\text{Nb})_N$  of 0.04-3.9 and  
22  
23  
24 637  $(\text{Sm}/\text{Yb})_N$  of 1.4-7.1. These variations are significantly larger than those found in MER and  
25  
26  
27 638 Afar mafic rocks [ $(\text{K}/\text{Nb})_N = 0.20-3.1$  and  $(\text{Sm}/\text{Yb})_N = 0.82-4.5$ ] (Supplementary Data Fig.  
28  
29  
30 639 S15). Among the Oligocene mafic rocks in the NW Ethiopian Plateau, the HT2 type has the  
31  
32  
33 640 highest  $(\text{La}/\text{Sm})_N$  and  $(\text{Sm}/\text{Yb})_N$ , whereas the LT type has the lowest values of these ratios  
34  
35  
36 641 (Pik *et al.*, 1998, 1999; Kieffer *et al.*, 2004; Beccaluva *et al.*, 2009). Given the spatial  
37  
38  
39 642 distributions of LT, HT1 and HT2 (Pik *et al.*, 1998; see Fig. 1),  $(\text{K}/\text{Nb})_N$  increases and  
40  
41  
42 643  $(\text{La}/\text{Sm})_N$  and  $(\text{Sm}/\text{Yb})_N$  decrease from south to north. The  $(^{87}\text{Sr}/^{86}\text{Sr})_i$  and  $(^{206}\text{Pb}/^{204}\text{Pb})_i$ ;  
43  
44  
45 644 isotopic compositions also show a decrease from south to north, whereas  $(^{143}\text{Nd}/^{144}\text{Nd})_i$  does  
46  
47  
48 645 not show a clear latitudinal variation. The Wollega basalts from the SW Plateau have  
49  
50  
51 646  $(\text{K}/\text{Nb})_N$ ,  $(\text{La}/\text{Sm})_N$  and  $(^{206}\text{Pb}/^{204}\text{Pb})_i$  comparable to those of HT2 mafic rocks in the NW  
52  
53  
54 647 Plateau, whereas their  $(\text{Sm}/\text{Yb})_N$ ,  $(^{87}\text{Sr}/^{86}\text{Sr})_i$  and  $(^{143}\text{Nd}/^{144}\text{Nd})_i$  are comparable to those of  
55  
56  
57 648 LT mafic rocks (Ayalew *et al.*, 1999). Overall, the latitudinal variations in  $(\text{La}/\text{Sm})_N$  and  
58  
59  
60

1  
2  
3  
4  
5  
6 649 (Sm/Yb)<sub>N</sub> of mafic rocks from the Plateau (Oligocene–Miocene) and rift (Oligocene to  
7  
8  
9 650 Recent) are concordant with each other (Pik *et al.*, 2006; Rooney *et al.*, 2012b; Ayalew *et al.*,  
10  
11  
12 651 2016).

13  
14  
15 652

## 16 17 18 653 **DISCUSSION**

### 19 20 21 654 **Origin of geochemical variation**

#### 22 23 24 655 *Fractional crystallization*

25  
26  
27 656 The majority of the mafic rocks for which data are presented in this study are differentiated  
28  
29  
30 657 (Figs 3, 4, S8 and S9), with low concentrations of MgO (<8 wt %), low Ni (<200 ppm), and  
31  
32  
33 658 low Cr (<400 ppm). Concentrations of MgO, CaO, Ni, and Cr show positive correlations,  
34  
35  
36 659 suggesting that variations in major and trace element compositions are controlled primarily  
37  
38  
39 660 by fractional crystallization of mafic phases (olivine, clinopyroxene, and spinel). Plagioclase  
40  
41  
42 661 is considered to play a minor role in producing the elemental variation, based on petrographic  
43  
44  
45 662 and major and trace element characteristics; a lack of clear linear correlations of Al<sub>2</sub>O<sub>3</sub> and Sr  
46  
47  
48 663 with MgO (Supplementary Data Figs S8 and S9), the lack of negative Eu and Sr anomalies in  
49  
50  
51 664 trace element abundance patterns (Figs 5, S10 and S11), and the sparse occurrence of  
52  
53  
54 665 plagioclase phenocrysts (Supplementary Data Table S1). These features in our samples are  
55  
56  
57 666 consistent with existing data for other Ethiopian mafic rocks (Figs 5 and S8–12).

1  
2  
3  
4  
5  
6 667 To examine phase assemblages and extents of fractional crystallization, the major  
7  
8  
9 668 element compositions of the Ethiopian mafic volcanic rocks are expressed as normative  
10  
11  
12 669 minerals and compared with the compositions of melts produced in fractional crystallization  
13  
14  
15 670 experiments (Thompson *et al.*, 2001; Supplementary Data Fig. S16). In the normative  
16  
17  
18 671 tetrahedron, the cotectic saturation of olivine + pyroxene + plagioclase at 1 atm forms a  
19  
20  
21 672 curved line (cotectic boundary), which with increasing pressure shifts to the olivine apex of  
22  
23  
24 673 the tetrahedron (Thompson *et al.*, 2001). Most mafic rocks plot below the 1-atm cotectic  
25  
26  
27 674 boundary and form broad arrays subparallel to this line. This variation is interpreted as  
28  
29  
30 675 fractionation at various pressures with a phase assemblage of olivine during early  
31  
32  
33 676 differentiation, then clinopyroxene (cpx) + olivine, in both alkaline and subalkaline magma  
34  
35  
36 677 suites. Subsequently, orthopyroxene begins to crystallize with plagioclase in subalkaline  
37  
38  
39 678 magmas, and melt compositions become more siliceous. This expected phase assemblage has  
40  
41  
42 679 been confirmed by thermodynamic modeling of mafic-felsic magmatic evolution in the MER  
43  
44  
45 680 (e.g., Peccerillo *et al.*, 2003; Rooney *et al.*, 2012c; Feyissa *et al.*, 2017). However, we also  
46  
47  
48 681 note that trace element and isotope compositions within each volcanic region vary  
49  
50  
51 682 significantly, and thus that processes other than fractional crystallization must also be  
52  
53  
54 683 involved (Fig. 8). Below, we discuss other possible mechanisms for the production of the  
55  
56  
57 684 observed compositional variations, including crustal assimilation, variable melting  
58  
59  
60

1  
2  
3  
4  
5  
6 685 conditions, and mixing of different magma sources.  
7  
8

9 686

10  
11  
12 687 *Crustal contamination*  
13  
14

15 688 Mantle-derived basaltic magmas have temperatures higher than the solidus of crustal

16  
17  
18 689 materials of intermediate to felsic composition (<1000 °C; Grove *et al.*, 1988). Consequently,

19  
20  
21 690 the magmas may have reacted to some extent with crustal materials during their ascent to the

22  
23  
24 691 surface (Baker *et al.*, 1996b; Rogers *et al.*, 2000; Peccerillo *et al.*, 2003; Rooney *et al.*, 2005,

25  
26  
27 692 2007; Rooney *et al.*, 2012c). Since Plateau and rift-escarpment regions have thicker

28  
29  
30 693 continental lithosphere than that beneath the rift-floor (Dugda *et al.*, 2007), a greater extent of

31  
32  
33 694 crustal assimilation is anticipated in the former. Crustal materials, mainly consisting of

34  
35  
36 695 evolved igneous rocks (intermediate to felsic intrusives), are expected to have high

37  
38  
39 696 abundances of incompatible elements (Rudnick & Gao, 2003). Element ratios such as La/Nb,

40  
41  
42 697 Ba/La, and Ce/Pb and isotope ratios such as  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{206}\text{Pb}/^{204}\text{Pb}$  can be useful tracers to

43  
44  
45 698 detect crustal input to mantle-derived magmas due to the large differences in these ratios

46  
47  
48 699 between magmas and crustal lithologies (Stewart & Rogers, 1996; Meshesha & Shinjo, 2008;

49  
50  
51 700 Shinjo *et al.*, 2011; Rooney *et al.*, 2005; Rooney, 2017). The low-Mg LT suite in the NW

52  
53  
54 701 Ethiopian Plateau (MgO <6 wt %) has higher Ba/La ratios than mantle-derived oceanic

55  
56  
57 702 basalts [mid-ocean ridge basalts (MORB) or ocean island basalts (OIB) after Willbold &



1  
2  
3  
4  
5  
6 703 Stracke (2006); Fig. 8], suggesting that the geochemistry of differentiated LT rocks is  
7  
8  
9 704 affected by crustal contamination (Pik *et al.*, 1998, 1999; Kieffer *et al.*, 2004; Beccaluva *et*  
10  
11  
12 705 *al.*, 2009). In contrast, HT1 and HT2 mafic rocks from the NW Plateau and Wollega basalts  
13  
14  
15 706 from the SW Plateau have Ba/La ratios mostly falling within the range of OIB and MORB,  
16  
17  
18 707 suggesting minor roles for crustal assimilation during their magmatic evolution. Some mafic  
19  
20  
21 708 rocks from the NMER show geochemical characteristics suggestive of crustal assimilation;  
22  
23  
24 709 they are characterized by high SiO<sub>2</sub> abundance and high Ba/La and (<sup>87</sup>Sr/<sup>86</sup>Sr)<sub>i</sub> (Figs 6 and 8).  
25  
26  
27 710 Below, the effect of crustal assimilation in these NMER rocks are discussed.

28  
29  
30 711         Crustal assimilation cools the magma and leads to crystallization, whereas the latent  
31  
32  
33 712 heat of fractional crystallization promotes assimilation. Such a positive feedback is referred  
34  
35  
36 713 to as AFC (assimilation combined with fractional crystallization; DePaolo, 1981). AFC is  
37  
38  
39 714 considered to result in co-variation of element abundance (dominantly by crystallization) and  
40  
41  
42 715 isotopic compositions (by mixing of crust and magma). In plots of (<sup>87</sup>Sr/<sup>86</sup>Sr)<sub>i</sub> vs SiO<sub>2</sub> (Fig. 8),  
43  
44  
45 716 the differentiated NMER rocks (with SiO<sub>2</sub> > 50 wt % or MgO < 6 wt %) exhibit higher  
46  
47  
48 717 (<sup>87</sup>Sr/<sup>86</sup>Sr)<sub>i</sub>, suggesting the influence of crustal materials (e.g., Pan-African crust: Stewart &  
49  
50  
51 718 Rogers, 2002; Shinjo *et al.*, 2011; Rooney, 2017) in the petrogenesis of these rocks. We  
52  
53  
54 719 exclude low-MgO NMER rocks (MgO < 6 wt %) in the following discussions about melting  
55  
56  
57 720 processes and source characteristics. The other SMER and Afar volcanic rocks do not show  
58  
59  
60

1  
2  
3  
4  
5  
6 721 such correlations (Fig. 8), suggesting that the role of crustal assimilation in these mafic rocks  
7  
8  
9 722 was insignificant; a conclusion consistent with previous studies (e.g., Furman *et al.*, 2006a;  
10  
11  
12 723 Rooney *et al.*, 2005).

13  
14  
15 724

16  
17  
18 725 *Melting conditions*

19  
20  
21 726 Since the mantle is compressible, its temperature varies with pressure to conserve heat  
22  
23  
24 727 content along the adiabatic gradient. It is therefore useful to have a conceptual reference,  
25  
26  
27 728 known as “mantle potential temperature” ( $T_p$ ), which represents the temperature of solid  
28  
29  
30 729 mantle expanded to atmospheric pressure (McKenzie & Bickle, 1988). To estimate  $T_p$  for the  
31  
32  
33 730 Ethiopian magmatism, we applied the geothermobarometry approaches of Putrika (2008),  
34  
35  
36 731 Lee *et al.* (2009) and Herzberg & Asimow (2015).

37  
38  
39 732 Data for mafic rocks used for this evaluation are from this study and previous studies  
40  
41  
42 733 (Gasparon *et al.*, 1993; Deniel *et al.*, 1994; Baker *et al.*, 1996b; Wolde, 1996; Barrat *et al.*,  
43  
44  
45 734 1998, 2003; Pik *et al.*, 1998, 1999; Ayalew *et al.*, 1999, 2016, 2018; George & Rogers, 2002;  
46  
47  
48 735 Kieffer *et al.*, 2004; Rooney *et al.*, 2005, 2014b; Furman *et al.*, 2006a; Beccaluva *et al.*, 2009;  
49  
50  
51 736 Daoud *et al.*, 2010; Natali *et al.*, 2011, 2016; Shinjo *et al.*, 2011; Alene *et al.*, 2017; Tadesse  
52  
53  
54 737 *et al.*, 2019) and filtered to exclude rocks with liquidus phases other than olivine. On major  
55  
56  
57 738 element plots (Supplementary Data Fig. S8), CaO generally shows an increase to MgO of *c.* 8  
58  
59  
60

1  
2  
3  
4  
5  
6 739 wt %, then it decreases with decreasing MgO. This variation is interpreted as a result of  
7  
8  
9 740 participation of clinopyroxene in crystallization (e.g., Rooney *et al.*, 2007; Rooney, 2010;  
10  
11  
12 741 Pinzuti *et al.*, 2013). We therefore used data for mafic rocks with MgO > 8.5 wt %. Highly  
13  
14  
15 742 magnesian rocks (MgO > 15 wt %) were avoided as they likely contain accumulated phases  
16  
17  
18 743 which were not equilibrated with the melt. Details of the thermobarometric modeling are  
19  
20  
21 744 described in Supplementary Data Text S3.

22  
23  
24 745 Results of  $P$ - $T$  estimates are summarized in Supplementary Data Table S4 and Fig.  
25  
26  
27 746 S17 [including calculated primary magma composition equilibrated with mantle (Fo<sub>89</sub>) and  
28  
29  
30 747 mantle potential temperature ( $T_p$ ) using an adiabatic gradient of 18 K GPa<sup>-1</sup> (McKenzie &  
31  
32  
33 748 Bickle, 1988; Katz *et al.*, 2003), or the gradients of Herzberg & Asimow (2015)]. Melting  $T$   
34  
35  
36 749 and  $P$  estimated using the methods of Putirka (2008), Lee *et al.* (2009), and Herzberg &  
37  
38  
39 750 Asimow (2015) are generally consistent with each other,  $\pm 50$  °C and  $\pm 1$  GPa (mostly < 0.5  
40  
41  
42 751 GPa), in the ranges Supplementary Data 1300–1600 °C and 1–3 GPa, respectively.  
43  
44  
45 752 Exceptions are thermobarometric estimates for the Maychew basanites ( $n = 2$ ) from this study  
46  
47  
48 753 (Supplementary Data Fig. S17). The large discrepancy for  $P$  (hence  $T$  by error propagation  
49  
50  
51 754 from  $P$ ) for basanites (3 GPa by the Putirka (2008) algorithm and 6 GPa by the Lee *et al.*  
52  
53  
54 755 (2009) algorithm) is probably due to inaccuracy of the Lee *et al.* thermobarometry in this  
55  
56  
57 756 case, which is not applicable to SiO<sub>2</sub>-deficient magmas formed in the garnet-stability field  
58  
59  
60

1  
2  
3  
4  
5  
6 757 (Till, 2017).  
7  
8

9 758 The Maychew rocks yield  $T_p$  of 1400–1550 °C (Fig. 9a) which is significantly higher  
10  
11  
12 759 than the ambient mantle [1340 °C; Cottrell & Kelley (2011)]. In particular, the HT2 basanites  
13  
14  
15 760 from the lower Maychew section show the highest  $T_p$  range found in the HT series in  
16  
17  
18 761 previous studies (1600 °C: Rooney *et al.*, 2012a; Beccaluva *et al.*, 2009; Rogers *et al.*, 2010;  
19  
20  
21 762 Natali *et al.*, 2016). We also reaffirm the gradation of  $T_p$  in the mantle for the production of  
22  
23  
24 763 HT1 and HT2 (1400–1600 °C) to LT (1350–1400 °C) proposed by Natali *et al.* (2016), who  
25  
26  
27 764 ascribed this variation to thermal zonation in the Afar mantle plume at 30 Ma, with  
28  
29  
30 765 integration of their earlier model (Beccaluva *et al.*, 2009) and He-Sr-Nd-Pb isotope data. The  
31  
32  
33 766 calculated  $T_p$  for the mantle beneath the SW Plateau (Wollega; 11 Ma) is 1380 °C, similar to  
34  
35  
36 767 that for LT rocks from the NW Plateau, and also consistent with  $T_p$  determined through a  
37  
38  
39 768 REE inversion model (*c.* 1375 °C; Ayalew & Gibson, 2009) for Miocene SW Plateau rocks  
40  
41  
42 769 (15-Ma Shewa to the northeast of Addis Ababa; Fig. 1).  
43  
44

45 770 The Miocene to Quaternary mafic rocks from the SMER, CMER, NMER and Afar  
46  
47  
48 771 yield  $T_p$  values mostly falling within the range of 1350–1500 °C (Fig. 9b). The obtained  
49  
50  
51 772 values are consistent with those of previous studies (1260–1490 °C; Rooney *et al.*, 2012a;  
52  
53  
54 773 Ayalew & Gibson, 2009; Ferguson *et al.*, 2013a; Pinzuti *et al.*, 2013; Armitage *et al.*, 2015).  
55  
56  
57 774 Lateral variation in  $T_p$  along the MER-Afar region are less clear (Fig. 9b), but show a slight  
58  
59  
60

1  
2  
3  
4  
5  
6 775 increase from the CMER and NMER to the south (SMER) and to the north (Afar), as  
7  
8  
9 776 suggested by Rooney *et al.* (2012a).

10  
11  
12 777 The maximum  $T_p > 1500$  °C is consistent with melting of adiabatically upwelling  
13  
14  
15 778 mantle for the genesis of the Plateau mafic rocks (Beccaluva *et al.*, 2009; Rogers *et al.*, 2010;  
16  
17  
18 779 Rooney *et al.*, 2012a; Natali *et al.*, 2016). Anomalously hot mantle began to melt at a greater  
19  
20  
21 780 depth, probably in the garnet stability field ( $P > 3.3$  GPa, depth  $> 100$  km; Walter *et al.*,  
22  
23  
24 781 1995). In addition, the thick lithosphere beneath the Plateau may have acted as a lid on the  
25  
26  
27 782 upwelling mantle, resulting in preferential sampling of melts from the deeper mantle (Ellam,  
28  
29  
30 783 1992). By contrast, the shallower lithosphere beneath the MER and Afar region may have led  
31  
32  
33 784 to preferential tapping of magmas from shallower regions of the upwelling mantle. To  
34  
35  
36 785 substantiate this inference, we apply a melting model and examine the role of a garnet-  
37  
38  
39 786 bearing source during magma production. Since garnet preferentially hosts the heavy REE  
40  
41  
42 787 (Johnson, 1998), melting of the source leaving garnet in the residue leads to elevated  
43  
44  
45 788 LREE/HREE (La/Yb) and MREE/HREE (Gd/Yb or Dy/Yb; Fig. 10) in the partial melts.  
46  
47  
48 789 Clinopyroxene is also known as a possible phase to fractionate these elements (Blundy *et al.*,  
49  
50  
51 790 1998). However, it is unlikely that this phase plays a major role in REE fractionation. The  
52  
53  
54 791 “garnet-like” REE partitioning of clinopyroxene occurs only in small-degree melts at shallow  
55  
56  
57 792 depths ( $F < 5\%$  and  $P < 1.5$  GPa, where  $F$  and  $P$  denote melting degree and pressure; Blundy  
58  
59  
60

1  
2  
3  
4  
5  
6 793 *et al.*, 1998); such conditions are distinctly different from those estimated for the Ethiopian  
7  
8  
9 794 mafic rocks (Supplementary Data Fig. S17 and Table S4). We thus consider that a melting  
10  
11  
12 795 model involving garnet-bearing mantle is appropriate to examine the causes of LREE/HREE  
13  
14  
15 796 and MREE/HREE variations. Superimposed on the plot in Fig. 10 are calculated curves for  
16  
17  
18 797 partial melting of lherzolite in garnet-bearing and garnet-free assemblages (see details  
19  
20  
21 798 regarding the modeling in the caption of Fig. 10). The HT2 mafic rocks have the highest  
22  
23  
24 799 Dy/Yb ratios among the Oligocene Plateau volcanic rocks, and are inferred to contain a  
25  
26  
27 800 greater contribution of melts from mantle in the garnet stability field. Differences in LREE  
28  
29  
30 801 enrichment within the HT2 series are attributed to various extents of melting ( $F$ ); 1–2% for  
31  
32  
33 802 basanite and 3–7% for basalt and picrite. The LT series have lower La/Sm and Dy/Yb ratios  
34  
35  
36 803 and can be explained by a larger extent of melting in the spinel stability field, consistent with  
37  
38  
39 804 the lower  $T_p$  estimates for these samples (Beccaluva *et al.*, 2009; Natali *et al.*, 2016).

40  
41  
42 805         The MER and Afar mafic rocks show larger contributions of melts formed in the  
43  
44  
45 806 spinel stability field. These mafic rocks, however, may have contributions from melts from  
46  
47  
48 807 garnet-bearing sources, inferred from elevated Dy/Yb ratios relative to spinel lherzolite melts  
49  
50  
51 808 calculated by our modeling. This inference is consistent with the REE models of Ferguson *et*  
52  
53  
54 809 *al.* (2013a) and Pinzuti *et al.* (2013). Since  $T_p$  is essentially constant among the MER mafic  
55  
56  
57 810 rocks (Fig. 9b), LREE enrichment in the SMER mafic rocks (Figs. 7) is largely due to the  
58  
59  
60

1  
2  
3  
4  
5  
6 811 geochemistry of the magma sources rather than LREE/HREE fractionation during partial  
7  
8  
9 812 melting (George & Rogers, 2002). As a possible origin of this source, localized lithosphere  
10  
11  
12 813 enriched by metasomatism has been proposed (Furman & Graham, 1999; George & Rogers,  
13  
14  
15 814 2002; Rooney, 2010).

16  
17  
18 815

20  
21 816 **Evolution of Ethiopian magmatism: interplay between melting conditions and source**  
22  
23  
24 817 **composition**

25  
26  
27 818 Previous studies have identified multiple end-member components in the genesis of mafic  
28  
29  
30 819 magmas in Ethiopia and adjacent regions (e.g., Marty *et al.*, 1996; Pik *et al.*, 1999, 2006;  
31  
32  
33 820 Rogers *et al.*, 2000; George & Rogers, 2002; Furman *et al.*, 2006a; Rooney *et al.*, 2012b). Pik  
34  
35  
36 821 *et al.* (1999) first identified four end-member components for Oligocene Plateau magmatism.  
37  
38  
39 822 Subsequently, Meshesha & Shinjo (2008) identified five end-member components for  
40  
41  
42 823 Oligocene to Recent magmatism across the entire region in Ethiopia. Since then, numerous  
43  
44  
45 824 isotope data have been published (e.g., Shinjo *et al.*, 2011; Rooney *et al.*, 2012b, 2014a;  
46  
47  
48 825 Natali *et al.*, 2016; Ayalew *et al.*, 2016, 2018; Alene *et al.*, 2017). Here we examine the end-  
49  
50  
51 826 member compositions proposed by Meshesha & Shinjo (2008) using data from the present  
52  
53  
54 827 study and compiled from the recent literature.

55  
56  
57 828 We used principal component analysis (PCA) to inspect the geometries of the data on  
58  
59  
60

1  
2  
3  
4  
5  
6 829 the plot. Details about the method are outlined in Supplementary Data Text S4; PCA score  
7  
8  
9 830 plots are given in Supplementary Data Fig. S18 in which the mantle end-member components  
10  
11  
12 831 of Meshesha & Shinjo (2008) are projected. The PCA outputs demonstrate that these end-  
13  
14  
15 832 member components explain the variability of Sr-Nd-Pb isotope data sets well, including  
16  
17  
18 833 those presented in the more recent studies, and in this study. It is noted that this evaluation  
19  
20  
21 834 does not include  $^3\text{He}/^4\text{He}$  data, as was done by Meshesha & Shinjo (2008). Based on the Sr-  
22  
23  
24 835 Nd-Pb isotopic compositions of high- $^3\text{He}/^4\text{He}$  lavas (Marty *et al.*, 1996; Pik *et al.*, 2006),  
25  
26  
27 836 Meshesha & Shinjo (2008) defined an additional end-member component (their C4, and its  
28  
29  
30 837 subtype C4'), and we used this composition to examine the effect of this source.

31  
32  
33 838 Meshesha & Shinjo (2008) inferred the origin of five end-member components as:  
34  
35  
36 839 C1, recycled gabbro in the Afar plume (in the Oligocene); C2, enriched lithospheric materials  
37  
38  
39 840 beneath the SMER (or lithosphere metasomatized by C2-dominated melts); C3, EM-1-like  
40  
41  
42 841 recycled crustal material in the Afar plume; C4, crust-mantle hybrid rocks from the lower  
43  
44  
45 842 mantle [essentially identical to the "C" component of Hanan & Graham (1996) or "FOZO" of  
46  
47  
48 843 Stracke *et al.* (2005)]; C5, unpolluted upper mantle (Schilling *et al.*, 1992). Furman (2007)  
49  
50  
51 844 and Rooney *et al.* (2014a, 2017a) argued for an origin of C2 as a 'metasome' within  
52  
53  
54 845 lithosphere formed by reaction with asthenosphere-derived melts. Ayalew *et al.* (2016) also  
55  
56  
57 846 suggested a similar scenario for the C3 isotopic signature; the EM1-like isotopic signature of  
58  
59  
60



1  
2  
3  
4  
5  
6 847 this source is preserved as veins in the lithosphere, presumably formed by infiltration of  
7  
8  
9 848 asthenosphere-derived melts into the lithosphere. Based on these inferences, the fusibility,  
10  
11  
12 849 i.e., how easy it is to be melted, is roughly estimated as  $C2 = C3 > C4 > C1 > C5$ . Thus, to a  
13  
14  
15 850 first order, contributions of C1 (Oligocene) or C5 (Miocene to recent) relative to the other  
16  
17  
18 851 end-member component are interpreted to reflect the dominance of a refractory source  
19  
20  
21 852 domain in the melting process.  
22  
23

24 853       When more than three end-member components are involved in mixing, the relative  
25  
26  
27 854 mass fraction of them cannot be solved mathematically (e.g., Schilling *et al.*, 1992). Instead,  
28  
29  
30 855 we use the PCA score as a proxy for the relative contribution from a specific end-member  
31  
32  
33 856 component. For Oligocene magmas, Meshesha & Shinjo (2008) suggested that C1 is the  
34  
35  
36 857 most depleted, hence considered to be the most refractory source. From the location of C1 in  
37  
38  
39 858 isotope correlation space, its contribution can be seen as a positive score of PC1 (first  
40  
41  
42 859 principal component; Supplementary Data Fig. S18). Figure 11 shows a clear negative  
43  
44  
45 860 correlation between the PC1 score and  $(La/Sm)_N$  ratio. Such a relationship can be interpreted  
46  
47  
48 861 as reflecting different averaging of melts sampled from a heterogeneous mantle consisting of  
49  
50  
51 862 materials with different fusibilities (e.g., Stracke *et al.*, 2003). The HT2 rocks represent melts  
52  
53  
54 863 sampled preferentially from a fusible source in the deep melting region, whereas LT mafic  
55  
56  
57 864 rocks represent melts sampled preferentially from a refractory source (C1) in the shallower  
58  
59  
60

1  
2  
3  
4  
5  
6 865 melting region (Fig. 12a). This inference is consistent with Pik *et al.* (1998), Furman *et al.*  
7  
8  
9 866 (2006a), Beccaluva *et al.* (2009), and Natali *et al.* (2016). A Maychew HT2 sample from the  
10  
11  
12 867 basal section (TR1V3) is one of the deepest melts sampled during Oligocene trap magmatism  
13  
14  
15 868 (estimated to have segregated at a pressure of 3 GPa; Supplementary Data Fig. S17), and its  
16  
17  
18 869 isotopic composition is similar to C4' of Meshesha & Shinjo (2008) (see also Figs 6 and  
19  
20  
21 870 S13). Meshesha & Shinjo (2008) argued that C4' observed in the Quaternary Afar basalts  
22  
23  
24 871 would have evolved from C4 over time. Instead, our data for HT2 basanites suggests that the  
25  
26  
27 872 composition of this end-member component did not change over time. To advance the  
28  
29  
30 873 knowledge of the evolution of this magma source, further studies on Maychew basanites,  
31  
32  
33 874 including  $^3\text{He}/^4\text{He}$  analysis, are necessary.

34  
35  
36 875 In the subsequent period (<30 Ma), volcanic activity coincided with rifting, and  
37  
38  
39 876 magma production was driven by adiabatic decompression of asthenospheric mantle through  
40  
41  
42 877 plate divergence (e.g., Deniel *et al.*, 1994; Rooney *et al.*, 2007, 2013; Rooney, 2010; Ayalew  
43  
44  
45 878 & Gibson, 2009; Pinzuti *et al.*, 2013; Feyissa *et al.*, 2017; Ayalew *et al.*, 2018). Previous  
46  
47  
48 879 studies have documented temporal and spatial changes in the melting regime associated with  
49  
50  
51 880 the development of the rift system; deeper melting occurred in regions of incipient rift zones  
52  
53  
54 881 such as Oligocene–Miocene rift axes and the Quaternary SDFZ, whereas shallow melting  
55  
56  
57 882 occurred in the regions of axial and mature rift zones (e.g., Rooney, 2010; Ferguson *et al.*,  
58  
59  
60

1  
2  
3  
4  
5  
6 883 2013a; Feyissa *et al.*, 2017; Ayalew *et al.*, 2018).  
7  
8

9 884 The Miocene to Recent mafic rocks in the MER have contributions from the C2 and  
10  
11  
12 885 C3 end-member components of Meshesha & Shinjo (2008) (Figs 6, S13, and S14). The C2  
13  
14  
15 886 end-member component mainly contributed to mafic rocks from the SEMR and Turkana  
16  
17  
18 887 region (Furman *et al.*, 2004, 2006b; Shinjo *et al.*, 2011), whereas the C3 component mainly  
19  
20  
21 888 contributed to the CMER and NMER mafic rocks (Furman *et al.*, 2006a; Ayalew *et al.*,  
22  
23  
24 889 2016). The C2 end-member component is characterized by radiogenic Pb isotopic  
25  
26  
27 890 compositions, and the C3 end-member component is clearly defined by higher  $^{87}\text{Sr}/^{86}\text{Sr}$  (Fig.  
28  
29  
30 891 6). The compositions of these end-member components of Meshesha & Shinjo (2008) are  
31  
32  
33 892 located on the lower extension of PC1 and PC2 in PCA score plots (Supplementary Data Fig.  
34  
35  
36 893 S18; PC1 and PC2 denote first and second principal components). The contribution of the C2  
37  
38  
39 894 end-member component (represented as a negative PC1 score) and  $(\text{La}/\text{Sm})_{\text{N}}$  ratio show a  
40  
41  
42 895 correlation, as seen in Oligocene Plateau mafic rocks. The decreasing effect of this end-  
43  
44  
45 896 member component in mafic rocks along the MER from south to north could be related to  
46  
47  
48 897 shallow melting of more refractory source (C5). The southward increase in LAB depth is  
49  
50  
51 898 documented as along-strike depth variation of a mid-lithosphere reflector (Maguire *et al.*,  
52  
53  
54 899 2006; Keir *et al.*, 2015). We suggest that thick lithosphere may act as an obstruction to the  
55  
56  
57 900 upwelling asthenospheric flow to shallower depths (Fig. 12b), resulting in preferential  
58  
59  
60

1  
2  
3  
4  
5  
6 901 sampling of melt from fusible sources. Lateral changes in the lithospheric structure (e.g., dip  
7  
8  
9 902 of its base; Kendall *et al.*, 2005; Keir *et al.*, 2015) may also enhance melt extraction and  
10  
11  
12 903 produce melt from refractory sources, as observed in the NMER at 9 °N (Fig. 7). The  
13  
14  
15 904 presence of two different fusible sources (C2 and C3) must be an intrinsic feature in the  
16  
17  
18 905 mantle beneath the MER, and may be attributed to a difference in phase assemblages in these  
19  
20  
21 906 sources, depending on the conditions of their formation [e.g., amphibole- vs phlogopite-  
22  
23  
24 907 bearing assemblage: Furman (2007); Rooney *et al.* (2017)].  
25  
26

27 908 Temporal and spatial variations of basalt compositions in Oligocene to Recent  
28  
29  
30 909 Ethiopian magmatism require changes in the relative contributions of multiple end-member  
31  
32  
33 910 components in the mantle. Correlations between major and trace element and isotopic  
34  
35  
36 911 compositions suggest that melting integrated chemically-variable melts formed across a range  
37  
38  
39 912 of pressures. Secular and lateral changes in magma compositions are probably due to changes  
40  
41  
42 913 in the melting regime related to the influence of the Afar plume in space and time (Furman *et*  
43  
44  
45 914 *al.*, 2006a; Rooney, 2010; Rooney *et al.*, 2012b; Ayalew *et al.*, 2016). The ongoing rifting in  
46  
47  
48 915 Ethiopia may represent the transition from a plume-driven to a plate-driven setting for the  
49  
50  
51 916 upwelling of asthenospheric mantle.  
52  
53

54 917  
55  
56  
57  
58  
59  
60

1  
2  
3  
4  
5  
6 918 **CONCLUSIONS**  
7

8  
9 919 Geochronological and geochemical results from this study are combined with existing data  
10  
11  
12 920 and yield constraints on petrologic processes and magma sources for Ethiopian magmatism  
13  
14  
15 921 since 30 Ma. The conclusions of this study are as follows.

- 16  
17  
18 922
- 19 • The K-Ar ages of this study are essentially consistent with the existing K-Ar and  
20  
21 923  $^{40}\text{Ar}/^{39}\text{Ar}$  ages. The ages range from *c.* 30 Ma to Recent (*c.* 0.1 Ma), and represent  
22  
23  
24 924 volcanism transitional from an Oligocene trap phase to a Miocene to Recent rift-  
25  
26  
27 925 related phase.
  - 28  
29  
30 926 • Maychew basanites record the highest range of mantle potential temperature among  
31  
32  
33 927 Oligocene Plateau rocks ( $T_p = c.$  1600 °C), and are considered to be the melting  
34  
35  
36 928 product of the starting Afar plume head. Oligocene to Recent mafic rocks from the  
37  
38  
39 929 MER and Afar regions yield lower  $T_p$  (1500–1340 °C), suggesting a decrease in  $T_p$  by  
40  
41  
42 930 100–260 °C in the post trap-phase magmatism.
  - 43  
44  
45 931 • Our new Sr-Nd-Pb isotope data for Plateau and rift-related mafic lavas reaffirm the  
46  
47  
48 932 involvement of the end-member source components defined by Meshesha & Shinjo  
49  
50  
51 933 (2008). Temporal and spatial changes in lava geochemistry can be explained by  
52  
53  
54 934 changes in the relative contributions these end-member components.
  - 55  
56  
57 935 • Relative contributions of these end-member components are primarily attributed to  
58  
59  
60

1  
2  
3  
4  
5  
6 936 change in sampling of melts derived from a heterogeneous mantle, as related to the  
7  
8  
9 937 thermal condition of the asthenosphere (for Oligocene magmatism) and the thickness  
10  
11  
12 938 of the lithosphere (for MER magmatism).  
13  
14  
15 939 • The ongoing rifting in Ethiopia may represent a transitional phase from a plume-  
16  
17  
18 940 driven to a plate-driven setting of magmatism.  
19  
20

21 941

22  
23  
24 942 **ACKNOWLEDGEMENTS**

25  
26  
27 943 We are grateful to Gray E. Bebout and Tyrone O. Rooney for discussion and improving the  
28  
29  
30 944 manuscript. We would also like to thank Tazue Nogi for help in K-Ar analysis. All members  
31  
32  
33 945 of the Pheasant Memorial Laboratory are thanked for their constructive discussion, technical  
34  
35  
36 946 support, and encouragement. Tanya Furman and two anonymous reviewers are acknowledged  
37  
38  
39 947 for their constructive review of the manuscript and Georg Zellmer is thanked for editorial  
40  
41  
42 948 handling. This study was supported by the MEXT (Ministry of Education, Culture, Sports,  
43  
44  
45 949 Science and Technology). We appreciate the Geological Survey of Ethiopia (GSE), in  
46  
47  
48 950 particular the Basic Geoscience Mapping Core Processes for their comprehensive support  
49  
50  
51 951 during the fieldwork. Figures were prepared using GMT (Wessel *et al.*, 2013) and R (R Core  
52  
53  
54 952 Team, 2019).  
55  
56  
57  
58  
59  
60

1  
2  
3  
4  
5  
6 953 **SUPPLEMENTARY DATA**  
7

8  
9 954 Supplementary data are available at Journal of Petrology online.  
10  
11

12 955  
13  
14

15 956 **REFERENCES**  
16

17  
18 957 Abebe, T., Mazzarini, F., Innocenti, F. & Manetti, P. (1998). The Yerer-Tullu Wellel  
19

20  
21 958 volcanotectonic lineament: A transtensional structure in central Ethiopia and the  
22

23  
24 959 associated magmatic activity. *Journal of African Earth Sciences*, 26(1), 135-150, doi:  
25

26  
27 960 10.1016/S0899-5362(97)00141-3.  
28  
29

30 961 Abebe, B., Acocella, V., Korme, T. & Ayalew, D. (2007). Quaternary faulting and volcanism  
31

32  
33 962 in the Main Ethiopian Rift. *Journal of African Earth Sciences*, 48(2-3), 115-124, doi:  
34

35  
36 963 10.1016/j.jafrearsci.2006.10.005.  
37  
38

39  
40 964 Alene, M., Hart, W. K., Saylor, B. Z., Deino, A., Mertzman, S., Haile-Selassie, Y. & Gibert,  
41

42  
43 965 L. B. (2017). Geochemistry of Woranso–Mille Pliocene basalts from west-central  
44

45  
46 966 Afar, Ethiopia: Implications for mantle source characteristics and rift evolution.  
47

48  
49 967 *Lithos*, 282, 187-200, doi: 10.1016/j.lithos.2017.03.005.  
50  
51

52 968 Armitage, J. J., Ferguson, D. J., Goes, S., Hammond, J. O., Calais, E., Rychert, C. A. &  
53

54  
55 969 Harmon, N. (2015). Upper mantle temperature and the onset of extension and break-  
56

57  
58 970 up in Afar, Africa. *Earth and Planetary Science Letters*, 418, 78-90, doi:  
59  
60

- 1  
2  
3  
4  
5  
6 971 10.1016/j.epsl.2015.02.039.  
7  
8  
9 972 Arndt, N. T., & Christensen, U. (1992). The role of lithospheric mantle in continental flood  
10  
11  
12 973 volcanism: thermal and geochemical constraints. *Journal of Geophysical Research:*  
13  
14  
15 974 *Solid Earth*, 97(B7), 10967-10981, doi: 10.1029/92JB00564.  
16  
17  
18 975 Audin, L., Quidelleur, X., Coulié, E., Courtillot, V., Gilder, S., Manighetti, I., Gillot, P.-Y.,  
19  
20  
21 976 Tapponnier, P. & Kidane, T. (2004). Palaeomagnetism and K-Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$  ages  
22  
23  
24 977 in the Ali Sabieh area (Republic of Djibouti and Ethiopia): constraints on the  
25  
26  
27 978 mechanism of Aden ridge propagation into southeastern Afar during the last 10 Myr.  
28  
29  
30 979 *Geophysical Journal International*, 158(1), 327-345, doi: 10.1111/j.1365-  
31  
32  
33 980 246X.2004.02286.x.  
34  
35  
36 981 Ayalew, D., Yirgu, G. & Pik, R. (1999). Geochemical and isotopic (Sr, Nd and Pb)  
37  
38  
39 982 characteristics of volcanic rocks from southwestern Ethiopia. *Journal of African Earth*  
40  
41  
42 983 *Sciences*, 29(2), 381-391, doi: 10.1016/S0899-5362(99)00104-9.  
43  
44  
45 984 Ayalew, D., Barbey, P., Marty, B., Reisberg, L., Yirgu, G. & Pik, R. (2002). Source, genesis,  
46  
47  
48 985 and timing of giant ignimbrite deposits associated with Ethiopian continental flood  
49  
50  
51 986 basalts. *Geochimica et Cosmochimica Acta*, 66(8), 1429-1448, doi: 10.1016/S0016-  
52  
53  
54 987 7037(01)00834-1.  
55  
56  
57 988 Ayalew, D. & Gibson, S. A. (2009). Head-to-tail transition of the Afar mantle plume:  
58  
59  
60



- 1  
2  
3  
4  
5  
6 989 Geochemical evidence from a Miocene bimodal basalt–rhyolite succession in the  
7  
8  
9 990 Ethiopian Large Igneous Province. *Lithos*, 112(3-4), 461-476, doi:  
10  
11  
12 991 10.1016/j.lithos.2009.04.005.  
13  
14  
15 992 Ayalew, D., Jung, S., Romer, R. L., Kersten, F., Pfänder, J. A. & Garbe-Schönberg, D.  
16  
17  
18 993 (2016). Petrogenesis and origin of modern Ethiopian rift basalts: Constraints from  
19  
20  
21 994 isotope and trace element geochemistry. *Lithos*, 258, 1-14, doi:  
22  
23  
24 995 10.1016/j.lithos.2016.04.001.  
25  
26  
27 996 Ayalew, D., Jung, S., Romer, R. L. & Garbe-Schönberg, D. (2018). Trace element  
28  
29  
30 997 systematics and Nd, Sr and Pb isotopes of Pliocene flood basalt magmas (Ethiopian  
31  
32  
33 998 rift): A case for Afar plume-lithosphere interaction. *Chemical Geology*, 493, 172-188,  
34  
35  
36 999 doi: 10.1016/j.chemgeo.2018.05.037.  
37  
38  
39 1000 Baker, J., Snee, L. & Menzies, M. (1996a). A brief Oligocene period of flood volcanism in  
40  
41  
42 1001 Yemen: implications for the duration and rate of continental flood volcanism at the  
43  
44  
45 1002 Afro-Arabian triple junction. *Earth and Planetary Science Letters*, 138(1-4), 39-55,  
46  
47  
48 1003 doi: 10.1016/0012-821X(95)00229-6.  
49  
50  
51 1004 Baker, J. A., Thirlwall, M. F. & Menzies, M. A. (1996b). Sr-Nd-Pb isotopic and trace  
52  
53  
54 1005 element evidence for crustal contamination of plume-derived flood basalts: Oligocene  
55  
56  
57 1006 flood volcanism in western Yemen. *Geochimica et Cosmochimica Acta*, 60(14),  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1007 2559-2581, doi: 10.1016/0016-7037(96)00105-6.  
7  
8  
9  
10 1008 Barberi, F., Bonatti, E., Marinelli, G. & Varet, J. (1974). Transverse tectonics during the split  
11  
12  
13 1009 of a continent: data from the Afar rift. *Tectonophysics*, 23(1-2), 17-29, doi:  
14  
15  
16 1010 10.1016/0040-1951(74)90108-5.  
17  
18  
19 1011 Barberi, F. & Varet, J. (1975). Nature of the Afar crust: a discussion. In: Pilger, A. & Rösler,  
20  
21  
22 1012 A. (Eds.), *Afar depression of Ethiopia*, Proceedings of an International Symposium on  
23  
24  
25 1013 the Afar Region and Related Rift Problems, Bad Bergzabern, F. R. Germany, April 1–  
26  
27  
28 1014 6, vol. 1, E. Schweizerbart'sche Verlagsbunchhandlung, Stuttgart, pp. 375–378.  
29  
30  
31 1015 Barberi, F. Santacroce, R. & Varet, J. (1975). Structural evolution of the Afar triple junction,  
32  
33  
34 1016 In: Pilger, A. & Rösler, A. (Eds.), *Afar depression of Ethiopia*, Proceedings of an  
35  
36  
37 1017 International Symposium on the Afar Region and Related Rift Problems, Bad  
38  
39  
40 1018 Bergzabern, F. R. Germany, April 1–6, vol. 1, E. Schweizerbart'sche  
41  
42  
43 1019 Verlagsbunchhandlung, Stuttgart, pp. 38–54.  
44  
45  
46 1020 Barrat, J. A., Jahn, B. M., Joron, J. L., Auvray, B. & Hamdi, H. (1990). Mantle heterogeneity  
47  
48  
49 1021 in northeastern Africa: evidence from Nd isotopic compositions and  
50  
51  
52 1022 hygromagmaphile element geochemistry of basaltic rocks from the Gulf of Tadjoura  
53  
54  
55 1023 and southern Red Sea regions. *Earth and Planetary Science Letters*, 101(2-4), 233-  
56  
57  
58 1024 247, doi: 10.1016/0012-821X(90)90156-R.  
59  
60

- 1  
2  
3  
4  
5  
6 1025 Barrat, J. A., Jahn, B. M., Fourcade, S. & Joron, J. L. (1993). Magma genesis in an ongoing  
7  
8  
9 1026 rifting zone: The Tadjoura Gulf (Afar area). *Geochimica et cosmochimica acta*,  
10  
11  
12 1027 57(10), 2291-2302, doi: 10.1016/0016-7037(93)90570-M.  
13  
14  
15 1028 Barrat, J. A., Fourcade, S., Jahn, B. M., Cheminée, J. L. & Capdevila, R. (1998). Isotope (Sr,  
16  
17  
18 1029 Nd, Pb, O) and trace-element geochemistry of volcanics from the Erta'Ale range  
19  
20  
21 1030 (Ethiopia). *Journal of Volcanology and Geothermal Research*, 80(1-2), 85-100, doi:  
22  
23  
24 1031 10.1016/S0377-0273(97)00016-4.  
25  
26  
27 1032 Barrat, J. A., Joron, J. L., Taylor, R. N., Fourcade, S., Nesbitt, R. W. & Jahn, B. M. (2003).  
28  
29  
30 1033 Geochemistry of basalts from Manda Hararo, Ethiopia: LREE-depleted basalts in  
31  
32  
33 1034 Central Afar. *Lithos*, 69(1-2), 1-13, doi: 10.1016/S0024-4937(03)00044-6.  
34  
35  
36 1035 Bastow, I. D., Nyblade, A. A., Stuart, G. W., Rooney, T. O. & Benoit, M. H. (2008). Upper  
37  
38  
39 1036 mantle seismic structure beneath the Ethiopian hot spot: Rifting at the edge of the  
40  
41  
42 1037 African low-velocity anomaly. *Geochemistry Geophysics Geosystems*, 9(12),  
43  
44  
45 1038 Q12022, doi: 10.1029/2008GC002107.  
46  
47  
48 1039 Beccaluva, L., Bianchini, G., Natali, C. & Siena, F. (2009). Continental flood basalts and  
49  
50  
51 1040 mantle plumes: a case study of the Northern Ethiopian Plateau. *Journal of Petrology*,  
52  
53  
54 1041 50(7), 1377-1403, doi: 10.1093/petrology/egp024.  
55  
56  
57 1042 Berhe, S. M. (1986). Geologic and geochronologic constraints on the evolution of the Red  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1043 Sea-Gulf of Aden and Afar Depression. *Journal of African Earth Sciences* (1983),  
7  
8  
9 1044 5(2), 101-117, doi: 10.1016/0899-5362(86)90001-1.  
10  
11  
12 1045 Berhe, S. M., Desta, B., Nicoletti, M. & Teferra, M. (1987). Geology, geochronology and  
13  
14  
15 1046 geodynamic implications of the Cenozoic magmatic province in W and SE Ethiopia.  
16  
17  
18 1047 *Journal of the Geological Society*, 144(2), 213-226, doi: 10.1144/gsjgs.144.2.0213.  
19  
20  
21 1048 Blundy, J. D., Robinson, J. A. C. & Wood, B. J. (1998). Heavy REE are compatible in  
22  
23  
24 1049 clinopyroxene on the spinel lherzolite solidus. *Earth and Planetary Science Letters*,  
25  
26  
27 1050 160(3-4), 493-504, doi: 10.1016/S0012-821X(98)00106-X.  
28  
29  
30 1051 Boccaletti, M., Mazzuoli, R., Bonini, M., Trua, T. & Abebe, B. (1999). Plio-Quaternary  
31  
32  
33 1052 volcanotectonic activity in the northern sector of the Main Ethiopian Rift:  
34  
35  
36 1053 relationships with oblique rifting. *Journal of African Earth Sciences*, 29(4), 679-698,  
37  
38  
39 1054 doi: 10.1016/S0899-5362(99)00124-4.  
40  
41  
42 1055 Bonini, M., Corti, G., Innocenti, F., Manetti, P., Mazzarini, F., Abebe, T. & Pecskey, Z.  
43  
44  
45 1056 (2005). Evolution of the Main Ethiopian Rift in the frame of Afar and Kenya rifts  
46  
47  
48 1057 propagation. *Tectonics*, 24(1), TC1007, doi: 10.1029/2004TC001680.  
49  
50  
51 1058 Bosworth, W., Huchon, P. & McClay, K. (2005). The Red Sea and Gulf of Aden basins.  
52  
53  
54 1059 *Journal of African Earth Sciences*, 43(1-3), 334-378, doi:  
55  
56  
57 1060 10.1016/j.jafrearsci.2005.07.020.  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1061 Boynton, W. V. (1983). Cosmochemistry of the rare earth elements: Meteorite studies. In:  
7  
8  
9 1062 Henderson, P. (Ed.) Rare earth element geochemistry, 63–114, New York, Elsevier,  
10  
11  
12 1063 doi: 10.1016/B978-0-444-42148-7.50008-3.  
13  
14  
15 1064 Chernet, T., Hart, W. K., Aronson, J. L. & Walter, R. C. (1998). New age constraints on the  
16  
17  
18 1065 timing of volcanism and tectonism in the northern Main Ethiopian Rift–southern Afar  
19  
20  
21 1066 transition zone (Ethiopia). *Journal of Volcanology and Geothermal Research*, 80(3-4),  
22  
23  
24 1067 267-280, doi: 10.1016/S0377-0273(97)00035-8.  
25  
26  
27 1068 Chiasera, B., Rooney, T. O., Girard, G., Yirgu, G., Grosfils, E., Ayalew, D., Mohr, P.,  
28  
29  
30 1069 Zimbelman, J. R. and Ramsey, M. S., (2018). Magmatically assisted off-rift  
31  
32  
33 1070 extension—The case for broadly distributed strain accommodation. *Geosphere*, 14(4),  
34  
35  
36 1071 1544–1563, doi: 10.1130/GES01615.1.  
37  
38  
39 1072 Civiero, C., Hammond, J. O. S., Goes, S., Fishwick, S., Ahmed, A., Ayele, A., Doubre, C.,  
40  
41  
42 1073 Goitom, B., Keir, D., Kendall, J.-M., Leroy, S., Ogubazghi, G., Rumpker, G. &  
43  
44  
45 1074 Stuart, G. W. (2015), Multiple mantle upwellings in the transition zone beneath the  
46  
47  
48 1075 northern East-Africa Rift system from relative P-wave travel-time tomography,  
49  
50  
51 1076 *Geochemistry Geophysics Geosystems*, 16, 2949–2968, doi: 10.1002/2015GC005948.  
52  
53  
54 1077 Conticelli, S., Sintoni, M. F., Abebe, T., Mazzarini, F., & Manetti, P. (1999). Petrology and  
55  
56  
57 1078 geochemistry of ultramafic xenoliths and host lavas from the Ethiopian Volcanic  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1079 Province: An insight into the upper mantle under eastern Africa. *Acta Vulcanologica*,  
7  
8  
9 1080 11, 143-160.  
10  
11  
12 1081 Corti, G. (2009). Continental rift evolution: from rift initiation to incipient break-up in the  
13  
14  
15 1082 Main Ethiopian Rift, East Africa. *Earth-science reviews*, 96(1-2), 1-53, doi:  
16  
17  
18 1083 10.1016/j.earscirev.2009.06.005.  
19  
20  
21 1084 Corti, G., Bastow, I. D., Keir, D., Pagli, C. & Baker, E. (2015), Rift-related morphology of  
22  
23  
24 1085 the Afar Depression, In: P. Billi (Ed.), *Landscapes and Landforms of Ethiopia*, World  
25  
26  
27 1086 Geomorphological Landscapes, doi: 10.1007/978-94-017-8026-1\_15, Springer  
28  
29  
30 1087 Science Business Media Dordrecht 2-15.  
31  
32  
33 1088 Cottrell, E. & Kelley, K. A. (2011). The oxidation state of Fe in MORB glasses and the  
34  
35  
36 1089 oxygen fugacity of the upper mantle. *Earth and Planetary Science Letters*, 305(3-4),  
37  
38  
39 1090 270-282, doi: 10.1016/j.epsl.2011.03.014.  
40  
41  
42 1091 Coulié, E., Quidelleur, X., Gillot, P. Y., Courtillot, V., Lefèvre, J. C. & Chiesa, S. (2003).  
43  
44  
45 1092 Comparative K–Ar and Ar/Ar dating of Ethiopian and Yemenite Oligocene  
46  
47  
48 1093 volcanism: implications for timing and duration of the Ethiopian traps. *Earth and*  
49  
50  
51 1094 *Planetary Science Letters*, 206(3-4), 477-492, doi: 10.1016/S0012-821X(02)01089-0.  
52  
53  
54 1095 Dalton, C. A., Langmuir, C. H. & Gale, A. (2014). Geophysical and geochemical evidence  
55  
56  
57 1096 for deep temperature variations beneath mid-ocean ridges. *Science*, 344(6179), 80-83,  
58  
59  
60

1  
2  
3  
4  
5  
6 1097 doi: 10.1126/science.1249466.  
7  
8  
9

10 1098 Daoud, M. A., Maury, R. C., Barrat, J.-A., Talyor, R. N., Gall, B. L., Guillou, H., Cotton, J.  
11  
12  
13 1099 & Rolet, J. (2010). A LREE-depleted component in the Afar plume: Further evidence  
14  
15  
16 1100 from Quaternary Djibouti basalts, *Lithos*, 114(3-4), 327-336, doi:  
17  
18  
19 1101 10.1016/j.lithos.2009.09.008.  
20  
21

22  
23 1102 Davidson, A. & Rex, D. C. (1980). Age of volcanism and rifting in southwestern Ethiopia.  
24  
25  
26 1103 *Nature*, 283(5748), 657, doi: 10.1038/283657a0.  
27

28  
29 1104 Deniel, C., Vidal, P., Coulon, C., Vellutini, P. J. & Piguet, P. (1994). Temporal evolution of  
30  
31  
32 1105 mantle sources during continental rifting: the volcanism of Djibouti (Afar). *Journal of*  
33  
34  
35 1106 *Geophysical Research: Solid Earth*, 99(B2), 2853-2869, doi: 10.1029/93JB02576.  
36

37  
38 1107 DePaolo, D. J. (1981). Trace element and isotopic effects of combined wallrock assimilation  
39  
40  
41 1108 and fractional crystallization. *Earth and Planetary Science Letters*, 53(2), 189–202,  
42  
43  
44 1109 doi: 10.1016/0012-821X(81)90153-9.  
45

46  
47 1110 Dugda, M. T., Nyblade, A. A., Julia, J., Langston, C. A., Ammon, C. J. and Simiyu, S.  
48  
49  
50 1111 (2005). Crustal structure in Ethiopia and Kenya from receiver function analysis:  
51  
52  
53 1112 Implications for rift development in eastern Africa. *Journal of Geophysical Research:*  
54  
55  
56 1113 *Solid Earth*, 110(B1), B01303, doi:10.1029/2004JB003065.  
57  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1114 Dugda, M. T., Nyblade, A. A., & Julia, J. (2007). Thin lithosphere beneath the Ethiopian  
7  
8  
9 1115 Plateau revealed by a joint inversion of Rayleigh wave group velocities and receiver  
10  
11  
12 1116 functions. *Journal of Geophysical Research: Solid Earth*, 112(B8), B08305, doi:  
13  
14  
15 1117 10.1029/2006JB004918.  
16  
17  
18 1118 Dupré, B., Blanc, G., Boulègue, J. & Allègre, C. J. (1988). Metal remobilization at a  
19  
20  
21 1119 spreading centre studied using lead isotopes. *Nature*, 333(6169), 165, doi:  
22  
23  
24 1120 10.1038/333165a0.  
25  
26  
27 1121 Ebinger, C. J., Yemane, T., WoldeGabriel, G., Aronson, J. L. & Walter, R. C. (1993). Late  
28  
29  
30 1122 Eocene–Recent volcanism and faulting in the southern main Ethiopian rift. *Journal of*  
31  
32  
33 1123 *the Geological Society*, 150(1), 99-108, doi: 10.1144/gsjgs.150.1.0099.  
34  
35  
36 1124 Ebinger, C. J. & Sleep, N. H. (1998). Cenozoic magmatism throughout east Africa resulting  
37  
38  
39 1125 from impact of a single plume. *Nature*, 395(6704), 788-791, doi: 10.1038/27417.  
40  
41  
42 1126 Ebinger, C. J., Yemane, T., Harding, D. J., Tesfaye, S., Kelley, S. & Rex, D. C. (2000). Rift  
43  
44  
45 1127 deflection, migration, and propagation: Link of the Ethiopian and Eastern rifts, Africa,  
46  
47  
48 1128 *Geological Society of America Bulletin*, 112(2), 163-176, doi: 10.1130/0016-  
49  
50  
51 1129 7606(2000)112<163:RDMAPL>2.0.CO;2.  
52  
53  
54 1130 Ebinger, C.J. & Casey, M. (2001). Continental breakup in magmatic provinces: An Ethiopian  
55  
56  
57 1131 example. *Geology*, 29(6), 527-530, doi: 10.1130/0091-  
58  
59  
60



- 1  
2  
3  
4  
5  
6 1132 7613(2001)029<0527:CBIMPA>2.0.CO;2.  
7  
8  
9 1133 Ellam, R. M. (1992). Lithospheric thickness as a control on basalt geochemistry. *Geology*,  
10  
11  
12 1134 20(2), 153-156, doi: 10.1130/0091-7613(1992)020<0153:LTAACO>2.3.CO;2.  
13  
14  
15  
16 1135 Ferguson, D. J., MacLennan, J., Bastow, I. D., Pyle, D. M., Jones, S. M., Keir, D., Blundy, J.  
17  
18  
19 1136 D., Plank, T. & Yirgu, G. (2013a). Melting during late-stage rifting in Afar is hot and  
20  
21  
22 1137 deep. *Nature*, 499(7456), 70-73, doi: 10.1038/nature12292.  
23  
24  
25 1138 Ferguson, D. J., Calvert, A. T., Pyle, D. M., Blundy, J. D., Yirgu, G. & Wright, T. J. (2013b),  
26  
27  
28 1139 Constraining timescales of focused magmatic accretion and extension in the Afar  
29  
30  
31 1140 crust using lava geochronology, *Nature Communications*, 4(1416), doi:  
32  
33  
34 1141 10.1038/ncomms2410.  
35  
36  
37 1142 Feyissa, D. H., Shinjo, R., Kitagawa, H., Meshesha D. & Nakamura, E. (2017). Petrologic  
38  
39  
40 1143 and geochemical characterization of rift-related magmatism at the northernmost Main  
41  
42  
43 1144 Ethiopian Rift: Implications for plume-lithosphere interaction and the evolution of rift  
44  
45  
46 1145 mantle sources. *Lithos*, 282, 240-261, doi: 10.1016/j.lithos.2017.03.011.  
47  
48  
49 1146 Fram, M. S., Leshner, C. E. & Volpe, A. M. (1998). Mantle melting systematics: transition  
50  
51  
52 1147 from continental to oceanic volcanism on the southeast Greenland margin. In  
53  
54  
55 1148 Saunders, A. D., Larsen, H. C. & Wise, S. W. (Eds.), *Proceedings of the Ocean*  
56  
57  
58 1149 *Drilling Program, Scientific Results*, 152, pp. 373-386, doi:  
59  
60

- 1  
2  
3  
4  
5  
6 1150 10.2973/odp.proc.sr.152.236.1998.  
7  
8  
9 1151 Furman, T. & Graham, D. (1999). Erosion of lithospheric mantle beneath the East African  
10  
11  
12 1152 Rift system: geochemical evidence from the Kivu volcanic province, *Lithos*, 48(1–4),  
13  
14  
15 1153 237–262, doi: 10.1016/S0024-4937(99)00031-6.  
16  
17  
18 1154 Furman, T., Bryce, J. G., Karson, J. & Iotti, A. (2004). East African Rift System (EARS)  
19  
20  
21 1155 plume structure: insights from Quaternary mafic lavas of Turkana, Kenya. *Journal of*  
22  
23  
24 1156 *Petrology*, 45(5), 1069-1088, doi: 10.1093/petrology/egh004.  
25  
26  
27 1157 Furman, T., Bryce, J., Rooney, T., Hanan, B., Yirgu, G. & Ayalew, D. (2006a). Heads and  
28  
29  
30 1158 tails: 30 million years of the Afar plume. Geological Society, London, Special  
31  
32  
33 1159 Publications, 259(1), 95-119, doi: 10.1144/GSL.SP.2006.259.01.09.  
34  
35  
36 1160 Furman, T., Kaleta, K. M., Bryce, J. G., & Hanan, B. B. (2006b). Tertiary mafic lavas of  
37  
38  
39 1161 Turkana, Kenya: constraints on East African plume structure and the occurrence of  
40  
41  
42 1162 high- $\mu$  volcanism in Africa. *Journal of Petrology*, 47(6), 1221-1244, doi:  
43  
44  
45 1163 10.1093/petrology/egl009.  
46  
47  
48 1164 Furman, T. (2007). Geochemistry of East African Rift basalts: an overview. *Journal of*  
49  
50  
51 1165 *African Earth Sciences*, 48(2-3), 147-160, doi: 10.1016/j.jafrearsci.2006.06.009.  
52  
53  
54 1166 Furman, T., Nelson, W. R. & Elkins-Tanton, L. T. (2016). Evolution of the East African rift:  
55  
56  
57 1167 Drip magmatism, lithospheric thinning and mafic volcanism. *Geochimica et*  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1168 Cosmochimica Acta, 185, 418-434, doi: 10.1016/j.gca.2016.03.024.  
7  
8  
9 1169 Gasparon, M., Innocenti, F., Manetti, P., Peccerillo, A. & Tsegaye, A. (1993). Genesis of the  
10  
11  
12 1170 Pliocene to Recent bimodal mafic-felsic volcanism in the Debre Zeyt area, central  
13  
14  
15 1171 Ethiopia: Volcanological and geochemical constraints. Journal of African Earth  
16  
17  
18 1172 Sciences (and the Middle East), 17(2), 145-165, doi: 10.1016/0899-5362(93)90032-L.  
19  
20  
21 1173 George, R., Rogers, N., & Kelley, S. (1998). Earliest magmatism in Ethiopia: Evidence for  
22  
23  
24 1174 two mantle plumes in one flood basalt province. Geology, 26(10), 923-926, doi:  
25  
26  
27 1175 10.1130/0091-7613(1998)026<0923:EMIEEF>2.3.CO;2.  
28  
29  
30 1176 George, R. (1999). The petrogenesis of Plio-Pleistocene alkaline volcanic rocks from the  
31  
32  
33 1177 Tosa Sucha region, Arba Minch, southern main Ethiopian rift. Acta Vulcanologica,  
34  
35  
36 1178 11, 121-131.  
37  
38  
39 1179 George, R. & Rogers, N. (2002). Plume dynamics beneath the African plate inferred from the  
40  
41  
42 1180 geochemistry of the Tertiary basalts of southern Ethiopia. Contributions to  
43  
44  
45 1181 Mineralogy and Petrology, 144(3), 286-304, doi: 10.1007/s00410-002-0396-z.  
46  
47  
48 1182 Giordano, F., D'Antonio, M., Civetta, L., Tonarini, S., Orsi, G., Ayalew, D., Yirgu, G.,  
49  
50  
51 1183 Dell'Erba, F., Di Vito, M. A. & Isaia, R. (2014). Genesis and evolution of mafic and  
52  
53  
54 1184 felsic magmas at Quaternary volcanoes within the Main Ethiopian Rift: Insights from  
55  
56  
57 1185 Gedemsa and Fanta'Ale complexes. Lithos, 188, 130-144, doi:  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1186 10.1016/j.lithos.2013.08.008.  
7  
8  
9 1187 Grove, T. L., Kinzler, R. J., Baker, M. B., Donnelly-Nolan, J. M. & Lesher, C. E. (1988).  
10  
11  
12 1188 Assimilation of granite by basaltic magma at Burnt Lava flow, Medicine Lake  
13  
14  
15 1189 volcano, northern California: decoupling of heat and mass transfer. Contributions to  
16  
17  
18 1190 Mineralogy and Petrology, 99(3), 320-343, doi: 10.1007/BF00375365.  
19  
20  
21 1191 GSE (2005), Geological Map of Ethiopia, Ethiopian Ministry of Mines, Geological Survey of  
22  
23  
24 1192 Ethiopia (GSE).  
25  
26  
27 1193 Hammond, J. O., Kendall, J. M., Stuart, G. W., Keir, D., Ebinger, C., Ayele, A., & Belachew,  
28  
29  
30 1194 M. (2011). The nature of the crust beneath the Afar triple junction: Evidence from  
31  
32  
33 1195 receiver functions. *Geochemistry Geophysics Geosystems*, 12(12), Q12004, doi:  
34  
35  
36 1196 10.1029/2011GC003738.  
37  
38  
39 1197 Hammond, J. O. S., Kendall, J.-M., Stuart, G. W., Ebinger, C. J., Bastow, I. D., Keir, D.,  
40  
41  
42 1198 Ayele, A., Belachew, M., Goitom, B., Ogubazghi, G. & Wright, T. J. (2013). Mantle  
43  
44  
45 1199 upwelling and initiation of rift segmentation beneath the Afar Depression. *Geology*,  
46  
47  
48 1200 41(6), 635-638, doi: 10.1130/G33925.1.  
49  
50  
51 1201 Hanan, B. B. & Graham, D. W. (1996). Lead and helium isotope evidence from oceanic  
52  
53  
54 1202 basalts for a common deep source of mantle plumes. *Science*, 272(5264), 991-995,  
55  
56  
57 1203 doi: 10.1126/science.272.5264.991.  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1204 Hart, W. K., WoldeGabriel, G., Walter, R. C. & Mertzman, S. A. (1989). Basaltic volcanism  
7  
8  
9 1205 in Ethiopia: constraints on continental rifting and mantle interactions. *Journal of*  
10  
11  
12 1206 *Geophysical Research: Solid Earth*, 94(B6), 7731-7748, doi:  
13  
14  
15 1207 10.1029/JB094iB06p07731.  
16  
17  
18 1208 Hayward, N. J. & Ebinger, C. J. (1996). Variations in the along-axis segmentation of the Afar  
19  
20  
21 1209 Rift system. *Tectonics*, 15(2), 244-257, doi: 10.1029/95TC02292.  
22  
23  
24 1210 Herzberg, C. & Asimow, P. D. (2015). PRIMELT3 MEGA.XLSM software for primary  
25  
26  
27 1211 magma calculation: peridotite primary magma MgO contents from the liquidus to the  
28  
29  
30 1212 solidus. *Geochemistry Geophysics Geosystems*, 16(2), 563–578, doi:  
31  
32  
33 1213 10.1002/2014GC005631.  
34  
35  
36 1214 Hofmann, C., Courtillot, V., Feraud, G., Rochette, P., Yirgu, G., Ketefo, E. & Pik, R. (1997).  
37  
38  
39 1215 Timing of the Ethiopian flood basalt event and implications for plume birth and global  
40  
41  
42 1216 change. *Nature*, 389(6653), 838-841, doi: 10.1038/39853.  
43  
44  
45 1217 Hutchison, W., Fusillo, R., Pyle, D. M., Mather, T. A., Blundy, J. D., Biggs, J., Yigru, G.,  
46  
47  
48 1218 Cohen, B. E., Brooker, R. A., Barford, D. N. & Calvert, A. T. (2016), A pulse of mid-  
49  
50  
51 1219 Pleistocene rift volcanism in Ethiopia at the dawn of modern humans, *Nature*  
52  
53  
54 1220 *communications*, 7(13192), doi: 10.1038/ncomms13192.  
55  
56  
57 1221 Irvine, T. N. J., & Baragar, W. R. A. (1971). A guide to the chemical classification of the  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1222 common volcanic rocks. Canadian journal of earth sciences, 8(5), 523-548, doi:  
7  
8  
9 1223 10.1139/e71-055.  
10  
11  
12 1224 JICA (2012). The study on groundwater resources assessment in the Rift Valley lakes basin  
13  
14  
15 1225 in the Federal Democratic Republic of Ethiopia. Japan International Cooperation  
16  
17  
18 1226 Agency (JICA), Kokusai Kogyo, Co. Ltd. [with supplementary documents  
19  
20  
21 1227 “Geological map of Konso-Yabelo area”  
22  
23  
24 1228 ([http://open\\_jicareport.jica.go.jp/pdf/12066361\\_06.pdf](http://open_jicareport.jica.go.jp/pdf/12066361_06.pdf)) and “Geological map of Arba  
25  
26  
27 1229 Minch-Agre Marryam area” ([http://open\\_jicareport.jica.go.jp/pdf/12066395\\_09.pdf](http://open_jicareport.jica.go.jp/pdf/12066395_09.pdf))].  
28  
29  
30  
31 1230 Johnson, K. T. (1998). Experimental determination of partition coefficients for rare earth and  
32  
33  
34 1231 high-field-strength elements between clinopyroxene, garnet, and basaltic melt at high  
35  
36  
37 1232 pressures. Contributions to Mineralogy and Petrology, 133(1-2), 60-68, doi:  
38  
39  
40 1233 10.1007/s004100050437.  
41  
42  
43  
44 1234 Jones, P. W. & Rex, D. C. (1974). New dates from the Ethiopian plateau volcanics. Nature,  
45  
46  
47 1235 252(5480), 218, doi: 10.1038/252218a0.  
48  
49  
50  
51 1236 Justin-Visentin, E., Nicoletti, M., Tolomeo, L. & Zanettin, B. (1974), Miocene and Pliocene  
52  
53  
54 1237 volcanic rocks of the Addis Ababa-Bebre Berhan area (Ethiopia). Geo-petrographic  
55  
56  
57 1238 and radiometric study, Bulletin Volcanologique, 38(1), 237–253, doi:  
58  
59  
60

1  
2  
3  
4  
5  
6 1239 10.1007/BF02599406.  
7  
8  
9

10 1240 Katz, R. F., Spiegelman, M. & Langmuir, C. H. (2003). A new parameterization of hydrous  
11  
12  
13 1241 mantle melting. *Geochemistry Geophysics Geosystems*, 4(9), 1073,  
14  
15  
16 1242 doi:10.1029/2002GC000433.  
17  
18  
19

20 1243 Kazmin, V. (1979). Stratigraphy and correlation of Cenozoic volcanic rocks in Ethiopia.  
21  
22  
23 1244 Reports of Ethiopian Institute of Geological Survey, 106, 1-26.  
24  
25

26 1245 Kelemen, P. B., Yogodzinski, G. M. & Scholl, D. W. (2003). Along-strike variation in lavas  
27  
28  
29 1246 of the Aleutian island arc: Implications for the genesis of high Mg# andesite and the  
30  
31  
32 1247 continental crust. In Eiler, J. (Ed.) *Inside the subduction factory*, Geophysical  
33  
34  
35 1248 Monograph, 138, 223-276, doi: 10.1029/138GM11.  
36  
37

38 1249 Kendall, J. M., Stuart, G. W., Ebinger, C. J., Bastow, I. D. & Keir, D. (2005). Magma-  
39  
40  
41 1250 assisted rifting in Ethiopia. *Nature*, 433(7022), 146-148, doi: 10.1038/nature03161.  
42  
43

44 1251 Kidane, T., Courtillot, V., Manighetti, I., Audin, L., Lahitte, P., Quidelleur, X., Gillot, P.-Y.,  
45  
46  
47 1252 Gallet, Y., Carlut, J. & Haile, T. (2003), New paleomagnetic and geochronological  
48  
49  
50 1253 results from Ethiopian Afar: Block rotations linked to rift overlap and propagation and  
51  
52  
53 1254 determination of a ~2 Ma reference pole for stable Africa, *Journal of Geophysical*  
54  
55  
56 1255 *Research*, 108(B2), 2102, doi: 10.1029/2001JB000645.  
57  
58

59 1256 Kieffer, B., Arndt, N., Lapierre, H., Bastien, F., Bosch, D., Pecher, A., Yirgu, G., Ayalew, D.,  
60

- 1  
2  
3  
4  
5  
6 1257 Weis, D., Jerram, D.A., Keller, F. & Meugniot, C. (2004). Flood and shield basalts  
7  
8  
9 1258 from Ethiopia: magmas from the African superswell. *Journal of Petrology*, 45(4),  
10  
11  
12 1259 793–834, doi: 10.1093/petrology/egg112.  
13  
14  
15 1260 Keir, D., Bastow, I. D., Corti, G., Mazzarini, F. & Rooney, T. O. (2015). The origin of along-  
16  
17  
18 1261 rift variations in faulting and magmatism in the Ethiopian Rift. *Tectonics*, 34(3), 464-  
19  
20  
21 1262 477, doi: 10.1002/2014TC003698.  
22  
23  
24 1263 Kitagawa, H., Kobayashi, K., Makishima, A. & Nakamura, E. (2008). Multiple pulses of the  
25  
26  
27 1264 mantle plume: evidence from Tertiary Icelandic lavas. *Journal of Petrology*, 49(7),  
28  
29  
30 1265 1365-1396, doi: 10.1093/petrology/egn029.  
31  
32  
33 1266 Korenaga, J. (2004). Mantle mixing and continental breakup magmatism. *Earth and Planetary*  
34  
35  
36 1267 *Science Letters*, 218(3-4), 463-473, doi: 10.1016/S0012-821X(03)00674-5.  
37  
38  
39 1268 Krans, S. R., Rooney, T. O., Kappelman, J., Yirgu, G. & Ayalew, D. (2018). From initiation  
40  
41  
42 1269 to termination: a petrostratigraphic tour of the Ethiopian Low-Ti Flood Basalt  
43  
44  
45 1270 Province. *Contributions to Mineralogy and Petrology*, 173(5), 37, doi:  
46  
47  
48 1271 10.1007/s00410-018-1460-7.  
49  
50  
51 1272 Lahitte, P., Gillot, P. Y. & Courtillot, V. (2003). Silicic central volcanoes as precursors to rift  
52  
53  
54 1273 propagation: the Afar case. *Earth and Planetary Science Letters*, 207(1-4), 103-116,  
55  
56  
57 1274 doi: 10.1016/S0012-821X(02)01130-5.  
58  
59  
60



- 1  
2  
3  
4  
5  
6 1275 Lavayssière, A., Rychert, C., Harmon, N., Keir, D., Hammond, J. O. S., Kendall, J.-M.,  
7  
8  
9 1276 Doubre, C. & Leroy, S. (2018), Imaging lithospheric discontinuities beneath the  
10  
11  
12 1277 northern East African Rift using S-to-P receiver functions, *Geochemistry Geophysics*  
13  
14  
15 1278 *Geosystems*, 19, 4048–4062, doi: 10.1029/2018GC007463.
- 16  
17  
18 1279 Le Bas, M. J., Le Maitre, R. W., Streckeisen, A., Zanettin, B. & IUGS Subcommittee on the  
19  
20  
21 1280 Systematics of Igneous Rocks. (1986). A chemical classification of volcanic rocks  
22  
23  
24 1281 based on the total alkali-silica diagram. *Journal of petrology*, 27(3), 745-750, doi:  
25  
26  
27 1282 10.1093/petrology/27.3.745.
- 28  
29  
30 1283 Lee, C. T. A., Luffi, P., Plank, T., Dalton, H. & Leeman, W. P. (2009). Constraints on the  
31  
32  
33 1284 depths and temperatures of basaltic magma generation on Earth and other terrestrial  
34  
35  
36 1285 planets using new thermobarometers for mafic magmas. *Earth and Planetary Science*  
37  
38  
39 1286 *Letters*, 279(1-2), 20-33, doi: 10.1016/j.epsl.2008.12.020.
- 40  
41  
42 1287 Mackenzie, G. D., Thybo, H., & Maguire, P. K. H. (2005). Crustal velocity structure across  
43  
44  
45 1288 the Main Ethiopian Rift: results from two-dimensional wide-angle seismic modelling.  
46  
47  
48 1289 *Geophysical Journal International*, 162(3), 994-1006, doi: 10.1111/j.1365-  
49  
50  
51 1290 246X.2005.02710.x.
- 52  
53  
54 1291 Maguire, P. K. H., Keller, G. R., Klemperer, S. L., Mackenzie, G. D., Keranen, K., Harder,  
55  
56  
57 1292 S., O'Reilly, B., Thybo, H., Asfaw, L., Khan, M. A. & Amha, M. (2006). Crustal  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1293 structure of the northern Main Ethiopian Rift from the EAGLE controlled-source  
7  
8  
9 1294 survey; a snapshot of incipient lithospheric break-up. In Yigru, G., Ebinger, C. J., &  
10  
11  
12 1295 Maguire, P. K. H. (Eds.) The Afar Volcanic Province within the East African Rift  
13  
14  
15 1296 System, Geological Society of London, Special Publications, 259, 269-291, doi:  
16  
17  
18 1297 10.1144/GSL.SP.2006.259.01.21.  
19  
20  
21 1298 Manighetti, I., Tapponnier, P., Gillot, P. Y., Jacques, E., Courtillot, V., Armijo, R., Ruegg, J.  
22  
23  
24 1299 C. & King, G. (1998). Propagation of rifting along the Arabia - Somalia plate  
25  
26  
27 1300 boundary: Into Afar. *Journal of Geophysical Research: Solid Earth*, 103(B3), 4947-  
28  
29  
30 1301 4974, doi: 10.1029/97JB02758.  
31  
32  
33 1302 Marty, B., Pik, R. & Gezahegn, Y. (1996). Helium isotopic variations in Ethiopian plume  
34  
35  
36 1303 lavas: nature of magmatic sources and limit on lower mantle contribution. *Earth and*  
37  
38  
39 1304 *Planetary Science Letters*, 144(1-2), 223-237, doi: 10.1016/0012-821X(96)00158-6.  
40  
41  
42 1305 Mazzarini, F., Le Corvec, N., Isola, I. & Favalli, M. (2016), Volcanic field elongation, vent  
43  
44  
45 1306 distribution, and tectonic evolution of a continental rift: The Main Ethiopian Rift  
46  
47  
48 1307 example, *Geosphere*, 12(3), 706–720, doi: 10.1130/GES01193.1.  
49  
50  
51 1308 McDonough, W. F. & Sun, S.-s. (1995). The composition of the Earth. *Chemical Geology*,  
52  
53  
54 1309 120(3-4), 223-253, doi: 10.1016/0009-2541(94)00140-4.  
55  
56  
57 1310 McKenzie, D. (1984). The generation and compaction of partially molten rock. *Journal of*  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1311 Petrology, 25(3), 713-765, doi: 10.1093/petrology/25.3.713.  
7  
8  
9 1312 McKenzie, D. & Bickle, M. J. (1988). The volume and composition of melt generated by  
10  
11  
12 1313 extension of the lithosphere, *Journal of Petrology*, 29(3), 625-679, doi:  
13  
14  
15 1314 10.1093/petrology/29.3.625  
16  
17  
18 1315 Meshesha, D. & Shinjo, R. (2008). Rethinking geochemical feature of the Afar and Kenya  
19  
20  
21 1316 mantle plumes and geodynamic implications. *Journal of Geophysical Research*, 113,  
22  
23  
24 1317 B09209, doi:10.1029/2007JB005549.  
25  
26  
27 1318 Meshesha, D., Shinjo, R., Matsumura, R. & Chekol, T. (2011), Metasomatized lithospheric  
28  
29  
30 1319 mantle beneath Turkana depression in southern Ethiopia (the East Africa Rift):  
31  
32  
33 1320 geochemical and Sr-Nd-Pb isotopic characteristics. *Contributions to Mineralogy and*  
34  
35  
36 1321 *Petrology*, 162, 889–907, doi: 10.1007/s00410-011-0630-7.  
37  
38  
39 1322 Mohr, P. A. (1967). Major volcano–tectonic lineament in the Ethiopian rift system. *Nature*,  
40  
41  
42 1323 213(5077), 664-665, doi: 10.1038/213664a0.  
43  
44  
45 1324 Mohr, P. & Zanettin, B. (1988). The Ethiopian Flood Basalt Province. In McDougall, J. D.  
46  
47  
48 1325 (Eds.) *Continental Flood Basalts. Petrology and Structural Geology*, vol 3. Springer,  
49  
50  
51 1326 Dordrecht, pp. 63–110, doi: 10.1007/978-94-015-7805-9\_3.  
52  
53  
54 1327 Morton, W. H., Rex, D. C., Mitchell, J. G. & Mohr, P. (1979). Riftward younging of volcanic  
55  
56  
57 1328 units in the Addis Ababa region, Ethiopian rift valley. *Nature*, 280(5720), 284-288,  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1329 doi: 10.1038/280284a0.  
7  
8  
9 1330 Nakamura, E., Makishima, A., Moriguti, T., Kobayashi, K., Sakaguchi, C., Yokoyama, T.,  
10  
11  
12 1331 Tanaka, R., Kuritani, T & Takei, H. (2003). Comprehensive geochemical analyses of  
13  
14  
15 1332 small amounts (< 100 mg) of extraterrestrial samples for the analytical competition  
16  
17  
18 1333 related to the sample return mission MUSES-C. The Institute of Space and  
19  
20  
21 1334 Astronautical Science report. SP, 16, 49-101.  
22  
23  
24 1335 Natali, C., Beccaluva, L., Bianchini, G. & Siena, F. (2011). Rhyolites associated to Ethiopian  
25  
26  
27 1336 CFB: clues for initial rifting at the Afar plume axis. Earth and Planetary Science  
28  
29  
30 1337 Letters, 312(1-2), 59-68, doi: 10.1016/j.epsl.2011.09.059.  
31  
32  
33 1338 Natali, C., Beccaluva, L., Bianchini, G., Ellam, R. M., Savo, A., Siena, F. & Stuart, F. M.  
34  
35  
36 1339 (2016). High-MgO lavas associated to CFB as indicators of plume-related  
37  
38  
39 1340 thermochemical effects: the case of ultra-titaniferous picrite–basalt from the Northern  
40  
41  
42 1341 Ethiopian–Yemeni Plateau. Gondwana Research, 34, 29-48, doi:  
43  
44  
45 1342 10.1016/j.gr.2016.02.009.  
46  
47  
48 1343 Nelson, W. R., Furman, T., van Keken, P. E., Shirey, S. B. & Hanan, B. B. (2012). Os-Hf  
49  
50  
51 1344 isotopic insight into mantle plume dynamics beneath the East African Rift System.  
52  
53  
54 1345 Chemical Geology, 320, 66-79, doi: 10.1016/j.chemgeo.2012.05.020.  
55  
56  
57 1346 Nyblade, A. A., Knox, R. P. & Gurrola, H. (2000). Mantle transition zone thickness beneath  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1347 Afar: implications for the origin of the Afar hotspot. *Geophysical Journal*  
7  
8  
9 1348 *International*, 142(2), 615-619, doi: 10.1046/j.1365-246x.2000.00179.x.  
10  
11  
12 1349 Peccerillo, A., Barberio, M. R., Yirgu, G., Ayalew, D., Barbieri, M. & Wu, T. W. (2003).  
13  
14  
15 1350 Relationships between mafic and peralkaline silicic magmatism in continental rift  
16  
17  
18 1351 settings: a petrological, geochemical and isotopic study of the Gedemsa volcano,  
19  
20  
21 1352 central Ethiopian rift. *Journal of Petrology*, 44(11), 2003-2032, doi:  
22  
23  
24 1353 10.1093/petrology/egg068.  
25  
26  
27 1354 Pik, R., Deniel, C., Coulon, C., Yirgu, G., Hofmann, C. & Ayalew, D. (1998). The  
28  
29  
30 1355 northwestern Ethiopian Plateau flood basalts: classification and spatial distribution of  
31  
32  
33 1356 magma types. *Journal of Volcanology and Geothermal Research*, 81(1-2), 91-111,  
34  
35  
36 1357 doi: 10.1016/S0377-0273(97)00073-5.  
37  
38  
39 1358 Pik, R., Deniel, C., Coulon, C., Yirgu, G. & Marty, B. (1999). Isotopic and trace element  
40  
41  
42 1359 signatures of Ethiopian flood basalts: evidence for plume–lithosphere interactions.  
43  
44  
45 1360 *Geochimica et Cosmochimica Acta*, 63(15), 2263-2279, doi: 10.1016/S0016-  
46  
47  
48 1361 7037(99)00141-6.  
49  
50  
51 1362 Pik, R., Marty, B. & Hilton, D. R. (2006). How many mantle plumes in Africa? The  
52  
53  
54 1363 geochemical point of view. *Chemical Geology*, 226(3-4), 100-114, doi:  
55  
56  
57 1364 10.1016/j.chemgeo.2005.09.016.  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1365 Pinzuti, P., Humler, E., Manighetti, I. & Gaudemer, Y. (2013). Petrological constraints on  
7  
8  
9 1366 melt generation beneath the Asal Rift (Djibouti) using Quaternary basalts.  
10  
11  
12 1367 *Geochemistry Geophysics Geosystems*, 14(8), 2932-2953, doi: 10.1002/ggge.20187.  
13  
14  
15 1368 Prave, A. R., Bates, C. R., Donaldson, C. H., Toland, H., Condon, D. J., Mark, D. & Raub, T.  
16  
17  
18 1369 D. (2016). Geology and geochronology of the Tana Basin, Ethiopia: LIP volcanism,  
19  
20  
21 1370 super eruptions and Eocene–Oligocene environmental change. *Earth and Planetary*  
22  
23  
24 1371 *Science Letters*, 443, 1-8, doi: 10.1016/j.epsl.2016.03.009.  
25  
26  
27 1372 Putirka, K. D., Perfit, M., Ryerson, F. J. & Jackson, M. G. (2007). Ambient and excess  
28  
29  
30 1373 mantle temperatures, olivine thermometry, and active vs. passive upwelling. *Chemical*  
31  
32  
33 1374 *Geology*, 241(3-4), 177-206, doi: 10.1016/j.chemgeo.2007.01.014.  
34  
35  
36 1375 Putirka, K. D. (2008). Thermometers and barometers for volcanic systems. In Putirka, K. D.  
37  
38  
39 1376 & Tepley III, F. J. (Eds) *Minerals, Inclusions and Volcanic Processes, Reviews in*  
40  
41  
42 1377 *Mineralogy and Geochemistry*, 69(1), 61-120, Mineralogical Society of America and  
43  
44  
45 1378 *Geochemical Society*, doi: 10.2138/rmg.2008.69.3.  
46  
47  
48 1379 R Core Team (2019). R: A language and environment for statistical computing. R Foundation  
49  
50  
51 1380 for Statistical Computing, Vienna, Austria (<https://www.R-project.org/>).  
52  
53  
54 1381 Robinson, J. A. C., Wood, B. J. & Blundy, J. D. (1998). The beginning of melting of fertile  
55  
56  
57 1382 and depleted peridotite at 1.5 GPa. *Earth and Planetary Science Letters*, 155(1-2), 97-  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1383 111, doi: 10.1016/S0012-821X(97)00162-3.  
7  
8  
9 1384 Rochette, P., Tamrat, E., Féraud, G., Pik, R., Courtillot, V., Ketefo, E., Coulon, C., Hofmann,  
10  
11  
12 1385 C., Vandamme, D. & Yirgu, G. (1998). Magnetostratigraphy and timing of the  
13  
14  
15 1386 Oligocene Ethiopian traps. *Earth and Planetary Science Letters*, 164(3-4), 497-510,  
16  
17  
18 1387 doi: 10.1016/S0012-821X(98)00241-6.  
19  
20  
21 1388 Rogers, N., Macdonald, R., Fitton, J. G., George, R., Smith, M. & Barreiro, B. (2000). Two  
22  
23  
24 1389 mantle plumes beneath the East African rift system: Sr, Nd and Pb isotope evidence  
25  
26  
27 1390 from Kenya Rift basalts. *Earth and Planetary Science Letters*, 176(3-4), 387-400, doi:  
28  
29  
30 1391 10.1016/S0012-821X(00)00012-1.  
31  
32  
33 1392 Rogers, N. W., Davies, M. K., Parkinson, I. J. & Yirgu, G. (2010). Osmium isotopes and  
34  
35  
36 1393 Fe/Mn ratios in Ti-rich picritic basalts from the Ethiopian flood basalt province: No  
37  
38  
39 1394 evidence for core contribution to the Afar plume. *Earth and Planetary Science Letters*,  
40  
41  
42 1395 296(3-4), 413-422, doi: 10.1016/j.epsl.2010.05.027.  
43  
44  
45 1396 Rooney, T. O., Furman, T., Yirgu, G. & Ayalew, D. (2005). Structure of the Ethiopian  
46  
47  
48 1397 lithosphere: Xenolith evidence in the Main Ethiopian Rift. *Geochimica et*  
49  
50  
51 1398 *Cosmochimica Acta*, 69(15), 3889-3910, doi: 10.1016/j.gca.2005.03.043.  
52  
53  
54 1399 Rooney, T., Furman, T., Bastow, I., Ayalew, D. & Yirgu, G. (2007). Lithospheric  
55  
56  
57 1400 modification during crustal extension in the Main Ethiopian Rift. *Journal of*  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1401 Geophysical Research: Solid Earth, 112(B10), B10201, doi:10.1029/2006JB004916.  
7  
8  
9 1402 Rooney, T. O. (2010). Geochemical evidence of lithospheric thinning in the southern Main  
10  
11  
12 1403 Ethiopian Rift. *Lithos*, 117(1-4), 33-48, doi: 10.1016/j.lithos.2010.02.002.  
13  
14  
15 1404 Rooney, T. O., Bastow, I. & Keir, D. (2011), Insights into extensional processes during  
16  
17  
18 1405 magma assisted rifting: Evidence from aligned scoria cones, *Journal of Volcanology*  
19  
20  
21 1406 and *Geothermal Research*, 201, 83–96, doi: 10.1016/j.jvolgeores.2010.07.019.  
22  
23  
24 1407 Rooney, T. O., Herzberg, C. & Bastow, I. D. (2012a). Elevated mantle temperature beneath  
25  
26  
27 1408 East Africa. *Geology*, 40(1), 27-30, doi: 10.1130/G32382.1.  
28  
29  
30 1409 Rooney, T. O., Hanan, B. B., Graham, D. W., Furman, T., Blichert-Toft, J. & Schilling, J.-G.  
31  
32  
33 1410 (2012b). Upper mantle pollution during Afar plume–continental rift interaction.  
34  
35  
36 1411 *Journal of Petrology*, 53(2), 365-389, doi: 10.1093/petrology/egr065.  
37  
38  
39 1412 Rooney, T. O., Hart, W. K., Hall, C. M., Ayalew, D., Ghiorso, M. S., Hidalgo, P., & Yirgu,  
40  
41  
42 1413 G. (2012c). Peralkaline magma evolution and the tephra record in the Ethiopian Rift.  
43  
44  
45 1414 *Contributions to Mineralogy and Petrology*, 164(3), 407-426, doi: 10.1007/s00410-  
46  
47  
48 1415 012-0744-6.  
49  
50  
51 1416 Rooney, T. O., Mohr, P., Dosso, L. & Hall, C. (2013). Geochemical evidence of mantle  
52  
53  
54 1417 reservoir evolution during progressive rifting along the western Afar margin.  
55  
56  
57 1418 *Geochimica et Cosmochimica Acta*, 102, 65-88, doi: 10.1016/j.gca.2012.08.019.  
58  
59  
60



- 1  
2  
3  
4  
5  
6 1419 Rooney, T. O., Nelson, W. R., Dosso, L., Furman, T. & Hanan, B. (2014a). The role of  
7  
8  
9 1420 continental lithosphere metasomes in the production of HIMU-like magmatism on the  
10  
11  
12 1421 northeast African and Arabian plates. *Geology*, 42(5), 419-422, doi:  
13  
14  
15 1422 10.1130/G35216.1.  
16  
17  
18 1423 Rooney, T. O., Bastow, I., Keir, D., Mazzarini, F., Movsesian, E., Grosfils, E. B.,  
19  
20  
21 1424 Zimbelman, J. R., Ramsey, M. S., Ayalew, D. & Yirgu, G. (2014b), The protracted  
22  
23  
24 1425 development of focused magmatic intrusion during continental rifting, *Tectonics*, 33,  
25  
26  
27 1426 875–897, doi: 10.1002/2013TC003514.  
28  
29  
30 1427 Rooney, T. O. (2017). The Cenozoic magmatism of East-Africa: Part I—flood basalts and  
31  
32  
33 1428 pulsed magmatism. *Lithos*, 286, 264-301, doi: 10.1016/j.lithos.2017.05.014.  
34  
35  
36 1429 Rooney, T. O., Nelson, W. R., Ayalew, D., Hanan, B., Yirgu, G., & Kappelman, J. (2017).  
37  
38  
39 1430 Melting the lithosphere: Metasomes as a source for mantle-derived magmas. *Earth*  
40  
41  
42 1431 and Planetary Science Letters, 461, 105-118, doi: 10.1016/j.epsl.2016.12.010.  
43  
44  
45 1432 Rooney, T. O., Krans, S. R., Mège, D., Arnaud, N., Korme, T., Kappelman, J. & Yirgu, G.  
46  
47  
48 1433 (2018), Constraining the magmatic plumbing system in a zoned continental flood  
49  
50  
51 1434 basalt province, *Geochemistry Geophysics Geosystems*, 19, 3917-3944, doi:  
52  
53  
54 1435 10.1029/2018GC007724.  
55  
56  
57 1436 Rudnick, R. L. & Gao, S. (2003). Composition of the continental crust. In Heinrich D.,  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1437 Holland, D. & Turekian, K. K. (Eds.) *Treatise on Geochemistry*, 3, 659, pp. 1–64,  
7  
8  
9 1438 Elsevier, doi: 10.1016/B0-08-043751-6/03016-4.  
10  
11  
12 1439 Rychert, C. A., Hammond, J. O. S., Harmon, N., Kendall, J.M., Keir, D., Ebinger, C.,  
13  
14  
15 1440 Bastow, I.D., Ayele, A., Belachew, M. & Stuart, G. (2012). Volcanism in the Afar  
16  
17  
18 1441 Rift sustained by decompression melting with minimal plume influence. *Nature*  
19  
20  
21 1442 *Geoscience*, 5(6), 406-409, doi: 10.1038/ngeo1455.  
22  
23  
24 1443 Sarafian, E., Gaetani, G. A., Hauri, E. H. & Sarafian, A. R. (2017). Experimental constraints  
25  
26  
27 1444 on the damp peridotite solidus and oceanic mantle potential temperature. *Science*,  
28  
29  
30 1445 355(6328), 942-945, doi: 10.1126/science.aaj2165.  
31  
32  
33 1446 Scarsi, P. & Craig, H. (1996). Helium isotope ratios in Ethiopian Rift basalts. *Earth and*  
34  
35  
36 1447 *Planetary Science Letters*, 144(3-4), 505-516, doi: 10.1016/S0012-821X(96)00185-9.  
37  
38  
39 1448 Schilling, J.-G., Kingsley, R. H., Hanan, B. B. & McCully, B. L. (1992). Nd-Sr-Pb isotopic  
40  
41  
42 1449 variations along the Gulf of Aden: Evidence for Afar mantle plume - continental  
43  
44  
45 1450 lithosphere interaction. *Journal of Geophysical Research: Solid Earth*, 97(B7), 10927-  
46  
47  
48 1451 10966, doi: 10.1029/92JB00415.  
49  
50  
51 1452 Shinjo, R., Chekol, T., Meshesha, D., Itaya, Y. & Tatsumi, Y. (2011), *Geochemistry and*  
52  
53  
54 1453 *geochronology of the mafic lavas from the southern Ethiopia rift (the East African*  
55  
56  
57 1454 *Rift System): assessment of models on magma sources, plume-lithosphere interaction*  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1455 and plume evolution, *Contributions to Mineralogy and Petrology*, 162, 209-230, doi:  
7  
8  
9 1456 10.1007/s00410-010-0591-2.  
10  
11  
12  
13 1457 Siegburg, M., Gernon, T. M., Bull, J. M., Kier, D., Barfod, D. N., Taylor, R. N., Abede, B. &  
14  
15  
16 1458 Ayele, A. (2018), Geological evolution of the Boset-Bercha Volcanic Complex, Main  
17  
18  
19 1459 Ethiopian Rift:  $^{40}\text{Ar}/^{39}\text{Ar}$  evidence for episodic Pleistocene to Holocene volcanism,  
20  
21  
22 1460 *Journal of Volcanology and Geothermal Research*, 351, 115-133, doi:  
23  
24  
25 1461 10.1016/j.jvolgeores.2017.12.014.  
26  
27  
28  
29 1462 Stab, M., Bellahsen, N., Pik, R., Quidelleur, X., Ayalew, D. & Leroy, S. (2015). Modes of  
30  
31  
32 1463 rifting in magma-rich settings: Tectono-magmatic evolution of Central Afar,  
33  
34  
35 1464 *Tectonics*, 35(1), 2-38, doi:10.1002/2015TC003893.  
36  
37  
38  
39 1465 Stewart, K. & Rogers, N. (1996). Mantle plume and lithosphere contributions to basalts from  
40  
41  
42 1466 southern Ethiopia. *Earth and Planetary Science Letters*, 139(1-2), 195-211, doi:  
43  
44  
45 1467 10.1016/0012-821X(96)00015-5.  
46  
47  
48  
49 1468 Stracke, A., Zindler, A., Salters, V. J. M., McKenzie, D., Blichert-Toft, J., Albarède, F. &  
50  
51  
52 1469 Grönvold, K. (2003). Theistareykir revisited. *Geochemistry Geophysics Geosystems*,  
53  
54  
55 1470 4(2), 8507, doi: 10.1029/2001GC000201.  
56  
57  
58 1471 Stracke, A., Hofmann, A. W., & Hart, S. R. (2005). FOZO, HIMU, and the rest of the mantle  
59  
60

- 1  
2  
3  
4  
5  
6 1472 zoo. *Geochemistry Geophysics Geosystems*, 6(5), Q05007, doi:  
7  
8  
9 1473 10.1029/2004GC000824.  
10  
11  
12  
13 1474 Tadesse, A. Z., Ayalew, D., Pik, R., Yigru, G. & Fontijn, K. (2019). Magmatic evolution of  
14  
15  
16 1475 the Boku volcanic complex, Main Ethiopian Rift, *Journal of African Earth Sciences*,  
17  
18  
19 1476 149, 109-130, doi: 10.1016/j.jafrearsci.2018.08.003.  
20  
21  
22 1477 Thompson, R. N., Gibson, S. A., Dickin, A. P. & Smith, P. D. (2001). Early Cretaceous  
23  
24  
25 1478 basalt and picrate dykes of the Southern Etendeka region, NW Namibia: Windows  
26  
27  
28 1479 into the role of the Tristan mantle plume in Paraná–Etendeka magmatism, *Journal of*  
29  
30  
31 1480 *Petrology*, 42(11), 2049–2081, doi: 10.1093/petrology/42.11.2049.  
32  
33  
34 1481 Thompson, D. A., Hammond, J. O., Kendall, J. M., Stuart, G. W., Helffrich, G. R., Keir, D.,  
35  
36  
37 1482 Ayele, A. & Goitom, B. (2015). Hydrous upwelling across the mantle transition zone  
38  
39  
40 1483 beneath the Afar Triple Junction. *Geochemistry Geophysics Geosystems*, 16(3), 834–  
41  
42  
43 1484 846, doi: 10.1002/2014GC005648.  
44  
45  
46 1485 Till, C. B. (2017). A review and update of mantle thermobarometry for primitive arc  
47  
48  
49 1486 magmas. *American Mineralogist*, 102(5), 931-947, doi: 10.2138/am-2017-5783.  
50  
51  
52 1487 Ukstins, I. A., Renne, P. R., Wolfenden, E., Baker, J., Ayalew, D. & Menzies, M. (2002).  
53  
54  
55 1488 Matching conjugate volcanic rifted margins:  $^{40}\text{Ar}/^{39}\text{Ar}$  chrono-stratigraphy of pre-and  
56  
57  
58 1489 syn-rift bimodal flood volcanism in Ethiopia and Yemen. *Earth and Planetary Science*  
59  
60

- 1  
2  
3  
4  
5  
6 1490 Letters, 198(3-4), 289-306, doi: 10.1016/S0012-821X(02)00525-3.  
7  
8  
9 1491 Varet, J. (1978). Geology of central and southern Afar (Ethiopia and Djibouti Republic), pp.  
10  
11  
12 1492 124, Centre National de la Recherche Scientifique (CNRS), Paris.  
13  
14  
15 1493 Volker, F., McColloch, M. T. & Altherr, R. (1993). Submarine basalts from the Red Sea: new  
16  
17  
18 1494 Pb, Sr, and Nd isotopic data, Geophysical Research Letters, 20(10), 927-930, doi:  
19  
20  
21 1495 10.1029/93GL00050.  
22  
23  
24 1496 Volker, F. Altherr, R., Jochum, K. P. & McCulloch, M. T. (1997). Quaternary volcanic  
25  
26  
27 1497 activity of the southern Red Sea: new data and assessment of models on magma  
28  
29  
30 1498 sources and Afar plume-lithosphere interaction, Tectonophysics, 278(1-4), 15-29,  
31  
32  
33 1499 doi: 10.1016/S0040-1951(97)00092-9.  
34  
35  
36 1500 Walter, M. J., Sisson, T. W. & Presnall, D. C. (1995). A mass proportion method for  
37  
38  
39 1501 calculating melting reactions and application to melting of model upper mantle  
40  
41  
42 1502 lherzolite. Earth and Planetary Science Letters, 135(1-4), 77-90, doi: 10.1016/0012-  
43  
44  
45 1503 821X(95)00148-6.  
46  
47  
48  
49 1504 Wessel, P., Smith, W. H., Scharroo, R., Luis, J. & Wobbe, F. (2013). Generic Mapping  
50  
51  
52 1505 Tools: Improved version released. Eos, Transactions American Geophysical Union,  
53  
54  
55 1506 94(45), 409-410, doi: 10.1002/2013EO450001.  
56  
57  
58 1507 White, R. S., Smith, L. K., Roberts, A. W., Christie, P. A. F. & Kusznir, N. J. (2008). Lower-  
59  
60

- 1  
2  
3  
4  
5  
6 1508 crustal intrusion on the North Atlantic continental margin. *Nature*, 452(7186), 460-  
7  
8  
9 1509 464, doi: 10.1038/nature06687.  
10  
11  
12 1510 White, R. & McKenzie, D. (1989). Magmatism at rift zones: the generation of volcanic  
13  
14  
15 1511 continental margins and flood basalts. *Journal of Geophysical Research: Solid Earth*,  
16  
17  
18 1512 94(B6), 7685-7729, doi: 10.1029/JB094iB06p07685.  
19  
20  
21 1513 Willbold, M. & Stracke, A. (2006). Trace element composition of mantle end-members:  
22  
23  
24 1514 Implications for recycling of oceanic and upper and lower continental crust,  
25  
26  
27 1515 *Geochemistry Geophysics Geosystems*, 7(4), Q04004, doi: 10.1029/2005GC001005.  
28  
29  
30 1516 Williams, F. M., Williams, M. A. J. & Aumento, F. (2004), Tensional fissures and crustal  
31  
32  
33 1517 extension rates in the northern part of the Main Ethiopian Rift, *Journal of African*  
34  
35  
36 1518 *Earth Sciences*, 38(2), 183-197, doi: 10.1016/j.jafrearsci.2003.10.007.  
37  
38  
39 1519 Wolde, B. (1996). Spatial and temporal variations in the compositions of upper Miocene to  
40  
41  
42 1520 recent basic lavas in the northern Main Ethiopian rift: implications for the causes of  
43  
44  
45 1521 Cenozoic magmatism in Ethiopia, *Geologische Rundschau*, 85, 380-389, doi:  
46  
47  
48 1522 10.1007/BF02422243.  
49  
50  
51 1523 WoldeGabriel, G., Aronson, J. L. & Walter, R. C. (1990). Geology, geochronology, and rift  
52  
53  
54 1524 basin development in the central sector of the Main Ethiopia Rift. *Geological Society*  
55  
56  
57 1525 of America Bulletin, 102(4), 439-458, doi: 10.1130/0016-  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1526 7606(1990)102<0439:GGARBD>2.3.CO;2.  
7  
8  
9 1527 WoldeGabriel, G., Yemane, T., Suwa, G., White, T. & Asfaw, B. (1991). Age of volcanism  
10  
11  
12 1528 and rifting in the Burji-Soyoma area, Amaro Horst, southern Main Ethiopian rift:  
13  
14  
15 1529 Geo-and biochronologic data. *Journal of African Earth Sciences (and the Middle*  
16  
17  
18 1530 *East)*, 13(3-4), 437-447, doi: 10.1016/0899-5362(91)90107-A.  
19  
20  
21 1531 WoldeGabriel, G., Walter, R. C., Aronson, J. L. & Hart, W. K. (1992a). Geochronology and  
22  
23  
24 1532 distribution of silicic volcanic rocks of Plio-Pleistocene age from the central sector of  
25  
26  
27 1533 the Main Ethiopian Rift. *Quaternary International*, 13-14, 69-76, doi: 10.1016/1040-  
28  
29  
30 1534 6182(92)90011-P.  
31  
32  
33 1535 WoldeGabriel, G., White, T., Suwa, G., Semaw, S., Beyene, Y., Asfaw, B., & Walter, R.  
34  
35  
36 1536 (1992b). Kesem-Kebena: a newly discovered paleoanthropological research area in  
37  
38  
39 1537 Ethiopia. *Journal of Field Archaeology*, 19(4), 471-493, doi: 10.2307/530428.  
40  
41  
42 1538 Wolfenden, E., Ebinger, C., Yirgu, G., Deino, A. & Ayalew, D. (2004). Evolution of the  
43  
44  
45 1539 northern Main Ethiopian rift: birth of a triple junction. *Earth and Planetary Science*  
46  
47  
48 1540 *Letters*, 224(1-2), 213-228, doi: 10.1016/j.epsl.2004.04.022.  
49  
50  
51 1541 Wolfenden, E., Ebinger, C., Yirgu, G., Renne, P. R. & Kelley, S. P. (2005). Evolution of a  
52  
53  
54 1542 volcanic rifted margin: Southern Red Sea, Ethiopia. *Geological Society of America*  
55  
56  
57 1543 *Bulletin*, 117(7-8), 846-864, doi: 10.1130/B25516.1.  
58  
59  
60

- 1  
2  
3  
4  
5  
6 1544 Yemane, T., WoldeGabriel, G., Tesfaye, S., Berhe, S. M., Durary, S., Ebingher, C. & Kelley,  
7  
8  
9 1545 S. (1999). Temporal and geochemical characteristics of Tertiary volcanic rocks and  
10  
11  
12 1546 tectonic history in the southern Main Ethiopian Rift and the adjacent volcanic fields.  
13  
14  
15 1547 *Acta Vulcanologica*, 11, 99–120.  
16  
17  
18 1548 Zanettin, B. & Justin-Visentin, E. (1974). The volcanic succession in central Ethiopia: the  
19  
20  
21 1549 volcanics of the western Afar and Ethiopian rift margins. *Memoirs of the Institute of*  
22  
23  
24 1550 *Geology and Mineralogy, University of Padova*, 31, 1-19.  
25  
26  
27 1551 Zanettin, B., Justin-Visentin, E. & Piccirillo, E. M. (1978). Volcanic succession, tectonics  
28  
29  
30 1552 and magmatology in central Ethiopia. *Atti e Memorie Accademia Patavina di Scienze*  
31  
32  
33 1553 *Lettere ed Arti*, 90(Parte II): 5–19  
34  
35  
36 1554 Zindler, A., & Hart, S. (1986). Chemical geodynamics. *Annual Review of Earth and*  
37  
38  
39 1555 *Planetary Sciences*, 14(1), 493-571, doi: 10.1146/annurev.ea.14.050186.002425.  
40  
41  
42 1556 Zumbo, V., Féraud, G., Vellutini, P., Piguet, P. & Vincent, J. (1995), First  $^{40}\text{Ar}/^{39}\text{Ar}$  dating  
43  
44  
45 1557 on Early Pliocene to Plio-Pleistocene magmatic events of the Afar – Republic of  
46  
47  
48 1558 Djibouti, *Journal of Volcanology and Geothermal Research*, 65(3-4), 281-295, doi:  
49  
50  
51 1559 10.1016/0377-0273(94)00107-R.  
52  
53

1560

1561 **FIGURE CAPTIONS**



1  
2  
3  
4  
5  
6  
7 1562 **Figure 1.** Geological map of the Horn of Africa and the southwestern Arabian Peninsula  
8  
9 1563 showing the distribution of volcanic rocks erupted from 45 Ma to Recent (Hayward &  
10  
11  
12 1564 Ebinger, 1996; Rooney, 2017). The border of low-Ti (LT) and high-Ti (HT) sub-provinces in  
13  
14  
15 1565 the NW Plateau is after Pik *et al.* (1998) and that in Yemen is after Beccaluva *et al.* (2009).  
16  
17  
18 1566 Abbreviations are as follows: MER, Main Ethiopian Rift; WFB, Wonji Fault Belt (a  
19  
20  
21 1567 Quaternary bounding fault belt; Mohr, 1967); YTVL, Yerer-Tullu Wellel volcanotectonic  
22  
23  
24 1568 lineament (a reactivated Precambrian suture zone; Abebe *et al.*, 1998). The inset map shows  
25  
26  
27 1569 the location of the Ethiopian volcanic province. The base maps were created using Generic  
28  
29  
30 1570 Mapping Tools (Wessel *et al.*, 2013).  
31  
32

33  
34 1571  
35  
36 1572 **Figure 2.** Total alkali-silica (TAS) diagrams. Nomenclature of volcanic rocks after Le Bas *et*  
37  
38  
39 1573 *al.* (1986). The alkaline-subalkaline divide is from Irvine & Baragar (1971). (a) Oligocene  
40  
41  
42 1574 flood basalts from the Maychew area at the eastern margin of the NW Ethiopian Plateau in  
43  
44  
45 1575 comparison with mafic rocks from the rift-bounding plateaus in Ethiopia and Yemen. The  
46  
47  
48 1576 classification of Plateau mafic rocks [LT (low-Ti type), HT1 (high-Ti1) and HT2 (high-Ti2  
49  
50  
51 1577 type)] is after Pik *et al.* (1998). Data for Oligocene mafic rocks from other regions in NW  
52  
53  
54 1578 Ethiopia are from Pik *et al.* (1998, 1999), Kieffer *et al.* (2004), Beccaluva *et al.* (2009), and  
55  
56  
57 1579 Natali *et al.* (2011, 2016). Data for Oligocene Yemen Plateau basalts (HT1 and HT2 types;  
58  
59  
60

1  
2  
3  
4  
5  
6 1580 Baker *et al.*, 1996b) and Miocene SW Ethiopian basalts (Wollega basalt; Ayalew *et al.*, 1999;  
7  
8  
9 1581 Conticelli *et al.*, 1999) are shown as compositional fields enclosed by lines. Data for the  
10  
11  
12 1582 Oligocene–Miocene shield volcanoes [Simien (30 Ma and 19 Ma), Choke (22 Ma), Gugufu  
13  
14  
15 1583 (23 Ma), and Gerba Guracha (25–24 Ma)] are from Keiffer *et al.* (2004) and Rooney *et al.*  
16  
17  
18 1584 (2014a, 2017a). (b) Mafic–intermediate rocks from the southern Main Ethiopian Rift (SMER;  
19  
20  
21 1585 Miocene Getra-Kele and Quaternary Tosa-Sucha mafic rocks) in comparison with literature  
22  
23  
24 1586 data for mafic rocks from the SMER and surrounding regions. Data sources are as follows:  
25  
26  
27 1587 Amaro-Gamo basalts (Eocene), Yemane *et al.* (1999) and George & Rogers (2002); Getra-  
28  
29  
30 1588 Kele (Miocene), George & Rogers (2002), Rooney (2010) and Shinjo *et al.* (2011); Tosa-  
31  
32  
33 1589 sucha (Quaternary), Rooney (2010) and Shinjo *et al.* (2011). (c) Mafic–intermediate rocks  
34  
35  
36 1590 from the central Main Ethiopian Rift (CMER) and adjacent regions, reported in the literature.  
37  
38  
39 1591 Data sources: SDFZ (Silti-Debre Zeyit Fault Zone), Gasparon *et al.* (1993), Wolde (1996),  
40  
41  
42 1592 Rooney *et al.* (2005) and Rooney (2010); WFB (Wonji Fault Belt), Boccaletti *et al.* (1999),  
43  
44  
45 1593 Rooney *et al.* (2007), Rooney (2010), Giordana *et al.* (2014), Ayalew *et al.* (2016) and  
46  
47  
48 1594 Tadesse *et al.* (2019); Akaki magmatic zone, Wolde (1996) and Rooney *et al.* (2014b);  
49  
50  
51 1595 Miocene Addis Ababa basalts from the Bishoftu embayment, Wolde (1996) and Furman *et*  
52  
53  
54 1596 *al.* (2006a). (d) Oligocene–Recent mafic rocks from the northern Main Ethiopian Rift  
55  
56  
57 1597 (NMER) and its escarpments. Data sources for Miocene-Plio/Pleistocene rocks (Nazret  
58  
59  
60

1  
2  
3  
4  
5  
6 1598 series) are from Wolde *et al.* (1996), Boccaletti *et al.* (1999), Furman *et al.* (2006a) and  
7  
8  
9 1599 Ayalew *et al.* (2018). Data sources for Quaternary mafic rocks from rift floor and magmatic  
10  
11  
12 1600 segments (Dofan, Fantale, Kone, Boset, enclosed by line) are from Wolde (1996), Boccaletti  
13  
14  
15 1601 *et al.* (1999), Furman *et al.* (2006a), Rooney *et al.* (2012b), Giordana *et al.* (2014) and  
16  
17  
18 1602 Ayalew *et al.* (2016). (e) Mafic rocks from the Afar region. The classification of Pliocene to  
19  
20  
21 1603 Recent volcanic rocks (stratoid, 4–1.1 Ma; Gulf basalt, 1.1–0.6 Ma; axial range, <0.6 Ma) is  
22  
23  
24 1604 after Stab *et al.* (2015). Compositional variations in the literature data are shown as fields  
25  
26  
27 1605 enclosed by lines: stratoid series, Deniel *et al.*, (1994) and Alene *et al.* (2017); Gulf basalts,  
28  
29  
30 1606 Deniel *et al.* (1994); axial range series, Deniel *et al.* (1994), Barrat *et al.* (1998, 2003), Daoud  
31  
32  
33 1607 *et al.* (2010) and Pinzuti *et al.* (2013). All data in Figs 2(a)–(e) are normalized to a 100%  
34  
35  
36 1608 volatile-free basis.

37  
38  
39 1609  
40  
41  
42 1610 **Figure 3.** Concentrations of SiO<sub>2</sub>, TiO<sub>2</sub> and FeO<sup>T</sup> (total Fe as FeO) in mafic volcanic rocks  
43  
44  
45 1611 plotted against MgO concentration (in wt %). Sources of literature data are the same as in Fig.  
46  
47  
48 1612 2. Variations of all major element concentrations are shown in Supplementary Data Fig. S8.

49  
50 1613  
51  
52 1614 **Figure 4.** Concentrations of Ni, Nb and Y (in ppm) in mafic volcanic rocks plotted against  
53  
54  
55 1615 MgO concentration (in wt %). Sources of literature data are the same as in Fig. 2. Variations

1  
2  
3  
4  
5  
6 1616 of the other trace element concentrations (Cr, Rb, Sr, Zr, La and Nd) are shown with Ni, Nb,  
7  
8  
9 1617 and Yb in Supplementary Data Fig. S9.  
10

11  
12 1618

13  
14 1619 **Figure 5.** Primitive mantle-normalized incompatible trace element diagrams for Ethiopian

15  
16  
17 1620 mafic volcanic rocks (MgO > 6 wt %, except for Oligocene and Miocene NMER mafic rocks

18  
19  
20 1621 and Afar axial-range series with MgO = 4–6 wt %): (a) Oligocene–Miocene mafic rocks from

21  
22  
23 1622 the rift-bounding plateaus; (b) Eocene–Quaternary mafic rocks in the SMER; (c) Oligocene–

24  
25  
26 1623 Quaternary mafic rocks in the NMER; (d) Pliocene–Quaternary mafic rocks from Afar.

27  
28  
29 1624 Element abundances of the primitive (upper) mantle (PUM) for normalization are from

30  
31  
32 1625 McDonough & Sun (1995). Data for mafic rocks from previous studies are shown for

33  
34  
35 1626 comparison: LT, HT1, and HT2 mafic rocks in the NW Ethiopian Plateau from Pik *et al.*

36  
37  
38 1627 (1998, 1999), Kieffer *et al.* (2004), Beccaluva *et al.* (2009), and Natali *et al.* (2011, 2016);

39  
40  
41 1628 HT1 and HT2 mafic rocks in the Yemen Plateau from Baker *et al.* (1996b); Wollega mafic

42  
43  
44 1629 rocks in the SW Plateau from Ayalew *et al.* (1999); Amaro and Gamo basalts in southern

45  
46  
47 1630 Ethiopia from Yemane *et al.* (1999) and George & Rogers (2002); Getra-Kele and Tosa-

48  
49  
50 1631 Sucha mafic rocks in the SMER from Yemane *et al.* (1999), George & Rogers (2002),

51  
52  
53 1632 Rooney (2010) and Shinjo *et al.* (2011); Miocene to Quaternary mafic rocks in the NMER

54  
55  
56 1633 (Nazret and Afar stratoid series) from Boccaletti *et al.* (1999), Furman *et al.* (2006a) and

57  
58  
59 1634 Ayalew *et al.* (2018); Quaternary mafic rocks in rift floor and magmatic segments along the

1  
2  
3  
4  
5  
6 1635 WFB from Wolde (1996), Boccaletti *et al.* (1999), Furman *et al.* (2006a), Rooney *et al.*  
7  
8  
9 1636 (2012b) and Ayalew *et al.* (2016); Afar mafic rocks (stratoid, Gulf basalt, axial range series)  
10  
11  
12 1637 from Deniel *et al.* (1994), Barrat *et al.* (1998, 2003), Daoud *et al.* (2010) and Alene *et al.*  
13  
14  
15 1638 (2017).  
16  
17  
18 1639  
19  
20  
21 1640 **Figure 6.** Sr-Nd-Pb isotope compositions of the Ethiopian mafic volcanic rocks (MgO > 6  
22  
23  
24 1641 wt %, except for Oligocene and Miocene NMER mafic rocks and Afar axial-range series with  
25  
26  
27 1642 MgO = 4–6 wt %): (a) Maychew HT1 and HT2 in comparison with the Oligocene–Miocene  
28  
29  
30 1643 flood basalts in the other regions of the Ethiopian and Yemen Plateaus and the shield  
31  
32  
33 1644 volcanoes on the plateaus (Baker *et al.*; 1996b ; Pik *et al.*, 1998, 1999; Ayalew *et al.*, 1999;  
34  
35  
36 1645 Kieffer *et al.*, 2004; Natali *et al.*, 2011, 2016; Rooney *et al.*, 2014a); (b) Miocene Getra-Kele  
37  
38  
39 1646 and Quaternary Tosa-Sucha mafic rocks in comparison with the existing data sets for these  
40  
41  
42 1647 rocks (George & Rogers, 2002; Rooney, 2010; Shinjo *et al.*, 2011), Eocene Amaro and Gamo  
43  
44  
45 1648 basalts (George & Rogers, 2002), and Miocene–Quaternary Turkana mafic rocks (Furman *et*  
46  
47  
48 1649 *al.*, 2004, 2006b). (c) Oligocene–Quaternary mafic rocks in the NMER in comparison with  
49  
50  
51 1650 the existing data sets for these rocks and adjacent regions (Furman *et al.* 2006a; Rooney *et al.*,  
52  
53  
54 1651 2012b; Ayalew *et al.*, 2016, 2018). (d) Afar stratoid series, Gulf basalts, and axial range  
55  
56  
57 1652 mafic rocks, in comparison with the existing data sets for these mafic rocks [shown by gray  
58  
59  
60

1  
2  
3  
4  
5  
6 1653 colored symbols with the same shapes as the samples from this study; data sources are Deniel  
7  
8  
9 1654 *et al.* (1994), Barrat *et al.* (1998, 2003), Daoud *et al.* (2010), Ayalew *et al.* (2016) and Alene  
10  
11  
12 1655 *et al.* (2017)]. In all plots, the compositions of seafloor basalts from the Red Sea (Dupré *et al.*,  
13  
14  
15 1656 1998; Volker *et al.*, 1993, 1997) and the Gulf of Aden (West Sheba Ridge; Schilling *et al.*,  
16  
17  
18 1657 1992) are shown for comparison (gray shaded fields). Literature data are normalized using  
19  
20  
21 1658 reference standard materials with the values obtained in this study. The mantle end-member  
22  
23  
24 1659 components of DMM, EM1, EM2, and HIMU are from Zindler & Hart (1986), and FOZO  
25  
26  
27 1660 from Stracke *et al.* (2005). The end-member components postulated for the sources of the  
28  
29  
30 1661 Ethiopian mafic volcanic rocks are also shown for reference [C1, C2, C3, C4, C4' and C5  
31  
32  
33 1662 from Meshesha & Shinjo (2008); PAL (Pan-African lithospheric material) from Rooney  
34  
35  
36 1663 (2017)].  
37  
38  
39 1664  
40  
41 1665 **Figure 7.** Latitudinal variations of  $(K/Nb)_N$ ,  $(La/Sm)_N$ ,  $(Sm/Yb)_N$ ,  $(^{87}Sr/^{86}Sr)_i$ ,  $(^{143}Nd/^{144}Nd)_i$   
42  
43  
44 1666 and  $(^{206}Pb/^{204}Pb)_i$  for mafic lavas in the MER and Afar. Subscript N denotes element  
45  
46  
47 1667 abundances of samples normalized to those of primitive mantle for K/Nb (Sun &  
48  
49  
50 1668 McDonough, 1989) and those of chondrite for La/Sm and Sm/Yb (Boynton, 1983). Large and  
51  
52  
53 1669 small symbols denote data obtained in this study and those from the literature, respectively.  
54  
55  
56 1670 Sources for literature data are the same as in Figs 2–6.  
57  
58 1671  
59  
60

1  
2  
3  
4  
5  
6 1672 **Figure 8.** Variation of MgO *versus* Ba/La and ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>i</sub> for Ethiopian volcanic rocks.

8  
9 1673 Sources of literature data are the same as in Figs 2–6. The range of Ba/La ratios for MORB

10  
11  
12 1674 and OIB is from Willbold & Stracke (2006), and the range of ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>i</sub> values for Pan-

13  
14  
15 1675 African crustal materials (0.710 or higher) is from Stewart & Rogers (2002) and Shinjo *et al.*

16  
17  
18 1676 (2011).

19  
20  
21 1677

22  
23  
24 1678 **Figure 9.** Latitudinal variations in mantle potential temperature ( $T_p$ ) estimated from primitive

25  
26  
27 1679 mafic rocks (MgO > 8.5 wt %) using the method of Putirka (2008): (a) Oligocene to Miocene

28  
29  
30 1680 magmatism in the rift-bounding plateaus; (b) Miocene to Quaternary magmatism in the MER.

31  
32  
33 1681 The literature data for mafic volcanic rocks used for calculation are from Gasparon *et al.*

34  
35  
36 1682 (1993), Deniel *et al.* (1994), Wolde (1996), Pik *et al.* (1998, 1999), Ayalew *et al.* (1999, 2016,

37  
38  
39 1683 2018), George & Rogers (2002), Barrat *et al.* (1998, 2003), Kieffer *et al.* (2004), Rooney *et*

40  
41  
42 1684 *al.* (2005, 2014b), Furman *et al.* (2006a), Beccaluva *et al.* (2009), Rooney (2010), Natali *et al.*

43  
44  
45 1685 (2011, 2016), Daoud *et al.* (2010), Shinjo *et al.* (2011), Alene *et al.* (2017), Tadesse *et al.*

46  
47  
48 1686 (2019); see Supplementary Data Table S4 [in which calculated compositions of primary

49  
50  
51 1687 magmas and the estimated  $T_p$  by the methods of Lee *et al.* (2009) and Herzberg & Asimow

52  
53  
54 1688 (2015) are also shown]. The  $T_p$  estimated by Rooney *et al.* (2012a) for the Oligocene Plateau

55  
56  
57 1689 mafic rocks and Miocene to Recent mafic rocks from the MER and Afar are shown for

1  
2  
3  
4  
5  
6 1690 comparison. The ambient mantle temperature of 1338 °C is from Cottrell & Kelley (2011),  
7  
8  
9 1691 which is used for estimation of excess mantle temperature ( $\Delta T_p$ ).

10  
11  
12 1692 **Figure 10.** Variation of  $(La/Sm)_N$  and  $(Dy/Yb)_N$  for Ethiopian mafic volcanic rocks ( $MgO >$   
13  
14  
15 1693 6 wt %, except for Oligocene–Miocene NMER rocks with  $MgO > 4$  wt %). Subscript N for  
16  
17  
18 1694 these ratios denotes normalization to abundances of these elements in chondrite (Boynton,  
19  
20  
21 1695 1983). Trajectories of melt composition with various extents of melting under spinel and  
22  
23  
24 1696 garnet stability conditions are calculated using non-modal batch partial melting (Shaw, 1970)  
25  
26  
27 1697 with the following variables: (1) primitive mantle of McDonough & Sun (1995) as the  
28  
29  
30 1698 magma source; (2) source mineral modes under spinel and garnet stability conditions from  
31  
32  
33 1699 Robinson *et al.* (1998) and Fram *et al.* (1998), respectively; (3) partition coefficients  
34  
35  
36 1700 compiled by Kelemen *et al.* (2003). The extent of melting is shown as dots on the curves (1 to  
37  
38  
39 1701 20% in 1% increments), and the melts formed under the same melting extents in garnet and  
40  
41  
42 1702 spinel stability conditions are connected by broken lines.

43  
44  
45 1703

46  
47 1704 **Figure 11.** Variation of  $(La/Sm)_N$  and the score of principal component 1 (PC1) for Pb-  
48  
49  
50 1705 isotope correlation for Ethiopian mafic volcanic rocks ( $MgO > 6$  wt %). The subscript N for  
51  
52  
53 1706  $La/Sm$  denotes chondrite normalization (Boynton, 1983). PC1 is calculated for the  
54  
55  
56 1707  $^{206}Pb/^{204}Pb$ - $^{207}Pb/^{204}Pb$ - $^{208}Pb/^{204}Pb$  correlation (Supplementary Data Fig. S18), and regarded  
57  
58  
59 1708 as a proxy of the contribution from the mantle end-member component C2 of Meshesha &  
60



1  
2  
3  
4  
5  
6 1709 Shinjo (2008; see Figs 6 and 13). The negative correlation of  $(La/Sm)_N$  with the score of PC1  
7  
8  
9 1710 suggests that sampling of melts from isotopically distinct end-member components is not a  
10  
11  
12 1711 random process, rather it occurs systematically as a function of pressure and temperature (i.e.,  
13  
14  
15 1712 melting degree). Fusible and isotopically enriched C2 would have been sampled  
16  
17  
18 1713 preferentially by small-degree partial melts formed at deeper levels in the mantle, and more  
19  
20  
21 1714 refractory sources (C1 and C5) are dominant in melts formed by larger extent of melting at  
22  
23  
24 1715 shallower depths.  
25

26  
27 1716

28  
29 1717 **Figure 12.** (a) Schematic model for the generation of Oligocene flood basalts [modified after  
30  
31  
32 1718 Beccaluva *et al.* (2009) and Natali *et al.* (2016) with data for Maychew mafic rocks from this  
33  
34  
35 1719 study]. The Afar mantle plume impinged on the base of lithosphere. The isothermal contours  
36  
37  
38 1720 are estimated from thermobarometric calculations in this study, and essentially consistent  
39  
40  
41 1721 with those by Natali *et al.* (2016). The Maychew HT2 mafic rocks yield the estimate of  
42  
43  
44 1722 highest pressure and temperature condition of melting among the Oligocene flood basalts,  
45  
46  
47 1723 and place constraints on the mantle potential temperature of the plume core ( $T_p > 1500$  °C).  
48  
49  
50 1724 The Maychew HT2 rocks have a greater contribution from the C4 or C4' end-member  
51  
52  
53 1725 components of Meshesha & Shinjo (2008), suggesting that this end-member component may  
54  
55  
56 1726 have been distributed as streaks or blobs within the plume in the Oligocene. (b) Schematic  
57  
58  
59 1727 model for the generation of magmas in the MER from Oligocene to Recent times. Along-rift  
60

1  
2  
3  
4  
5  
6 1728 variation in crustal thickness is from Dugda *et al.* (2005). The asthenospheric mantle beneath  
7  
8  
9 1729 the MER includes fusible streaks or blobs [C2 and C3 end-member components of Meshesha  
10  
11  
12 1730 & Shinjo (2008)] in matrix of a refractory component [C5 of Meshesha & Shinjo (2008)].  
13  
14  
15 1731 Deep melting in the region with thicker crust (SMER and off-rift of CMER) preferentially  
16  
17  
18 1732 samples melts from the C2 or C3 domains. Shallow melting in the region with thinner crust  
19  
20  
21 1733 (NMER and Afar) samples melt from a refractory domain (C5). See text for a full discussion.  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

Table 1. Isotopic data for mafic volcanic rocks from Maychew in NW Plateau, Getra-Kele and Tosa-Sucha in SMER, NMER, and Afar

Sample	Latitude	Longitude	*Age (Ma)	<sup>87</sup> Sr/ <sup>86</sup> Sr	<sup>143</sup> Nd/ <sup>142</sup> Nd	<sup>206</sup> Pb/ <sup>204</sup> Pb	<sup>207</sup> Pb/ <sup>204</sup> Pb	<sup>208</sup> Pb/ <sup>204</sup> Pb	( <sup>87</sup> Sr/ <sup>86</sup> Sr) <sub>c</sub>	( <sup>143</sup> Nd/ <sup>142</sup> Nd) <sub>c</sub>	ε <sub>Nd</sub>	( <sup>206</sup> Pb/ <sup>204</sup> Pb) <sub>c</sub>	( <sup>207</sup> Pb/ <sup>204</sup> Pb) <sub>c</sub>	( <sup>208</sup> Pb/ <sup>204</sup> Pb) <sub>c</sub>
Maychew (NW Plateau)														
HT2 basalt														
MH12A	12°47'N	39°35'E	30	0.703610	0.512869	19.378	15.640	39.512	0.703584	0.512847	4.86	19.255	15.635	39.334
MH12B	12°47'N	39°35'E	30	0.703662	0.512851	19.344	15.652	39.555	0.703607	0.512830	4.52	19.261	15.648	39.413
MH11B	12°47'N	39°35'E	30	0.703797	0.512912	18.319	15.568	38.610	0.703784	0.512885	5.60	18.222	15.563	38.504
MH14	12°47'N	39°35'E	30	0.703879	0.512984	18.812	15.564	38.552	0.703761	0.512958	7.01	18.689	15.558	38.418
MH15	12°47'N	39°35'E	30	0.703855	0.512964	19.034	15.593	38.929	0.703814	0.512938	6.63	18.947	15.589	38.826
TR3V23	12°50'N	39°34'E	30	0.703535	0.512912	19.257	15.614	39.256	0.703472	0.512891	5.71	19.148	15.609	39.102
MA1905	12°52'N	39°33'E	<b>28.3</b>	0.703878	0.512927	18.776	15.560	38.149	0.703831	0.512902	5.92	18.681	15.556	38.055
MA1907	12°52'N	39°33'E	30	0.703918	0.512930	18.939	15.570	38.452	0.703850	0.512905	5.98	18.795	15.563	38.285
BK01	12°46'N	39°31'E	<b>27.8</b>	0.703674	0.512867	19.299	15.640	39.443	0.703602	0.512846	4.84	19.216	15.637	39.311
BK02	12°46'N	39°31'E	30	0.703678	0.512856	19.270	15.643	39.416	0.703635	0.512834	4.60	19.204	15.640	39.285
TR1V3	12°46'N	39°31'E	29	0.703577	0.512916	19.379	15.655	39.608	0.703549	0.512896	5.80	19.259	15.650	39.444
TR1V38	12°46'N	39°31'E	29	0.703554	0.512973	18.795	15.558	38.514	0.703528	0.512947	6.81	18.726	15.554	38.414
BK07	12°50'N	39°30'E	29	0.704273	0.512937	18.844	15.568	38.546	0.704266	0.512912	6.12	18.747	15.564	38.432
TS06	12°52'N	39°30'E	29	0.703979	0.512942	19.045	15.592	38.986	0.703956	0.512915	6.19	18.929	15.586	38.848
HT1 basalt														
MA06A	12°50'N	39°34'E	<b>28.0</b>	0.705073	0.512816	18.502	15.550	38.509	0.705017	0.512791	3.73	18.445	15.547	38.428
MA08	12°50'N	39°34'E	28	0.704591	0.512900	18.618	15.552	38.367	0.704554	0.512875	5.38	18.557	15.549	38.294
MA01	12°50'N	39°34'E	28	0.703512	0.512914	18.887	15.555	38.895	0.703476	0.512889	5.62	18.784	15.550	38.772
MA02A	12°50'N	39°34'E	28	0.703715	0.512931	18.947	15.563	38.958	0.703700	0.512907	5.97	18.841	15.558	38.830
MA1810c	12°52'N	39°33'E	29	0.704209	0.512943	18.593	15.554	38.465	0.704170	0.512918	6.24	18.533	15.551	38.388
MA1810a	12°52'N	39°33'E	29	0.704488	0.512898	18.538	15.548	38.416	0.704426	0.512873	5.35	18.472	15.545	38.340
A3	12°52'N	39°33'E	29	0.703594	0.512917	18.533	15.550	38.527	0.703538	0.512891	5.71	18.433	15.546	38.414
A5	12°52'N	39°33'E	<b>27.9</b>	0.704091	0.512964	18.906	15.576	38.660	0.704069	0.512938	6.64	18.823	15.572	38.568
A2	12°52'N	39°33'E	28	–	–	18.602	15.554	38.211	–	–	–	18.522	15.550	38.124
MA1815	12°52'N	39°33'E	28	0.704100	0.512949	18.597	15.554	38.202	0.704055	0.512923	6.32	18.506	15.550	38.104
I2S3	12°52'N	39°33'E	28	0.703541	0.512832	18.938	15.560	38.941	0.703474	0.512807	4.03	18.846	15.555	38.848
BK10	12°46'N	39°31'E	30	0.703721	0.512922	18.600	15.553	38.343	0.703699	0.512896	5.80	18.511	15.549	38.240
BK06	12°50'N	39°30'E	29	0.704690	0.512911	–	–	–	0.704656	0.512886	5.61	–	–	–
TS03	12°52'N	39°30'E	30	0.704204	0.512985	–	–	–	0.704166	0.512959	7.05	–	–	–

1																
2																
3	TS12	12°52'N	39°30'E	28	0.703803	0.512905	18.403	15.541	38.033	0.703762	0.512880	5.47	18.334	15.537	37.963	
4	TS13	12°52'N	39°30'E	28	0.704159	0.512922	18.638	15.556	38.150	0.704079	0.512897	5.81	18.560	15.552	38.076	
5	TS16	12°52'N	39°30'E	28	0.704933	0.512826	18.532	15.545	38.456	0.704875	0.512801	3.92	18.472	15.543	38.380	
6	B2	12°52'N	39°30'E	28	0.703566	0.512917	18.825	15.555	38.805	0.703529	0.512893	5.69	18.724	15.551	38.682	
7	TS36	12°52'N	39°30'E	28	0.703878	0.512894	18.415	15.558	38.235	0.703836	0.512868	5.22	18.353	15.555	38.164	
8	TS41	12°52'N	39°30'E	28	0.703813	0.512953	18.931	15.572	38.640	0.703769	0.512926	6.34	18.841	15.568	38.546	
9	TS44	12°52'N	39°30'E	28	0.704065	0.512915	19.157	15.584	38.677	0.704027	0.512888	5.61	19.067	15.580	38.588	
10	TS45	12°52'N	39°30'E	28	0.703766	0.512929	19.039	15.573	38.748	0.703736	0.512902	5.88	18.938	15.569	38.642	
11	TS46	12°52'N	39°30'E	28	0.703994	0.513003	19.045	15.570	38.746	0.703894	0.512976	7.32	18.963	15.566	38.649	
12	TS35	12°52'N	39°30'E	28	0.704244	0.512866	18.867	15.568	38.393	0.704161	0.512841	4.69	18.779	15.564	38.308	
13	TS39	12°52'N	39°30'E	28	0.704065	0.512864	18.597	15.560	38.154	0.704039	0.512838	4.62	18.528	15.557	38.082	
14	TS40	12°52'N	39°30'E	28	0.703956	0.512883	18.809	15.565	38.544	0.703898	0.512857	5.01	18.726	15.561	38.456	
15	TS42	12°52'N	39°30'E	28	0.703828	0.512933	–	–	–	0.703771	0.512906	5.95	–	–	–	
16	<hr/>															
17	Getra-Kele (SMER)															
18	TD-1815	5°00'30"N	37°45'56"E	11.0	–	–	19.604	15.632	39.385	–	–	–	19.554	15.630	39.320	
19	TD-1816A	5°01'11"N	37°44'47"E	11	0.702969	0.512895	19.662	15.632	39.422	0.702950	0.512887	5.14	19.603	15.629	39.342	
20	TD-1816B	5°01'11"N	37°44'47"E	11	–	–	19.660	15.632	39.420	–	–	–	19.600	15.629	39.340	
21	TD-1817	5°42'56"N	37°42'56"E	11.3	0.703012	0.512901	19.793	15.681	39.601	0.702998	0.512891	5.22	19.752	15.679	39.543	
22	TD-1825	5°50'32"N	37°54'04"E	10.8	0.703075	0.512881	19.553	15.639	39.339	0.703055	0.512872	4.84	19.515	15.637	39.287	
23	TD-1826A	5°50'32"N	37°54'04"E	16.4	0.703061	0.512879	19.677	15.646	39.422	0.703032	0.512868	4.89	19.613	15.643	39.330	
24	TD-1826B	5°50'32"N	37°54'04"E	16.4	0.703062	0.512882	19.700	15.652	39.458	0.703032	0.512871	4.96	19.632	15.648	39.361	
25	TD-1833	5°37'58"N	37°37'26"E	12.2	0.703401	0.512797	19.081	15.630	39.088	0.703378	0.512788	3.23	19.036	15.628	39.021	
26	<hr/>															
27	Tosa-Sucha (SMER)															
28	TD-1836	5°59'32"N	37°32'23"E	0.58	0.703415	0.512858	19.029	15.609	39.041	0.703414	0.512857	4.29	19.027	15.609	39.037	
29	TD-1837A	5°59'37"N	37°32'21"E	0.56	0.703299	0.512878	19.250	15.625	39.225	0.703297	0.512878	4.69	19.249	15.625	39.221	
30	TD-1838	5°58'17"N	37°35'29"E	0.56	0.703317	0.512867	19.142	15.622	39.148	0.703315	0.512867	4.47	19.140	15.622	39.143	
31	TD-1839	5°58'06"N	37°36'00"E	0.57	0.703376	0.512851	19.103	15.618	39.123	0.703374	0.512850	4.16	19.101	15.618	39.119	
32	TD-1841	5°58'04"N	37°39'12"E	1.2	0.703200	0.512826	19.933	15.660	39.728	0.703198	0.512826	3.69	19.927	15.659	39.721	
33	TD-1842	5°57'53"N	37°39'19"E	1.26	0.703360	0.512867	19.523	15.638	39.412	0.703358	0.512866	4.48	19.519	15.638	39.403	
34	<hr/>															
35	NMER															
36	Quaternary															
37	DBDH-4	9°08'58"N	39°57'14"E	0.20	0.703949	0.512857	18.757	15.597	38.814	0.703949	0.512857	4.27	18.757	15.597	38.814	
38	DBAG-115	9°08'22"N	39°56'14"E	0.24	0.703839	0.512893	18.783	15.595	38.915	0.703839	0.512893	4.98	18.782	15.595	38.914	
39	TG-31	9°08'06"N	39°56'18"E	0.25	0.704536	0.512807	18.698	15.592	38.774	0.704536	0.512807	3.30	18.698	15.592	38.773	

## Afar Stratoid/Nazret series/Bofa/Bishoftu

DBAG-74	9°58'35"N	40°33'59"E	<b>6.54</b>	0.703880	0.512873	18.588	15.576	38.732	0.703872	0.512868	4.64	18.577	15.575	38.712
DBZ-34	9°55'52"N	40°16'10"E	<i>3.0</i>	0.703528	0.512924	19.121	15.582	39.041	0.703524	0.512921	5.60	19.113	15.582	39.028
DBAG-77	9°58'23"N	40°11'36"E	<b>2.95</b>	0.703630	0.512915	18.647	15.574	38.762	0.703627	0.512912	5.43	18.640	15.574	38.753
DBAG-72A	9°56'26"N	40°04'24"E	<b>4.20</b>	0.703906	0.512861	18.508	15.569	38.706	0.703902	0.512857	4.38	18.500	15.569	38.695
DBAG-73	9°58'26"N	40°05'45"E	<i>4.2</i>	0.703994	0.512854	18.548	15.595	38.794	0.703991	0.512850	4.25	18.539	15.595	38.782
TG-51	9°02'27"N	40°23'32"E	<b>4.95</b>	0.704326	0.512823	18.631	15.585	38.890	0.704325	0.512819	3.65	18.626	15.585	38.883
TG-54	9°07'19"N	40°27'26"E	<b>5.53</b>	0.704457	0.512793	19.090	15.641	39.302	0.704454	0.512788	3.07	19.085	15.641	39.295
DBAG-63	9°45'20"N	40°01'51"E	<b>5.05</b>	0.703860	0.512843	18.546	15.572	38.715	0.703855	0.512839	4.04	18.534	15.572	38.700
MM-560	9°05'45"N	40°01'01"E	<i>2.7</i>	0.703960	0.512866	18.685	15.594	38.715	0.703957	0.512864	4.47	18.678	15.594	38.707
MM-534	9°01'16"N	39°33'00"E	<i>2.7</i>	0.704004	0.512779	18.452	15.586	38.540	0.704001	0.512777	2.78	18.446	15.586	38.532
MM-559B	9°01'26"N	39°33'13"E	<b>2.68</b>	0.704378	0.512799	18.446	15.546	38.572	0.704376	0.512797	3.16	18.441	15.546	38.566
TG-14	9°00'38"N	39°44'39"E	<i>2.7</i>	0.704249	0.512834	18.848	15.608	38.890	0.704248	0.512832	3.84	18.842	15.608	38.883

## Tarmaber Megezez Formation

DBZ-8	9°50'21"N	39°50'51"E	<b>14.7</b>	0.703844	0.512844	18.546	15.591	38.570	0.703827	0.512832	4.16	18.509	15.589	38.524
DH-429	9°33'21"N	39°51'40"E	<b>19.9</b>	0.706270	0.512559	17.859	15.563	38.837	0.706236	0.512542	-1.38	17.832	15.562	38.789
DH-438	9°32'51"N	39°53'33"E	<i>20</i>	0.703806	0.512864	18.681	15.597	38.715	0.703773	0.512848	4.59	18.625	15.594	38.645
TG-24B	9°15'07"N	39°42'53"E	<i>10</i>	0.704913	0.512757	18.472	15.593	38.784	0.704877	0.512749	2.42	18.451	15.592	38.755
TG-27C	9°09'44"N	39°43'14"E	<i>10</i>	0.704144	0.512818	18.928	15.611	39.022	0.704139	0.512810	3.60	18.908	15.610	38.995
TG-50	9°01'12"N	40°21'53"E	<i>10</i>	0.704451	0.512744	17.959	15.555	38.268	0.704431	0.512735	2.15	17.944	15.554	38.249

## Alage basalt

DBZ-22	9°52'51"N	39°48'55"E	<b>26.7</b>	0.705188	0.512581	17.909	15.589	38.723	0.705134	0.512559	-0.88	17.877	15.587	38.664
DBZ-30	9°57'57"N	39°51'54"E	<b>24.6</b>	0.706864	0.512588	18.624	15.636	39.486	0.706827	0.512570	-0.71	18.556	15.633	39.379

## Afar

## Stratoid Series

DHA-16	12°20'26"N	41°09'57"E	<b>1.18</b>	0.703763	0.512912	18.395	15.551	38.389	0.703762	0.512911	5.35	18.391	15.551	38.385
DHA-13	12°04'51"N	41°15'09"E	<b>1.25</b>	0.703810	0.512856	–	–	–	0.703808	0.512855	4.26	–	–	–
DHA-12	12°02'42"N	41°15'38"E	<i>1.3</i>	0.703701	0.512905	18.562	15.572	38.709	0.703700	0.512904	5.22	18.559	15.572	38.706
DHA-11	11°59'56"N	41°17'25"E	<i>1.3</i>	0.703827	0.512905	18.537	15.565	38.669	0.703826	0.512904	5.22	18.535	15.565	38.666
DHA-10	11°58'17"N	41°18'08"E	<b>1.32</b>	0.703745	0.512906	18.569	15.573	38.740	0.703739	0.512905	5.24	18.565	15.573	38.735
DHA-4	11°57'46"N	41°22'59"E	<b>1.65</b>	0.703843	0.512890	18.743	15.587	38.967	0.703841	0.512889	4.93	18.738	15.587	38.960
DHA-6A	11°55'09"N	41°33'49"E	<b>1.35</b>	0.703667	0.512894	18.614	15.566	38.803	0.703664	0.512893	5.00	18.609	15.566	38.797
DHA-31	11°53'27"N	41°38'02"E	<b>1.66</b>	0.703489	0.512923	18.669	15.566	38.820	0.703485	0.512922	5.57	18.664	15.566	38.813
DHA-34	11°53'24"N	41°39'18"E	<b>1.85</b>	0.703503	0.512911	18.989	15.566	39.034	0.703501	0.512909	5.34	18.982	15.566	39.024

1															
2															
3	DHA-36A	11°53'26"N	41°42'56"E	<b>2.87</b>	0.703510	0.512933	18.995	15.566	39.031	0.703506	0.512931	5.78	18.984	15.565	39.017
4	DHA-9	11°50'51"N	41°41'11"E	<b>1.54</b>	0.703656	0.512887	18.711	15.568	38.840	0.703652	0.512886	4.87	18.706	15.568	38.833
5	DHA-20	11°42'04"N	40°56'10"E	<b>1.53</b>	0.704100	0.512872	18.342	15.573	38.715	0.704099	0.512871	4.58	18.339	15.573	38.710
6	DHA-24	11°36'01"N	40°56'01"E	<b>2.00</b>	0.703573	0.512911	18.990	15.568	39.058	0.703569	0.512909	5.34	18.982	15.568	39.048
7	DHA-26	11°26'59"N	40°45'10"E	<b>2.77</b>	0.703280	0.512982	18.540	15.512	38.523	0.703279	0.512979	6.73	18.532	15.512	38.514
8	DHA-29	11°25'20"N	40°40'34"E	<b>4.06</b>	0.703582	0.512887	18.599	15.573	38.720	0.703580	0.512883	4.88	18.590	15.573	38.708
9	DHA-30	11°25'29"N	40°38'23"E	<b>2.95</b>	0.703503	0.512928	18.434	15.561	38.631	0.703496	0.512925	5.68	18.425	15.561	38.619
10	DHA-40	11°22'07"N	40°43'57"E	<b>3.02</b>	0.703326	0.512957	18.551	15.515	38.539	0.703319	0.512954	6.24	18.540	15.514	38.526
11	DHA-41	11°12'53"N	40°44'27"E	<b>2.57</b>	0.703261	0.512992	18.528	15.506	38.495	0.703259	0.512989	6.92	18.519	15.506	38.486
12	DHA-45	10°43'33"N	40°40'59"E	<b>4.50</b>	0.703556	0.512951	18.640	15.558	38.780	0.703548	0.512947	6.14	18.625	15.557	38.760
13	DHA-46	10°32'05"N	40°43'49"E	<i>4.5</i>	0.703625	0.512914	18.478	15.547	38.699	0.703613	0.512910	5.42	18.465	15.546	38.682
14															
15	Gulf basalt														
16	DHA-18	11°37'56"N	41°24'32"E	<b>0.79</b>	0.703441	0.512956	18.512	15.560	38.659	0.703440	0.512955	6.21	18.510	15.560	38.657
17	DHA-17	11°40'04"N	41°22'40"E	<i>0.79</i>	0.703460	0.512921	18.502	15.557	38.648	0.703459	0.512920	5.53	18.501	15.557	38.646
18	Axial Range series														
19	DHA-43	11°02'08"N	41°11'08"E	<i>0.12</i>	0.703482	0.512929	–	–	–	0.703482	0.512929	5.68	–	–	–
20	DHA-39	11°46'27"N	41°00'22"E	<i>0.12</i>	0.703608	0.512897	18.505	15.569	38.657	0.703608	0.512897	5.05	18.505	15.569	38.657
21	DHA-15	12°11'42"N	40°44'51"E	<i>0.12</i>	0.703750	0.512884	18.363	15.552	38.353	0.703750	0.512884	4.80	18.363	15.552	38.353
22	DHA-3	11°55'30"N	41°12'32"E	<i>0.12</i>	0.703683	0.512871	18.432	15.570	38.596	0.703683	0.512871	4.55	18.432	15.570	38.596
23	DHA-2	11°54'37"N	41°10'46"E	<i>0.12</i>	0.703752	0.512896	–	–	–	0.703752	0.512896	5.03	–	–	–
24	DHA-1	11°48'21"N	41°00'58"E	<b>0.12</b>	0.703600	0.512924	18.506	15.567	38.653	0.703600	0.512924	5.58	18.506	15.567	38.653

\*Age: bold, dated by K-Ar in this study; italic, inferred from K-Ar ages for the other samples from the adjacent locality or literatures.

Internal precisions ( $2\sigma_m$ ) of  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  are better than 0.000010 and 0.000009, respectively.

The values are reported relative to the following values for the reference standard materials:

NIST SRM 987  $^{87}\text{Sr}/^{86}\text{Sr}=0.710240$ , La Jolla  $^{143}\text{Nd}/^{144}\text{Nd}=0.511860$ , and NIST SRM 981  $^{206}\text{Pb}/^{204}\text{Pb} = 16.9424$ ,  $^{207}\text{Pb}/^{204}\text{Pb}=15.5003$  and  $^{208}\text{Pb}/^{204}\text{Pb} = 36.7266$ , respectively.

Initial isotope ratios of Sr, Nd, and Pb are denoted as ( $^{87}\text{Sr}/^{86}\text{Sr}$ ), ( $^{143}\text{Nd}/^{144}\text{Nd}$ ),  $\epsilon_{\text{Nd}}$ , ( $^{206}\text{Pb}/^{204}\text{Pb}$ ), ( $^{207}\text{Pb}/^{204}\text{Pb}$ ), and ( $^{208}\text{Pb}/^{204}\text{Pb}$ ), respectively.

Table 2. Results of K-Ar dating for mafic volcanic rocks from NW plateau (Maychew), SMER (Getra-Kele and Tosa-Sucha), NMER and Afar

Sample	Location (section)	[K] (wt%)	[ <sup>36</sup> Ar] (10 <sup>-9</sup> ccSTP·g <sup>-1</sup> )	[ <sup>40</sup> Ar <sub>rad</sub> ] (10 <sup>-9</sup> ccSTP·g <sup>-1</sup> )	<sup>40</sup> Ar/ <sup>36</sup> Ar	age (Ma)	air fraction (%)
NW plateau (Maychew)							
BK01	12°46' N	1.26	2.905 ± 0.049	1359 ± 23	757.7 ± 3.7	27.55 ± 0.72	38.8
(HT2, Seq. 1)	39°31' E		2.198 ± 0.047	1379 ± 23	761.5 ± 3.8	27.95 ± 0.72	38.5
	(Bekura)				mean	<b>27.8 ± 0.6</b>	
			2.45 ± 0.03	1330 ± 23	839 ± 6	27.0 ± 0.7	35.3
			2.45 ± 0.04	1355 ± 51	849 ± 19	27.5 ± 1.2	34.9
					mean	<b>27.2 ± 0.7</b>	
MA1905	12°52' N	1.16	0.729 ± 0.012	1279 ± 20	1952 ± 11	28.16 ± 0.71	14.4
(HT2, Seq. 2)	39°33' E		0.639 ± 0.011	1295 ± 21	2186 ± 22	28.52 ± 0.73	12.8
	(Aysi)				mean	<b>28.3 ± 0.5</b>	
			0.694 ± 0.018	1245 ± 36	2090 ± 24	27.4 ± 1.0	14.2
			0.694 ± 0.017	1270 ± 39	2126 ± 32	28.0 ± 1.0	13.9
					mean	<b>27.7 ± 0.7</b>	
MA1809	12°50' N	1.12	0.701 ± 0.011	1230 ± 18	1939 ± 7	28.06 ± 0.70	14.4
(HT1, Seq. 2)	39°34' E		0.608 ± 0.010	1237 ± 19	2185 ± 15	28.21 ± 0.71	12.7
	(Bolonta)				mean	<b>28.1 ± 0.5</b>	
			0.890 ± 0.017	1219 ± 28	1665 ± 18	27.8 ± 0.9	17.8
			0.828 ± 0.021	1219 ± 42	1768 ± 36	27.8 ± 1.1	16.7
					mean	<b>27.8 ± 0.7</b>	
A5	12°52' N	1.20	0.560 ± 0.009	1318 ± 20	2464 ± 18	28.05 ± 0.70	11.2
(HT1, Seq. 3)	39°33' E		0.539 ± 0.009	1307 ± 21	2531 ± 16	27.82 ± 0.70	10.9
	(Aysi)				mean	<b>27.9 ± 0.5</b>	
			1.91 ± 0.02	1266 ± 16	959 ± 4	26.9 ± 0.6	30.9
			1.85 ± 0.02	1316 ± 37	1008 ± 18	28.0 ± 1.0	29.4
					mean	<b>27.5 ± 0.6</b>	
BK06	12°50' N	1.15	1.380 ± 0.024	1018 ± 16	1010 ± 15	22.64 ± 0.57	28.6
(HT1, Seq. 3)	39°30' E		1.445 ± 0.023	1029 ± 16	987.4 ± 4.5	22.88 ± 0.58	29.4
	(Debri)				mean	<b>22.8 ± 0.4</b>	
			1.24 ± 0.02	1017 ± 20	1116 ± 12	22.6 ± 0.6	26.5
			1.24 ± 0.03	1014 ± 34	1134 ± 18	22.6 ± 0.9	26.1
					mean	<b>22.6 ± 0.6</b>	

1								
2								
3	MA06A	12°50' N	1.69	0.973 ± 0.016	1862 ± 30	2121 ± 13	28.15 ± 0.71	13.4
4								
5	(HT1, Seq. 4)	39°34' E		1.271 ± 0.021	1843 ± 30	1697 ± 10	27.86 ± 0.72	17.0
6								
7		(Bolonta)				mean	<b>28.0 ± 0.5</b>	
8								
9				1.67 ± 0.07	1705 ± 80	1317 ± 21	25.8 ± 1.3	22.5
10								
11				1.67 ± 0.02	1701 ± 19	1315 ± 6	25.7 ± 0.6	22.5
12						mean	<b>25.8 ± 0.8</b>	
13								
14	TS12	12°52' N	1.02	0.628 ± 0.010	1023 ± 16	1817 ± 10	25.64 ± 0.65	15.4
15								
16	(HT1, Seq. 4)	39°30' E		0.668 ± 0.011	1031 ± 17	1749 ± 11	25.82 ± 0.66	16.1
17						mean	<b>25.7 ± 0.5</b>	
18		(Tsibet)						
19				0.615 ± 0.015	1005 ± 37	1930 ± 44	25.2 ± 1.1	15.3
20								
21	TS35	12°52' N	1.05	1.594 ± 0.041	890 ± 22	849.5 ± 2.2	21.68 ± 0.63	34.7
22								
23	(HT1, Seq. 5)	39°30' E		1.634 ± 0.041	877 ± 22	828.7 ± 2.2	21.39 ± 0.62	35.5
24								
25		(Tsibet)		1.665 ± 0.042	887 ± 22	824.6 ± 1.8	21.62 ± 0.62	35.7
26						mean	<b>21.6 ± 0.2</b>	
27								
28	TS38	12°52' N	0.789	0.862 ± 0.014	879 ± 14	1267 ± 7	28.46 ± 0.72	22.5
29								
30	(HT1, Seq. 6)	39°30' E		0.791 ± 0.013	866 ± 14	1336 ± 7	28.05 ± 0.71	21.3
31						mean	<b>28.3 ± 0.6</b>	
32		(Tsibet)						
33				1.67 ± 0.05	866 ± 38	815 ± 18	28.0 ± 1.3	36.3
34								
35				1.67 ± 0.02	851 ± 35	806 ± 20	27.6 ± 1.3	36.7
36						mean	<b>27.8 ± 0.9</b>	
37								
38	TS43	12°52' N	0.370	1.004 ± 0.026	342.9 ± 8.7	635.1 ± 1.4	23.70 ± 0.70	46.4
39								
40	(HT1, Seq. 6)	39°30' E		0.998 ± 0.026	345.1 ± 8.8	639.3 ± 1.9	23.85 ± 0.70	46.1
41								
42		(Tsibet)		0.961 ± 0.025	344.3 ± 8.9	649.6 ± 1.2	23.80 ± 0.70	45.3
43								
44				0.976 ± 0.025	345.2 ± 8.8	645.4 ± 1.5	23.86 ± 0.70	45.5
45						mean	<b>23.8 ± 0.1</b>	
46								
47	TS45	12°52' N	0.497	1.119 ± 0.018	405.4 ± 6.6	645.5 ± 2.9	20.88 ± 0.54	45.0
48								
49	(HT1, Seq. 6)	39°30' E		1.153 ± 0.019	412.5 ± 6.8	641.5 ± 2.9	21.24 ± 0.55	45.3
50						mean	<b>21.1 ± 0.4</b>	
51		(Tsibet)						
52				0.953 ± 0.015	410 ± 12	727 ± 10	21.7 ± 0.7	40.7
53								
54	SMER							
55	Getra-Kele							
56								
57	TD-1815	5°00'30" N	1.95	0.489 ± 0.013	837 ± 10	2008 ± 41	11.01 ± 0.25	14.7
58								
59		37°45'56" E		0.418 ± 0.008	827 ± 9	2278 ± 14	10.88 ± 0.24	13.1
60								
				0.429 ± 0.006	836 ± 9	2247 ± 14	11.00 ± 0.25	13.2





1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

						mean	1.26 ± 0.02	
<hr/>								
NMER								
Quaternary basalt								
DBDH-4	9°08'58" N	0.704	0.834 ± 0.014	5.4 ± 0.5		302.4 ± 0.6	0.20 ± 0.02	97.9
	39°57'14" E		0.705 ± 0.012	5.3 ± 0.4		303.6 ± 0.6	0.20 ± 0.02	97.5
						mean	0.20 ± 0.01	
<hr/>								
DBAG-115	9°08'22" N	0.540	1.176 ± 0.019	5.0 ± 0.5		300.2 ± 0.4	0.24 ± 0.03	98.6
	39°56'14" E		1.175 ± 0.019	5.3 ± 0.5		300.5 ± 0.4	0.25 ± 0.03	98.5
						mean	0.24 ± 0.02	
<hr/>								
Afar Stratoid/Nazret series/Bofa/Bishoftu								
DBAG-74	9°58'35" N	0.482	1.312 ± 0.022	123.3 ± 2.3		387.8±1.4	6.57 ± 0.35	75.9
	40°33'59" E		1.314 ± 0.021	122.0 ± 2.2		386.6±1.4	6.51 ± 0.34	76.1
						mean	6.54 ± 0.25	
<hr/>								
DBAG-77	9°58'23" N	0.432	1.580 ± 0.025	49.8 ± 1.0		327.5 ± 0.4	2.97 ± 0.16	90.4
	40°11'36" E		1.603 ± 0.025	49.2 ± 1.0		326.7 ± 0.5	2.93 ± 0.16	90.6
						mean	2.95 ± 0.11	
<hr/>								
DBAG-72A	9°56'26" N	0.347	0.902 ± 0.015	56.0 ± 1.1		357.8±0.7	4.16 ± 0.22	82.7
	40°04'24" E		0.603 ± 0.011	57.4 ± 1.0		386.7±1.3	4.25 ± 0.22	75.7
						mean	4.20 ± 0.16	
<hr/>								
TG-51	9°02'27" N	0.447	1.867 ± 0.032	83.1 ± 3.2		340.2±2.0	4.79 ± 0.30	87.0
	40°23'32" E		1.866 ± 0.031	88.5 ± 4.1		343.0±2.4	5.10 ± 0.35	86.3
						mean	4.95 ± 0.28	
<hr/>								
TG-54	9°07'19" N	0.606	1.012 ± 0.017	130.4 ± 2.3		420.7±1.7	5.53 ± 0.29	69.7
	40°27'26" E		1.246 ± 0.021	131.4 ± 2.4		398.9±1.6	5.57 ± 0.30	73.7
						mean	5.53 ± 0.21	
<hr/>								
DBAG-63	9°45'20" N	0.521	0.958 ± 0.016	101.3 ± 1.6		398.4±0.9	5.00 ± 0.26	73.7
	40°01'51" E		0.916 ± 0.015	103.1 ± 1.7		405.1±1.1	5.11 ± 0.27	72.4
						mean	5.05 ± 0.20	
<hr/>								
MM-559B	9°01'26" N	0.649	1.040 ± 0.017	66.9 ± 1.3		360.0 ± 0.8	2.65 ± 0.14	82.2
	39°33'13" E		0.823 ± 0.014	68.4 ± 1.1		375.9 ± 0.9	2.71 ± 0.14	78.1
						mean	2.68 ± 0.10	
<hr/>								
Tarmaber Megezez Formation								
DBZ-8	9°50'21" N	0.893	2.452 ± 0.039	510 ± 8		501.0±0.5	14.6 ± 0.8	58.7
	39°50'51" E		2.967 ± 0.047	513 ± 8		467.0±0.5	14.7 ± 0.8	63.1

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

						<b>mean</b>	<b>14.7 ± 0.5</b>	
DH-429	9°33'21" N	0.990	1.695 ± 0.027	766 ± 12		738.2±1.3	19.8 ± 1.0	39.6
	39°51'40" E		1.669 ± 0.027	770 ± 12		747.5±1.2	19.9 ± 1.0	39.1
						<b>mean</b>	<b>19.9 ± 0.7</b>	
<b>Alage basalt</b>								
DBZ-22	9°52'51" N	0.725	1.784 ± 0.029	760 ± 12		713.7±2.8	26.8 ± 1.4	41.0
	39°48'55" E		1.824 ± 0.029	757 ± 12		701.5±2.4	26.6 ± 1.4	41.7
						<b>mean</b>	<b>26.7 ± 1.0</b>	
DBZ-30	9°57'57" N	0.958	1.475 ± 0.024	927 ± 15		910.1±6.5	24.7 ± 1.3	32.0
	39°51'54" E		1.645 ± 0.026	921 ± 15		844.2±5.9	24.6 ± 1.3	34.6
						<b>mean</b>	<b>24.6 ± 0.9</b>	
<b>Afar</b>								
<b>Stratoid series</b>								
DHA-16	12°20'26" N	0.979	2.13 ± 0.03	47.2 ± 1.5		318.2 ± 0.7	1.24 ± 0.07	93.0
	41°09'57" E		2.15 ± 0.03	42.8 ± 1.2		315.9 ± 0.5	1.13 ± 0.06	93.7
						<b>mean</b>	<b>1.18 ± 0.08</b>	
DHA-13	12°04'51" N	0.698	2.27 ± 0.04	34.0 ± 2.9		310.9 ± 1.3	1.25 ± 0.12	95.2
	41°15'09" E		2.19 ± 0.03	34.1 ± 2.7		311.6 ± 1.3	1.26 ± 0.12	95.0
						<b>mean</b>	<b>1.25 ± 0.09</b>	
DHA-10	11°58'17" N	1.52	1.51 ± 0.02	80.1 ± 1.8		349.0 ± 1.0	1.36 ± 0.07	84.8
	41°18'08" E		1.41 ± 0.02	75.6 ± 1.8		349.3 ± 1.1	1.28 ± 0.07	84.7
						<b>mean</b>	<b>1.32 ± 0.06</b>	
DHA-4	11°57'46" N	0.556	2.18 ± 0.04	35.2 ± 2.2		312.1 ± 1.0	1.63 ± 0.13	94.8
	41°22'59" E		2.12 ± 0.03	36.2 ± 2.1		313.1 ± 1.0	1.68 ± 0.13	94.5
						<b>mean</b>	<b>1.65 ± 0.09</b>	
DHA-6A	11°55'09" N	0.828	2.21 ± 0.04	42.8 ± 4.1		315.3 ± 2.0	1.33 ± 0.14	93.9
	41°33'49" E		2.36 ± 0.04	43.9 ± 4.4		314.6 ± 2.0	1.37 ± 0.15	94.1
						<b>mean</b>	<b>1.35 ± 0.10</b>	
DHA-31	11°53'27" N	1.04	3.37 ± 0.05	67.2 ± 3.8		315.9 ± 1.2	1.67 ± 0.13	93.7
	41°38'02" E		3.32 ± 0.05	66.8 ± 1.2		316.1 ± 1.2	1.66 ± 0.12	93.6
						<b>mean</b>	<b>1.66 ± 0.09</b>	
DHA-34	11°53'24" N	0.626	1.47 ± 0.02	46.2 ± 1.9		327.3 ± 1.3	1.90 ± 0.12	90.4
	41°39'18" E		1.37 ± 0.02	43.9 ± 1.6		328.1 ± 1.2	1.81 ± 0.11	90.2

1								
2								
3								
4						<b>mean</b>	<b>1.85 ± 0.10</b>	
5	DHA-36A	11°53'26" N	0.463	1.87 ± 0.03	52.1 ± 1.3	333.9 ± 0.6	2.90 ± 0.16	91.4
6								
7		41°42'56" E		1.89 ± 0.03	50.9 ± 1.3	322.9 ± 0.6	2.83 ± 0.16	91.7
8								
9						<b>mean</b>	<b>2.87 ± 0.12</b>	
10	DHA-9	11°50'51" N	0.823	1.39 ± 0.02	49.2 ± 1.1	331.2 ± 0.7	1.54 ± 0.08	89.4
11								
12		41°41'11" E		1.44 ± 0.02	49.2 ± 1.1	333.0 ± 0.7	1.54 ± 0.09	89.7
13								
14						<b>mean</b>	<b>1.54 ± 0.06</b>	
15	DHA-20	11°42'04" N	0.694	1.05 ± 0.02	42.0 ± 1.2	336.1 ± 1.0	1.56 ± 0.09	88.1
16								
17		40°56'10" E		1.09 ± 0.02	40.3 ± 1.1	333.0 ± 1.1	1.49 ± 0.09	88.9
18								
19						<b>mean</b>	<b>1.53 ± 0.07</b>	
20	DHA-24	11°36'01" N	0.695	2.78 ± 0.05	53.5 ± 2.6	315.2 ± 0.9	1.98 ± 0.14	93.9
21								
22		40°56'01" E		2.86 ± 0.04	54.6 ± 2.6	315.1 ± 0.9	2.02 ± 0.14	93.9
23								
24						<b>mean</b>	<b>2.00 ± 0.10</b>	
25	DHA-26	11°26'59" N	0.182	1.21 ± 0.02	20.8 ± 1.2	313.1 ± 1.0	2.94 ± 0.22	94.5
26								
27		40°45'10" E		1.17 ± 0.02	18.5 ± 1.1	311.8 ± 1.0	2.61 ± 0.22	94.9
28								
29						<b>mean</b>	<b>2.77 ± 0.22</b>	
30	DHA-29	11°25'20" N	0.273	1.89 ± 0.03	41.7 ± 1.9	318.0 ± 1.0	3.93 ± 0.27	93.1
31								
32		40°40'34" E		2.02 ± 0.03	44.3 ± 2.0	318.0 ± 1.0	4.18 ± 0.28	93.1
33								
34						<b>mean</b>	<b>4.06 ± 0.23</b>	
35	DHA-30	11°25'29" N	0.617	2.92 ± 0.05	71.2 ± 3.4	320.4 ± 1.2	2.97 ± 0.21	92.4
36								
37		40°38'23" E		2.86 ± 0.05	70.0 ± 1.2	320.5 ± 1.2	2.92 ± 0.20	92.4
38								
39						<b>mean</b>	<b>2.95 ± 0.15</b>	
40	DHA-40	11°22'07" N	0.539	2.33 ± 0.04	63.9 ± 2.7	323.4 ± 1.2	3.05 ± 0.20	91.5
41								
42		40°43'57" E		2.34 ± 0.04	62.6 ± 2.7	322.7 ± 1.2	2.99 ± 0.20	91.7
43								
44						<b>mean</b>	<b>3.02 ± 0.14</b>	
45	DHA-41	11°12'53" N	0.284	1.41 ± 0.02	29.0 ± 1.3	316.6 ± 0.9	2.63 ± 0.18	93.5
46								
47		40°44'27" E		1.44 ± 0.02	27.8 ± 1.3	315.2 ± 0.9	2.52 ± 0.17	93.9
48								
49						<b>mean</b>	<b>2.57 ± 0.14</b>	
50	DHA-45	10°43'33" N	0.532	1.84 ± 0.03	64.4 ± 1.9	330.9 ± 1.0	4.51 ± 0.26	89.5
51								
52		40°40'59" E		1.77 ± 0.03	64.3 ± 1.9	332.2 ± 1.0	4.50 ± 0.26	89.1
53								
54						<b>mean</b>	<b>4.50 ± 0.19</b>	
55	Gulf basalt							
56								
57	DHA-18	11°37'56" N	0.323	1.16 ± 0.02	8.9 ± 2.9	303.7 ± 2.5	0.71 ± 0.23	97.5
58								
59		41°24'32" E		1.10 ± 0.02	10.9 ± 2.0	305.9 ± 1.9	0.87 ± 0.17	96.8
60								

					<b>mean</b>	<b>0.79 ± 0.16</b>		
Axial Range series								
DHA-1	11°48'21" N	0.827	1.76 ± 0.03	4.7 ± 1.5	298.7 ± 0.9	0.15 ± 0.05	99.1	
	41°00'58" E		1.85 ± 0.03	2.7 ± 1.6	297.5 ± 0.9	0.09 ± 0.05	99.5	
					<b>mean</b>	<b>0.12 ± 0.05</b>		

<sup>40</sup>Ar<sub>rad</sub>, radiogenic component in <sup>40</sup>Ar

Values expressed in italic are obtained by the unspiked method.

For Peer Review

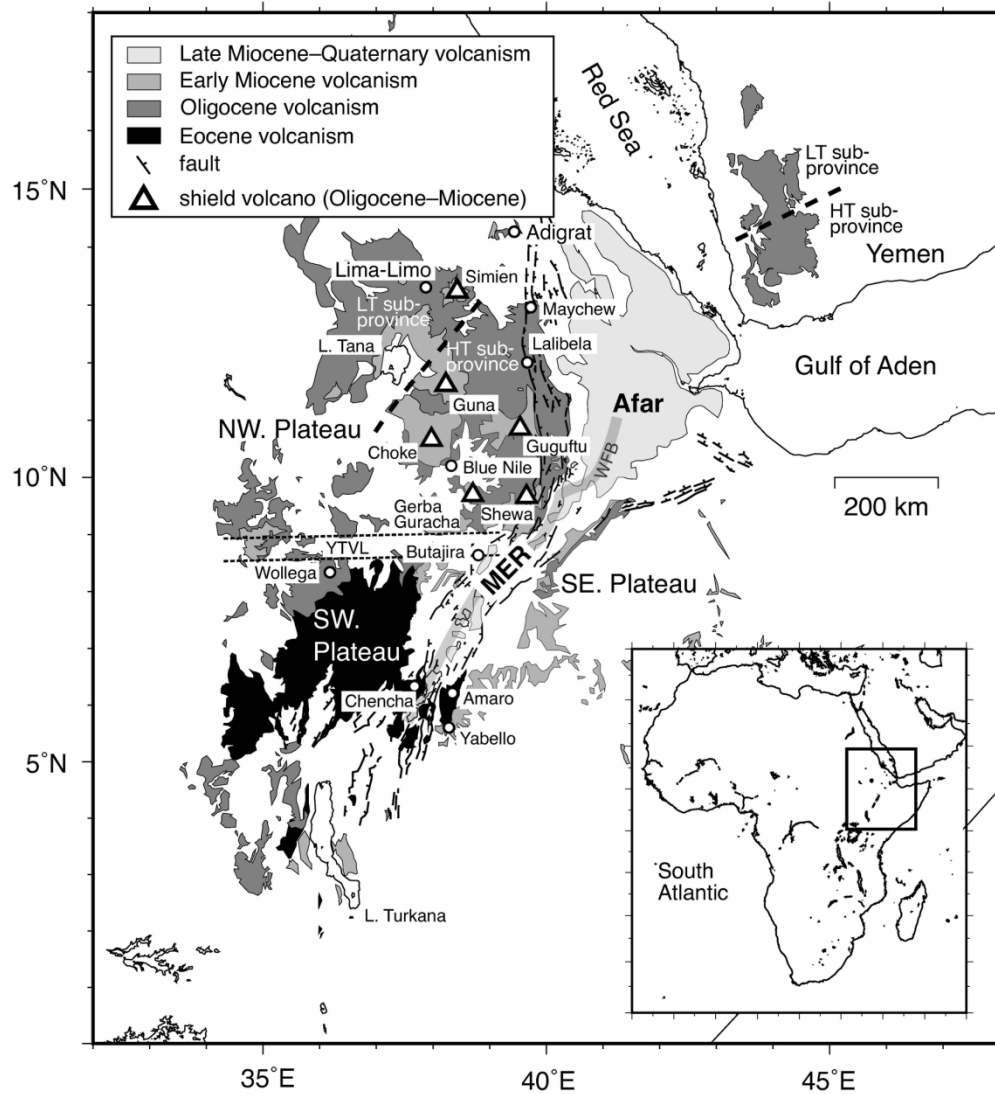


figure 1

163x178mm (300 x 300 DPI)

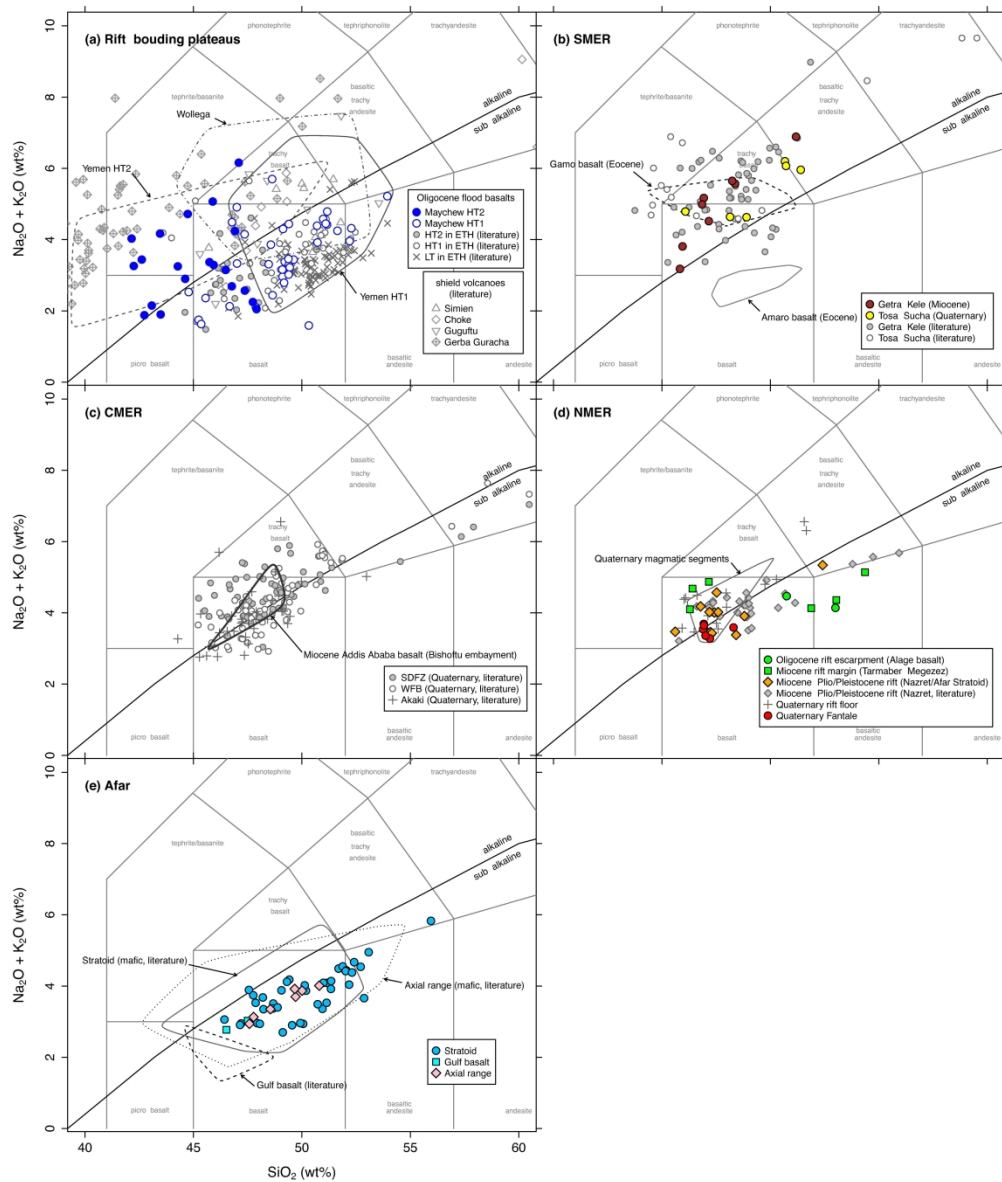


figure 2

300x352mm (300 x 300 DPI)

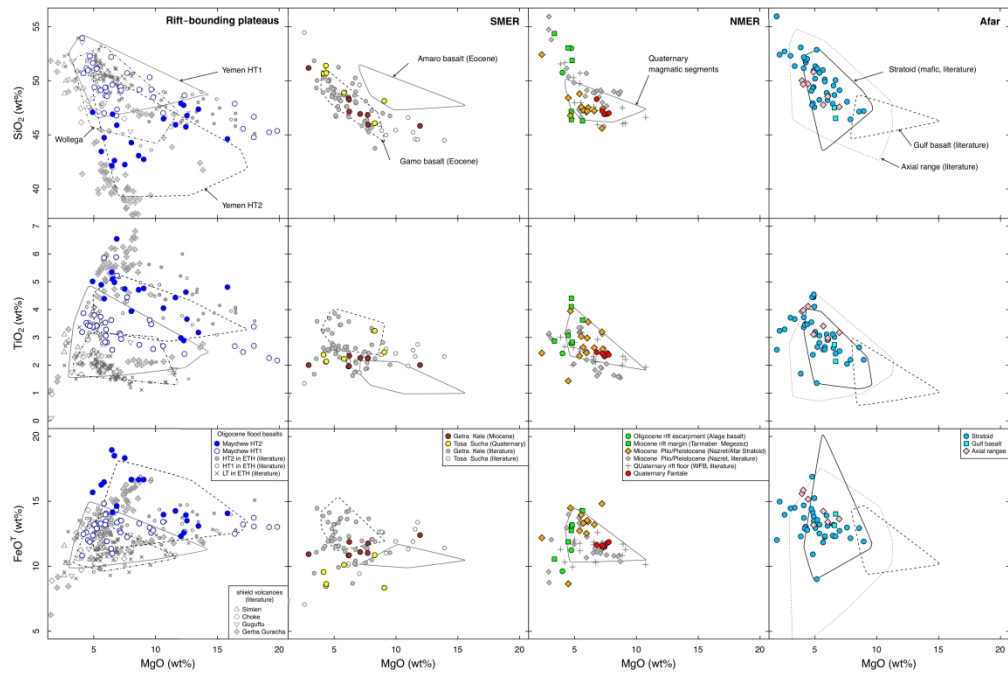


figure 3

451x299mm (300 x 300 DPI)





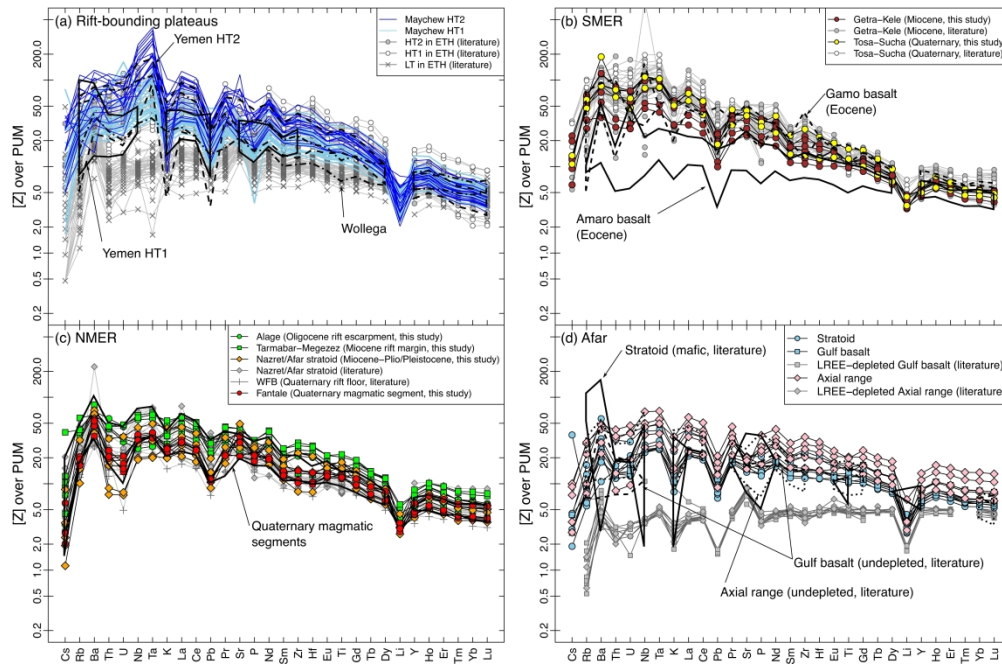


figure 5

447x293mm (300 x 300 DPI)

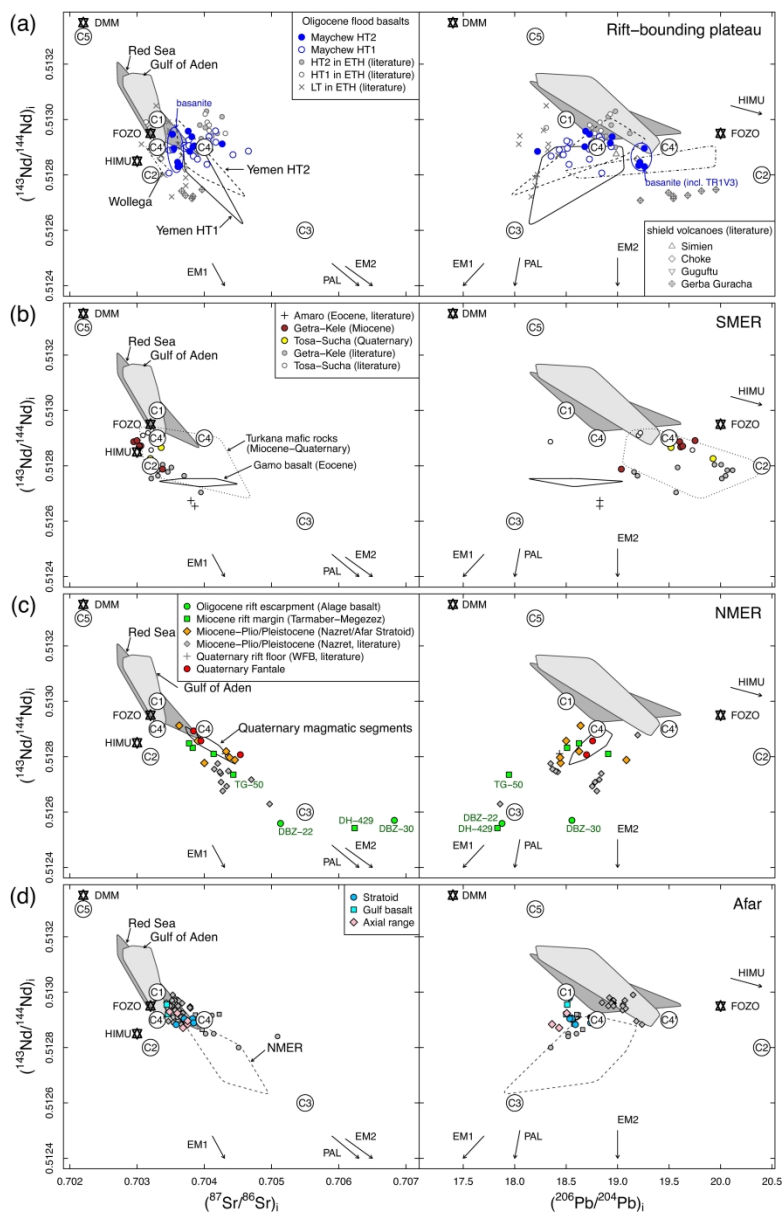


figure 6

290x451mm (300 x 300 DPI)

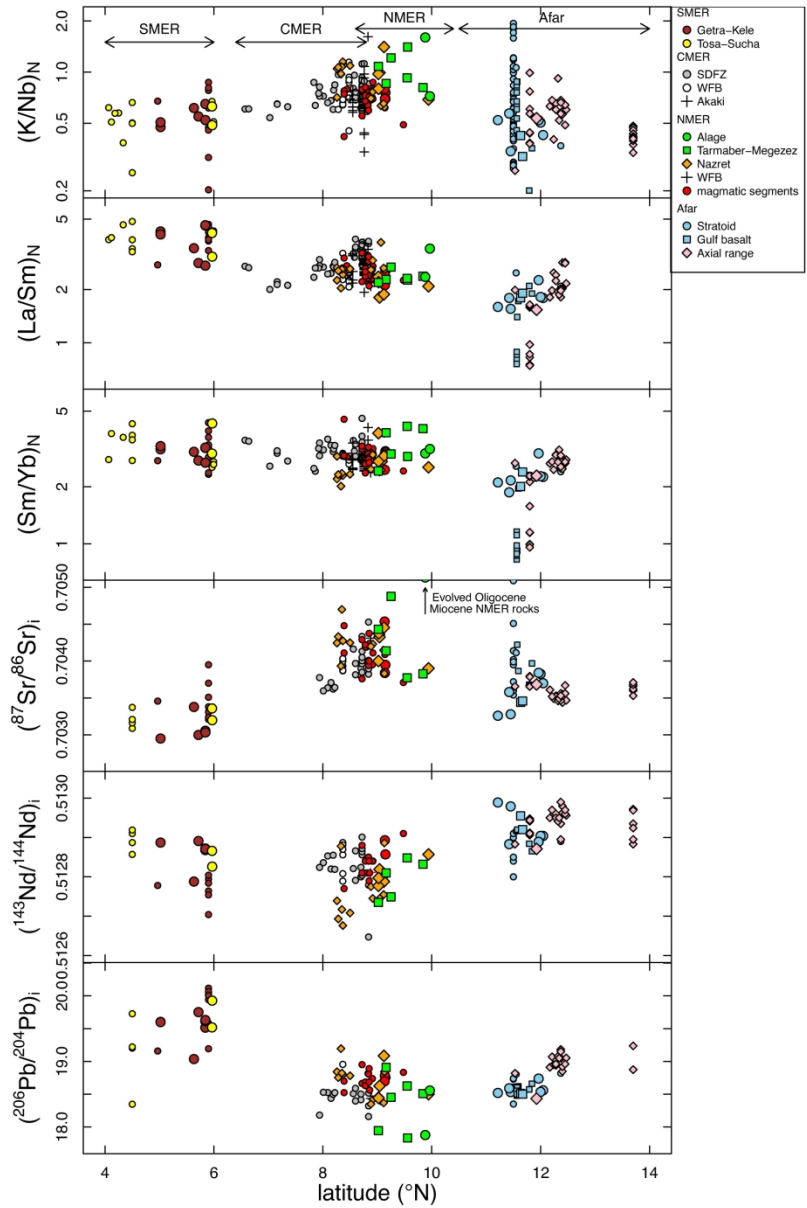


figure 7

197x298mm (300 x 300 DPI)

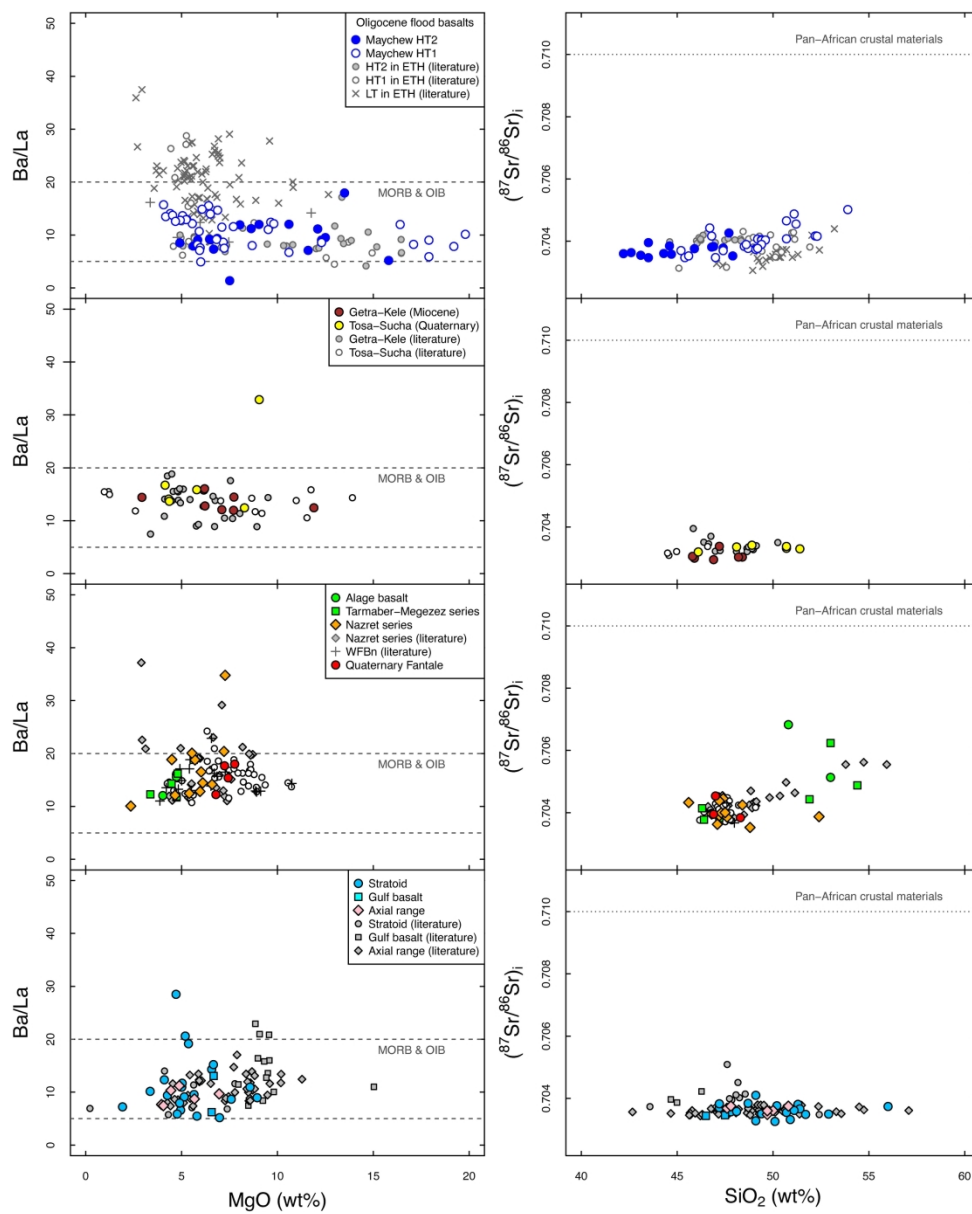


figure 8

241x299mm (300 x 300 DPI)

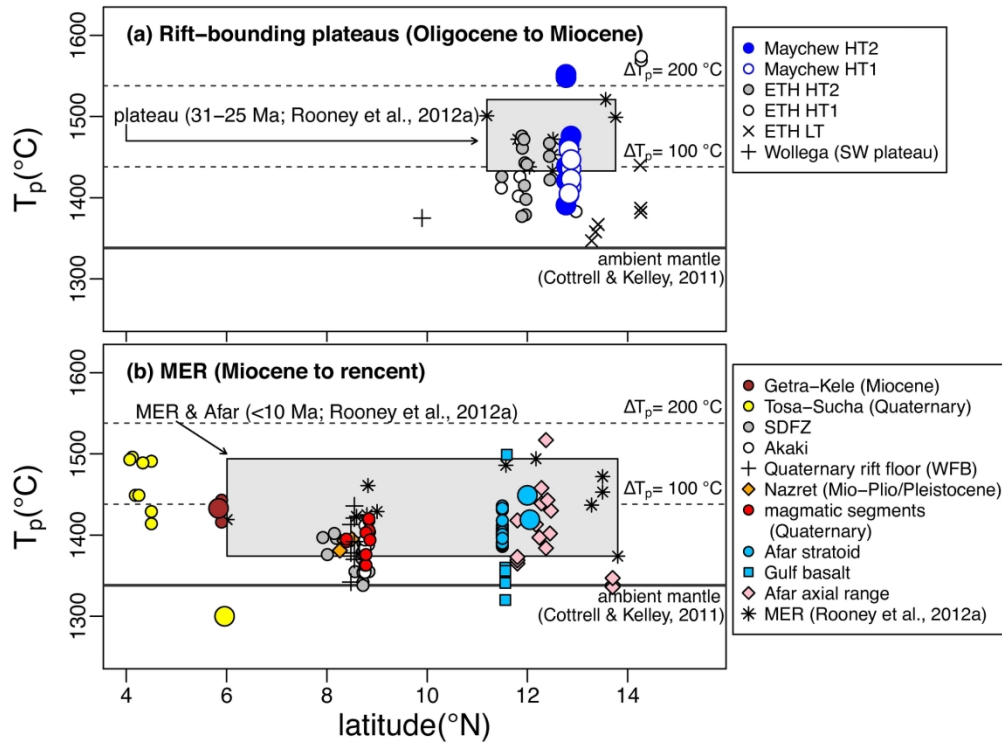


figure 9

195x144mm (300 x 300 DPI)

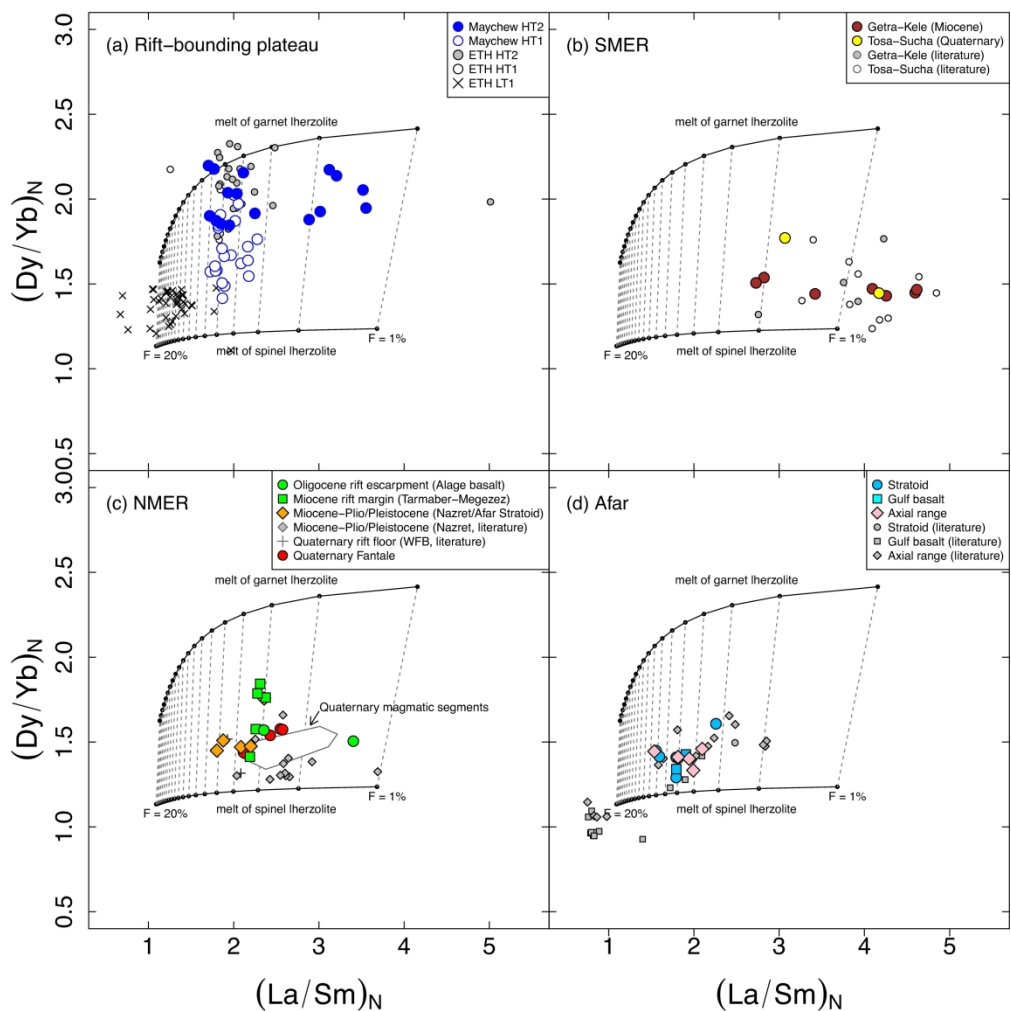


figure 10

298x298mm (300 x 300 DPI)

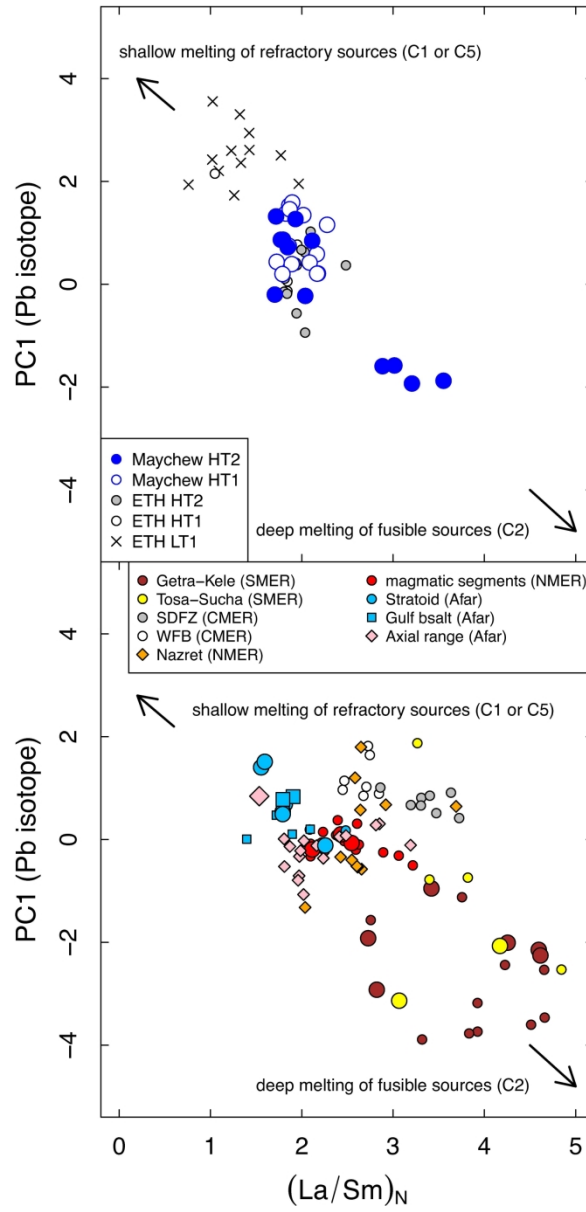
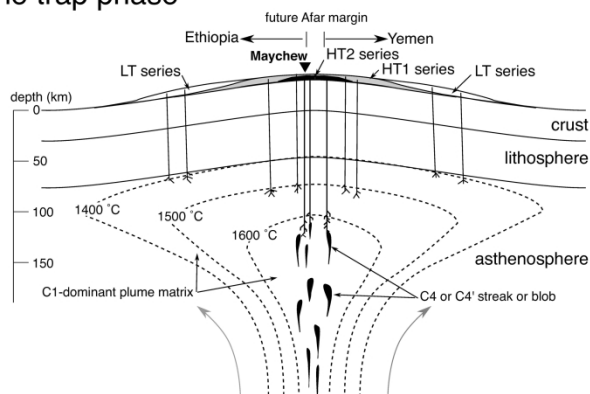


figure 11

143x296mm (300 x 300 DPI)



(a) Oligocene trap phase



(b) Oligocene-recent rift development

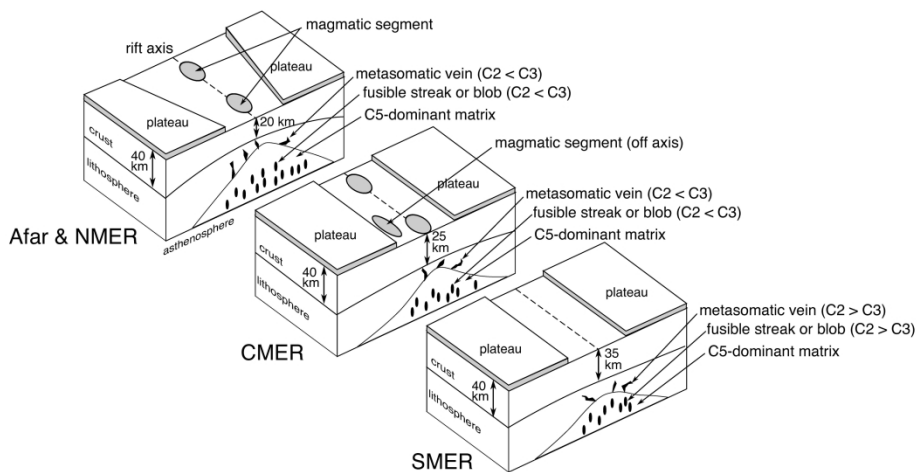


figure 12

328x324mm (300 x 300 DPI)