1 **Tephrostratigraphy of the Waki-Mille area of the Woranso-Mille**

2 **Paleoanthropological Research Project, Afar, Ethiopia**

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18 **Abstract**

19 Tephra geochemistry and ⁴⁰Ar/³⁹Ar geochronology are reported for the Waki-Mille area

20 in the northwestern part of the Woranso-Mille paleoanthropological project area in the

21 west central Afar region of Ethiopia. Previous studies documented dentognathic fossils

22 that are morphologically intermediate between *Australopithecus anamensis* and

23 *Australopithecus afarensis* and some that are attributed to *Australopithecus afarensis*.

Additional dentognathic remains from the study area were assigned to the newly identified species *Australopithecus deyiremeda*. These fossil hominin taxa were recovered from volcanic and sedimentary strata containing tuffs ranging in age from more than 3.77 million years ago (Ma) to less than 3.469 Ma. One of the tuffs was correlated based on geochemistry, feldspar mineralogy, and age to the Lokochot Tuff of the Omo-Turkana Basin of southern Ethiopia and Kenya. Variations in major and minor element abundances in volcanic glass demarcate ten geochemically distinct tuffs and tuff sequences, including three that are geochemically similar to widespread regional tuffs, specifically the Lomogol, Lokochot, and β -□Tulu Bor/Sidi Hakoma tuffs. A new $^{40}\text{Ar}/^{39}\text{Ar}$ age for the Waki Tuff, which is geochemically similar to the Lomogol Tuff, is 3.664 ± 0.016 Ma. Other tuffs in the Waki-Mille area are geochemically dissimilar to regional tuffs documented to date. Identification of tuffs based on character, stratigraphic position, and geochemistry refines local stratigraphic correlations and delineates the geographic distributions of precisely dated fossiliferous levels within the Waki-Mille area.

Keywords: tephrochemistry, $^{40}\text{Ar}/^{39}\text{Ar}$ dating, *Australopithecus*, Woranso-Mille, Afar, hominin

Introduction

This paper presents glass tephrochemical and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronologic data for volcanic tuffs of the Woranso-Mille paleoanthropological research area (WORMIL) in Ethiopia (Haile-Selassie et al., 2007; Haile-Selassie et al., 2010a, b). WORMIL is located on the western flank of the Afar Depression, between the Ida Ale and Gura Ale volcanic

centers and southwest of the Tendaho Graben where the eastern African Rift meets the on-land extensions of the boundary faults for the Red Sea and Gulf of Aden rifts (Wolfenden et al., 2004; Beyene and Abdelsalam, 2005; Acocella, 2010). WORMIL lies to the north of, and in some cases borders, paleoanthropological research areas of the Lower Awash Valley, including Hadar, Gona, Dikika, and Ledi-Geraru. It lies about 100 km to the north of the Middle Awash research area (Figs. 1A, B).

Thus far, paleontological and geological work has focused on the northwestern part of WORMIL (Fig. 1C), more than 25 km north of Hadar, Ledi-Geraru, and Gona, the nearest of the neighboring paleoanthropological field areas. There, exposures of Pliocene age volcanic and sedimentary strata in the watershed of the Mille River, near the confluence with the Waki River, have yielded numerous hominin fossils, particularly from the Am-Ado, Aralee Issie, Mesgid Dora, and Makah Mera collection areas.

Hominin fossils from these areas are radioisotopically dated to between ~3.6 million years ago (Ma) and ~3.8 Ma, a critical time period for testing hypotheses about the transition from *Australopithecus anamensis* to *Australopithecus afarensis* (Haile-Selassie et al., 2010b). *Au. anamensis* is known from sites in Kenya and Ethiopia and dated to between 4.2 Ma and 3.9 Ma (Leakey et al., 1995, 1998; White et al., 2006). These dates yield an apparent last appearance date of 3.9 Ma for *Au. anamensis*. The first appearance date of *Au. afarensis* appears to be around 3.7 Ma at Laetoli, Tanzania (Harrison, 2011), although it may have appeared slightly earlier (ca. 3.8 Ma) if the Belohdelie frontal belongs to *Au. afarensis* (Asfaw, 1987), or even much earlier if the Fejej fossils (4.18 – 4.0 Ma) are assigned to this species (Fleagle et al., 1991; Kappelman et al., 1996; but see Ward, 2014). The presence of *Au. anamensis*-like species at

WORMIL around 3.7 Ma probably indicates that the transition from *Au. anamensis* to *Au. afarensis* took place at about this time. Alternatively, the earliest *Au. afarensis* populations may have retained more *Au. anamensis*-like dentognathic features than later members of the species, although *Au. afarensis* is a direct descendant of *Au. anamensis* (Kimbel et al., 2006). The WORMIL hominins play a crucial role in terms of testing the hypothesis of whether a phyletic or cladogenic speciation event led to the origin of *Au. afarensis*. This is where a refined stratigraphic placement of the WORMIL hominins dated to between 3.6 Ma and 3.8 Ma becomes of paramount importance.

Other hominin-bearing localities of WORMIL include Korsi Dora (KSD-VP-1), 3.5 km southeast of the Waki-Mille confluence, where the earliest (~3.57 Ma) partial skeleton of an adult *Au. afarensis* was found (Haile-Selassie et al., 2010a). The recovered skeletal elements of this individual demonstrate that *Au. afarensis* had evolved more human-like postcranial anatomy as early as 3.6 Ma (Haile-Selassie et al., 2010a). A 3.4-3.3 Ma partial foot was recovered at another locality, Burtele (BRT-VP-2), 4.5 km east of Korsi Dora. In contrast to the contemporaneous *Au. afarensis*, the Burtele foot (BRT-VP-2/73) possesses an opposable big toe and demonstrates the presence of multiple early hominin locomotor adaptations during the middle Pliocene (Haile-Selassie et al., 2012). Recently, dentognathic remains from Burtele (BRT-VP-3) and Waytaleyta (WYT-VP-2), localities dated to between 3.5 Ma and 3.3 Ma, were assigned to a new species, *Australopithecus deyiremeda*, and described as a close relative of *Au. afarensis* (Haile-Selassie et al., 2015).

Radioisotopic ages for some of the volcanic rocks within the WORMIL study area have been published elsewhere (Deino et al., 2010; Haile-Selassie et al., 2010a, Haile-

Selassie et al., 2012). This report focuses on the tephrochemistry of interbedded volcanic tuffs at published fossil localities and across the broader area of exposure of the volcano-sedimentary succession. This exposure area, henceforth defined as the Waki-Mille area, extends from Kerare eastward to Burtele, and from the Guda Plateau southward to the Kerare-Korsi Dora-Burtele basalts (Fig.1C). In the immediate vicinity of the Waki-Mille confluence (WMC), volcanic tuffs form marker beds that extend across the confluence to Mesgid Dora (MSD) and Makah Mera (MKM) (Fig. 2), tying together relatively short, incomplete sections (Fig. 3) into a well-dated composite section more than 32 m thick (Deino et al., 2010) (Fig. 4C). The WMC-MSD-MKM composite section overlies the Mille basalt with a whole rock $^{40}\text{Ar}/^{39}\text{Ar}$ age of 3.82 ± 0.18 Ma and extends upward to include the Kilaytoli Tuff (KT), a correlate of the Lokochot Tuff in the Omo-Turkana Basin of Kenya and southern Ethiopia (Deino et al., 2010), as well as more recently recognized tuffs above it (Haile-Selassie et al., 2010a; Saylor et al., 2016).

Tephrochemical data are reported for the tuffs in the WMC-MSD-MKM composite section and partially correlative sections across the Waki-Mille area. All together, tuffs included in this study are from positions immediately below the Mille Tuff sequence (MLT), the oldest of several named tuffs in the area, up to and above the Kerare-Korsi Dora-Burtele basalts. They are constrained to the interval 3.82 ± 0.18 Ma (the age of the Mille basalt) to less than 3.570 ± 0.014 Ma (Deino et al., 2010). A new $^{40}\text{Ar}/^{39}\text{Ar}$ age is reported for the Waki Tuff (WT), positioned approximately midway in the WMC-MSD-MKM composite section.

Glass geochemical data and $^{40}\text{Ar}/^{39}\text{Ar}$ ages for tuffs of the Waki-Mille area are used to test previously published correlations among fossil collection areas and to extend

those correlations to new areas (Deino et al., 2010; Haile-Selassie et al., 2010a; Saylor et al., 2016). The geochemical data are further used to assess whether tuffs in the Waki-Mille area extend into the Lower and Middle Awash Valley, or further across larger portions of the eastern African Rift System, including deep sea cores (e.g., Sarna-Wojcicki et al., 1985; Brown et al., 1992; deMenocal and Brown, 1999; WoldeGabriel et al., 2013). Correlations of tephra based on geochemistry, physical character, and relative and absolute age map the geographic distributions of fallout from discrete eruptive events and closely associated sequences of events, and thus identify stratigraphic horizons that are, essentially, isochronous, and that demarcate the land surface at specific points in time. As such, these correlations have implications for the distribution of time recorded by the sedimentary succession in the Waki-Mille area and for the age of fossil layers there. They provide insight into the paleogeography and connectivity of sedimentary basins around the Awash Valley, as well as into the history of volcanic eruptions and the source and distribution of volcanic ejecta.

Methods

Tephra samples were collected and analyzed from overlapping sections of the WMC-MSD-MKM composite section (Figs. 2, 3, and 4C) and also from Aralee Issie, where many of the same tuffs, recognized on the basis of stratigraphic position and physical similarity, are present in a single continuous section (ARI-5 in Fig. 4B). The KT is the highest tuff present at Aralee Issie, but at Mesgid Dora and Makah Mera, as well as at Am-Ado and Korsi Dora (Fig. 4), the sections include tuffs above KT (Haile-Selassie et al., 2010a,b; Saylor et al., 2016). The highest stratigraphic level examined in this study

is above basalt flows that overlie KT, specifically, above the Kerare-Korsi Dora-Burtele basalts along the southern margin of the Waki-Mille area and above similarly positioned basalt on the escarpment to the Guda Plateau on the northern margin of the area (Fig.1C).

Electron probe micro-analysis of glass shard geochemistry

Samples were prepared as in Deino et al. (2010) except that for some samples glass separates were obtained by picking, crushing, and sieving >10 lapilli-size fragments of pumice rather than crushing and sieving a subsample of whole rock. Elemental analyses were conducted using wavelength dispersive spectroscopy at the University of Wisconsin, Madison, using a Cameca SX-51 electron probe micro-analyzer and Probe for EPMA software (Donovan et al., 2015). Analyses were conducted on four occasions; on each occasion polished grain mounts were carbon coated at the same time as standards in order to compute H₂O as measured O minus halogen-corrected stoichiometric O (Nash, 1992). Element concentrations were converted to oxides computing all Fe as Fe₂O₃. Major and minor elements were measured with standards Kilbourne Olivine for Mg, Minas Gerais rutile for Ti, Monash andesine for Ca, synthetic manganese olivine for Mn, Rockport fayalite, Okahandja hematite, synthetic Fe₃O₄ or Harvard Fe₂O₃ for Fe, USMN chlor-apatite for Cl, and Lipari Obsidian for Si, Al, O, Na, K. During the initial sessions, matrix effects produced negative abundances for most F analyses, which were excluded from oxide totals, though going forward, a multi-point background model fixes the problem. Al, Mg, Na, and Si were measured on TAP, K, Ca, Cl, on PET, Ti, Mn, and Fe on LIF, and O on PC1 (60Å 2d pseudocrystal).

Bombardment by the electron beam during analysis of hydrous glass causes time-dependent loss of Na and K, and corresponding “grow in” of Al, Si, and O. Although these

analytical effects can be reduced by using a defocused beam with a large spot size (e.g. 20 μm) and a low beam current (e.g. 2 nA) (Morgan and London, 1996, 2005), the small width ($<5 \mu\text{m}$) of bubble walls in many of the studied tephras prevented application of this approach. Instead, all analyses were conducted using a focused beam (0 μm), an accelerating voltage of 15 KeV, a beam current of 10 nA, with on-peak and off-peak count times of 20 s. For each analysis point, a time series of data was acquired for the first subset of elements, Na, K, O, and Si, which allows them to be corrected for ion migration by fitting curves to time-dependent intensity (TDI) data, extrapolating to time=0.

Abundance data for Na_2O , O, and K_2O were corrected using a quadratic, self-calibrated fit to TDI data. A linear self-calibrated fit was applied to SiO_2 . Although Al_2O_3 also is subject to beam-induced migration, the crystal-spectrometer set-up disallowed generation of TDI data for both SiO_2 and Al_2O_3 ; SiO_2 was prioritized because of its greater abundance. Na_2O and K_2O have the largest beam effects with TDI-adjusted values ~15% to ~50% of corrected values for Na_2O and ~40% to ~70% for K_2O . The adjustments for O and SiO_2 are about 1 wt. % to 2 wt. % downward. Measurement of a water-saturated synthetic experimental glass standard (Corning Haplogranite glass; Morgan and London, 2005) as an unknown yielded good agreement between the published value and TDI corrected value for SiO_2 (73.13 TDI wt. % versus 73.05 book wt. %). Na_2O was still too high by 8% (4.45 TDI wt. % versus 4.12 book wt. %) and K_2O was too low by 2% (4.336 TDI wt. % versus 4.43 book wt. %), but these abundances were not used for correlation. Al_2O_3 , which was not analyzed for TDI and therefore not corrected for beam-induced ion migration, was too high by 2% (12.056 measured wt. % versus 11.79 published wt. %). Al_2O_3 concentrations between 10 wt. % and 14 wt. %, as reported here for the Waki-Mille area tuffs, are likely too high by 0.2 wt. % to 0.24 wt. %, which is greater than 1 σ variation for some of the samples, but less

than the variation in reported Al_2O_3 values for individual, widely correlated eastern African tuffs, for which there has been no standardization of analytical methods.

After eliminating analyses with oxide totals $<98\%$ or $>102\%$, average oxide abundances were calculated for each sample and then normalized for differences in hydration. In order to compare Waki-Mille area tuffs with each other and with other eastern African tuffs (Table 1), normalized abundance data (Tables 2 and 3) were plotted on bivariate plots (Figures 5 & 6) and compared quantitatively using similarity coefficients (SC) (Borchardt et al., 1971, 1972). Clear outlier grains were not included in sample averages, but are listed separately in Table 3. These grains differ from the sample average by more than one standard deviation in multiple elements, and in three out of five cases are similar to a known stratigraphically lower tuff, and thus are possibly detrital in origin, reworked from below. Similarity coefficients (SC) were calculated using Fe_2O_3 , Al_2O_3 , TiO_2 , CaO , SiO_2 , MnO , and MgO excluding, on a case-by-case basis, oxides for which abundances are below detection limits.

$^{40}\text{Ar}/^{39}\text{Ar}$ dating

Phenocrysts of K-feldspar were extracted from tuffs using standard mineral separation procedures and irradiated for seven hours in the Cadmiun-Lined In-Core Irradiation Tube (CLICIT) facility of the Oregon State University Triga reactor (see Deino et al., 2010, for details of the dating procedure). The samples were distributed on two levels of aluminum disks irradiated as a single package, using sanidine of the Fish Canyon Tuff as a neutron flux monitor. The $^{40}\text{Ar}/^{39}\text{Ar}$ age calculations employ a reference age for the Fish Canyon Tuff of 28.198 ± 0.044 Ma (as reported in Kuiper et al., 2008, for the Steiger and Jäger, 1977, decay constants), Steiger and Jäger (1977) ^{40}K

decay constants, and a $^{40}\text{Ar}/^{36}\text{Ar}$ atmospheric ratio of 298.56 ± 0.31 (Lee et al., 2006). Previous dating of Waki-Mille area tuffs (Deino et al., 2010; Haile-Selassie et al., 2010a, 2012) employed a reference age of 28.201 ± 0.046 Ma, which is also from Kuiper et al. (2008), but calculated using the decay constants of Min et al. (2000). These decay constants have been substantially revised by Renne et al. (2010). Both the Min et al. (2000) and the Renne et al. (2010) decay constants are optimized to an intercomparison of $^{40}\text{Ar}/^{39}\text{Ar}$ to U/Pb ages, but the Kuiper et al. (2008) reference ages, and much of the work of one of the authors here, are based on an intercalibration to astronomical time. Consequently, we use the Steiger and Jäger (1977) decay constants and the reference age (28.198 ± 0.044 Ma) calculated for them. In practice, the differences are too small to observe for Cenozoic tuffs; ‘unknown’ sample ages calculated using either 28.198 ± 0.044 Ma or 28.201 ± 0.046 Ma as a reference and corresponding decay constants yield indistinguishable results.

Reactor-induced isotopic production ratios for this irradiation were: $(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 2.65 \pm 0.02 \times 10^{-4}$, $(^{38}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 1.96 \pm 0.08 \times 10^{-5}$, $(^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 6.95 \pm 0.09 \times 10^{-4}$, $(^{37}\text{Ar}/^{39}\text{Ar})_{\text{K}} = 2.24 \pm 0.16 \times 10^{-4}$, $(^{38}\text{Ar}/^{39}\text{Ar})_{\text{K}} = 1.220 \pm 0.003 \times 10^{-2}$, $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}} = 2.5 \pm 0.9 \times 10^{-4}$. Analyses proceeded by total fusion of individual phenocrysts with a focused CO_2 laser, with argon isotopes measured on a MAP-215 Noble gas mass spectrometer.

Eastern African tuffs between 4.0 Ma and 3.4 Ma

As a basis for comparison with Waki-Mille area tuffs, geochronologic and representative tephrochemical data were compiled for eastern African tuffs between 4.0 Ma and 3.4 Ma (Tables 1 and 2, Sarna-Wojcicki et al., 1985; Brown et al., 1992; Hart et

al., 1992; Haileab and Brown, 1993; Walter and Aronson, 1993; White et al., 1993; deMenocal and Brown, 1999; Renne et al., 1999; Gathogo and Brown, 2006; Wynn et al., 2006; Feakins et al., 2007; Campisano and Feibel, 2008; McDougall and Brown, 2008; Deino et al., 2010; Haile-Selassie et al., 2010a, 2012; McDougall et al., 2012; Woldegabriel et al., 2013). Included in the compilations are widespread tuffs of the Omo-Turkana Basin that also are recognized, on the basis of geochemistry and age, in deep-sea cores around the Horn of Africa and in paleoanthropological study areas of the Lower and Middle Awash Valley. Additional, more locally distributed tuffs, recognized only in the Awash Valley, are included in the compilations, but discussed separately.

Widespread Omo-Turkana Basin tuffs

Five Omo-Turkana Basin tuffs between 4.0 Ma to 3.4 Ma have been recognized in the Awash Valley and deep-sea cores. These include, in stratigraphic order from oldest to youngest, the Moiti, Wargolo, Lomogol, Lokochot, and β -Tulu Bor tuffs. As has been shown previously (McDougall and Brown, 2008; Brown et al., 2013) in compilations adjusting to a reference age 28.10 ± 0.04 Ma (from Spell and McDougall, 2003), $^{40}\text{Ar}/^{39}\text{Ar}$ ages for these tuffs and their correlates agree well between the Omo-Turkana Basin and the Awash Valley (Table 1). There is also good agreement between radioisotopic ages and the astronomically tuned model ages from deep-sea cores, though using 28.198 Ma (or 28.201 Ma) for the reference age (Kuiper et al., 2008), as is done here, yields adjusted $^{40}\text{Ar}/^{39}\text{Ar}$ ages for the β -Tulu Bor Tuff and its correlate, the Sidi Hakoma Tuff, that are statistically older than the model age (Table 1). The $^{40}\text{Ar}/^{39}\text{Ar}$ age for the β -Tulu Bor Tuff is considered a maximum, however. Tuff B-delta, part of the

Tuff B complex, which is also correlated with β -Tulu Bor, has an adjusted $^{40}\text{Ar}/^{39}\text{Ar}$ age that is in good agreement with the model age (Table 1). Of the widespread Omo-Turkana Basin tuffs, only the Lomogol Tuff has no previously published radioisotopic age.

Normalized oxide abundances of Omo-Turkana Basin tuffs and their correlates (Table 2) are indicated by open symbols in the bivariate plots of Figure 5. Moiti, Lokochot, and Lomogol glass shards have $\text{Al}_2\text{O}_3 < 11.5$ wt. % and $\text{Fe}_2\text{O}_3 > 2.5$ wt. % (Fig. 5A), $\text{CaO} < 0.4$ wt. % (Fig. 5B), and $\text{MnO} > 0.08$ wt. % (Fig. 5C). Although these tuffs cluster together on the bivariate plots they are distinguishable from each other based on age and composition. The ~3.96 Ma Moiti Tuff and the ~3.58 Ma Lokochot Tuff both have bimodal felsic glass compositions, each with a high Fe mode that is relatively enriched in Fe_2O_3 (> 3.5 wt. %) and depleted in Al_2O_3 (mostly <11 wt. %) compared to the corresponding low Fe mode (Fig. 5A). Although very similar, the Moiti and Lokochot tuffs may be distinguished geochemically by differences in CaO and TiO_2 abundance, especially in their high Fe modes. The ~3.62 Ma Lomogol Tuff has a unimodal glass composition that is similar to the high Fe mode of the Lokochot Tuff; it is distinguishable from the Lokochot and Moiti tuffs by the absence of a low Fe mode.

The ~3.80 Ma Wargolo Tuff has lower abundances of Fe_2O_3 (~2.5 wt. %), TiO_2 (<0.2 wt. %), and MnO (mostly <0.1 wt. %) than the Moiti, Lokochot, and Lomogol tuffs, but other oxides are similar. The Ikini Tuff, a proposed Wargolo-correlate in the Dikika area of the Lower Awash Valley (Wynn et al., 2006, 2008), has higher reported Al_2O_3 abundances (about 12.4 wt. %) than other examples of the Wargolo Tuff, or its correlates (about 11.4 wt. %). Other glass compositions of regional tuffs reported from Dikika (e.g.,

SHT/ β - Tulu Bor) have similar, comparatively elevated Al_2O_3 abundances (Table 2) that may be due to differences in analytical methods, possibly corrections for electron beam-induced ion mobility, standards, or procedures for calculating water content (Roman et al., 2008).

The ~3.41 Ma Tulu Bor Tuff includes multiple layers and at least two chemical variants, α - Tulu Bor and β - Tulu Bor (Cerling and Brown, 1982). Correlates of the β - Tulu Bor are recognized widely across the Lower and Middle Awash Valley as the Sidi Hakoma Tuff (SHT) (see WoldeGabriel et al., 2013, for a review), which defines the contact between the Basal Member and the Sidi Hakoma Member of the Hadar Formation (Taieb et al., 1976). Tuff B in the Shungura Formation of the Omo-Turkana Basin has a dominant glass compositional mode that is similar to β - Tulu Bor and a more variable, high Fe mode that is not documented in the Tulu Bor Tuff or the SHT, but is present in a proposed correlate of these tuffs in the Gulf of Aden (Brown et al., 1992) (Fig. 5 and Table 2). The β - Tulu Bor Tuff and its correlates differ from the other widespread Turkana Basin tuffs in having higher Al_2O_3 abundance (>12 wt. %) and lower Fe_2O_3 abundance (~1.6 wt. %) (Fig. 5A, B). Reported MnO abundances are low (< 0.1 wt. %), near detection limits, similar to the Wargolo Tuff (Fig. 5C).

For each of these Omo-Turkana Basin tuffs and their correlates, SiO_2 abundances range between 74 wt. % and 81 wt. %, with as much variation reported among samples of the same tuff as between samples of different tuffs. Reported SiO_2 abundances above 78 wt. %, the upper limit of SiO_2 in rhyolite, are almost certainly artifacts of analysis or normalization. MgO abundances are low and consequently have not commonly been used for correlation of Pliocene eastern African tuffs (Fig. 5D).

Locally recognized Middle and Lower Awash Valley tuffs

Several tuffs in the Lower and Middle Awash Valley are not recognized outside of the Awash Valley and, in some cases, are recognized in only one or a few sections (Table 1). Among these, tuffs for which there is published glass compositional data include VT-2, ERV-046, and the Cindery Tuff, which, in that order, are positioned in the Sagantole Formation of Middle Awash (Renne et al., 1999) between correlates of the ~3.96 Ma Moiti Tuff (VT-1) and the ~3.80 Ma Wargolo Tuff (VT-3) (Haileab and Brown, 1992; White et al., 1993). No radioisotopic ages are available for VT-2 or ERV-046, but the Cindery Tuff, the youngest of the three, is ~3.91 Ma (Table 1).

Other Awash Valley tuffs for which there are tephrochemical data are less well constrained in age and relative stratigraphic position (Table 1). ERV-036 in the Middle Awash lies approximately 18 meters below ERV-032, a geochemical correlate of the Lomogol Tuff (Haileab and Brown, 1992). The Maka Sand Tuff in formation “W” lies about 15 m above the Wargolo-equivalent VT-3, but is separated from it by an unconformity (White et al., 1993). Based on sedimentologic and faunal similarities to sections containing the SHT, White et al. (1993) suggested a similar age (~3.42 Ma) for the Maka Sand Tuff. Wynn et al. (2006) geochemically correlated the Arbosh Tuff in the Basal Member of the Hadar Formation with the Maka Sand Tuff. The Arbosh Tuff is overlain and underlain by tuffs that are geochemically similar to the SHT.

Normalized oxide abundances of these Awash Valley tephras (Table 2) are indicated by solid symbols in the bimodal plots of Fig. 5. The Cindery Tuff has basaltic and rhyolitic glass populations, as well as a range of less common intermediate

compositions (Walter et al., 1987). ERV-036 is polymodal as well, with rhyolitic and intermediate glass compositions (Haileab and Brown, 1992). White et al. (1993) reported a “heterogeneous” composition for the Maka Sand Tuff. Although rhyolitic in composition, it has a high Fe mode that is enriched in Fe_2O_3 , CaO and TiO_2 relative to its low Fe mode. The Arbosh Tuff, which has been correlated with the Maka Sand Tuff, has a mean composition that is intermediate between the two modes (Wynn et al., 2006, 2008). In general, these and other Lower and Middle Awash Valley tuffs have higher Al_2O_3 than the widespread Turkana Basin tuffs (Fig. 5A). CaO abundances are variable, ranging from less than 0.4 wt. % for VT-2 and the rhyolitic mode of ERV-036 to ~ 1 wt. % for the rhyolitic mode of the Cindery Tuff (Fig. 5B). MgO and MnO data are limited for Awash Valley tuffs and, where available, are mostly <0.1 wt. % (Fig. 5C, D). Normalized SiO_2 abundances for the rhyolitic glass components vary between 75 wt. % and 81 wt. % and are indistinguishable from Omo-Turkana Basin tuffs.

Results: tephrochemistry, radioisotopic dating, and correlations

Tuffs in the Waki-Mille area comprise three different types: pumice lapillistone tuffs with rhyolitic pumice several millimeters to more than a few centimeters in diameter; bimodal lapillistone tuffs containing both scoria and rhyolitic pumice up to several centimeters across; and vitric ash consisting primarily of very fine to coarse sand-sized shards of volcanic glass. Normalized, average oxide abundances for Waki-Mille tuffs are listed in Table 3. To facilitate visual comparisons with each other and with other eastern African tuffs (Table 2; Figure 5), average oxide data for individual Waki-Mille samples are overlain on outlines of the compositional fields of eastern African tuffs (Fig.

6). Vitric ash, which, because of the small grain size, has a potentially much greater transport distance than lapillistone tuff, is indicated by open symbols in the plots.

Similarity coefficients (SC) (Borchardt et al., 1971, 1972) were calculated from the abundance data in order to compare Waki-Mille area tuffs with each other and with eastern African tuffs. An SC is not a rigorous test of correlation and its value depends on the elements included in the calculation, but in general an SC of 0.92 is a useful lower limit for correlation (Frogatt, 1992). Comparisons among tuffs of the Waki-Mille area, for which all analyses were conducted at the same facility using similar methods, yielded SCs of 0.95 or above for most marker tuffs. Comparisons of Waki-Mille area tuffs with regional tuffs yielded SCs of 0.93 and above for three of the Waki-Mille area marker tuffs, all deposits of vitric ash.

Four of the Waki-Mille area tuffs have previously been assigned informal names (Deino et al., 2010). Here, formal names are assigned to tuffs that are identifiable, based on stratigraphic position, physical characteristics, and geochemistry, in more than one section. Priority is given to names and type locations already in the literature. In stratigraphic order, formally named tuffs include the Mille Tuff sequence (MLT), Araskimiro Tuff (AKT), Waki Tuff (WT), Mesgid Dora Tuff (MDT), Kilaytoli Tuff (KT), Am-Ado Tuff sequence (AAT), and Sidi Hakoma Tuff (SHT).

ARI-09-1 tuff

The oldest tuff for which tephrochemical data were generated is ARI-09-1. This coarse vitric ash is present at Aralee Issie (ARI-5), just below the MLT sequence of pumice lapillistone tuffs (Fig. 4B). With relatively high CaO (~0.75 wt. %) and Al₂O₃ (~13.2 wt. %) abundances, ARI-09-1 glass overlaps in composition with lapillistone tuffs

higher in the section. It is distinguishable from them primarily by stratigraphic position and physical characteristics, but also by small differences in average Fe_2O_3 , TiO_2 , and MgO abundances (Fig. 6). Similarity coefficients comparing ARI-09-1 with stratigraphically higher tuffs, including the AKT and MDT, are not greater than 0.86.

ARI-09-1 is enriched in Al_2O_3 and CaO relative to widespread Omo-Turkana Basin tuffs (Fig. 6A, B). It has several oxide abundances that overlap with the Maka Sand Tuff of Middle Awash and its proposed correlate, the Arbosh Tuff, in the Dikika area of the Lower Awash Valley, but is enriched in Fe_2O_3 compared to these tuffs. The Maka Sand and Arbosh tuffs are thought to be close to 3.42 Ma (White et al., 1993; Wynn et al., 2006, 2008), but ARI-09-1 is older than 3.76 ± 0.02 Ma, the age of the lowest bed in the MLT sequence (Fig. 4; Deino et al., 2010). Given these differences, it is unlikely that ARI-09-1 correlates with the Maka Sand or Arbosh tuffs. No correlate of ARI-09-1 is yet recognized in the Waki-Mille area or the broader region.

Mille Tuff (MLT) sequence

The Mille Tuff (MLT) is the uppermost of a sequence of three similar airfall lapillistone tuffs first described at the Waki-Mille confluence (WMC-1, Fig. 3), the lowest of which, WM-W-2, has a sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ age of 3.76 ± 0.02 Ma (Deino et al., 2010). These tuffs, which are 70 cm to >2 m thick, consist of large (up to 4 cm across) white, angular pumice in a matrix of finer pumice and ash. The size of pumice fragments decreases and the ash and detrital silt content of the matrix increases upward in each bed. Rhizoliths descend from bed tops indicating breaks between periods of tephra accumulation that allowed plant colonization and bioturbation of the substrate. In

addition to the Waki-Mille confluence, the MLT sequence is recognized at Mesgid Dora and Aralee Issie (ARI-5). Across Mesgid Dora it crops out as a single bed, > 1 m thick, below which the section is covered (Figs. 2 and 3). At ARI-5, two lapillistone tuffs are present, each about 1 m thick, separated by pebbly sandstone (Fig. 4B).

Glass compositions of the ARI-5 tuffs (ARI-08-3 and ARI-08-4) are similar to each other ($SC = 0.97$) and also are similar to MSD-08-2 ($SC > 0.98$), a sample of MLT from the MSD-5 section. MLT glass consists of a single compositional mode, for which Al_2O_3 (~12.3 wt. %) and CaO (~0.46 wt. %) abundances are low compared to other lapillistone tuffs in the Waki-Mille area, and high compared to the vitric ash layers WT and KT (Figs. 6A, B). SiO_2 abundances are lower than WT and KT, but higher than other lapillistone tuffs in the area, and MgO and MnO abundances are near to or below detection limits (Fig. 6C). The tuffs in the MLT sequence are geochemically similar to each other and distinguishable from other tuffs in the Waki-Mille area, supporting field correlations between the WMC-MSD-MKM composite section and Aralee Issie (Fig. 4).

Regionally, the MLT sequence is close in age to the Wargolo Tuff, but Deino et al. (2010) argued that its $^{40}Ar/^{39}Ar$ age of 3.76 ± 0.02 Ma is sufficiently different from the Wargolo Tuff's astronomically tuned age of 3.8 ± 0.01 Ma (deMenocal and Brown, 1999) that correlation is unlikely (Table 1). Glass geochemical data support this conclusion. Although Al_2O_3 , Fe_2O_3 , TiO_2 , MgO, and MnO abundances overlap with the reported values for the Wargolo Tuff, higher CaO abundance distinguishes MLT glass (CaO ~ 0.46 wt. %) from Wargolo glass (CaO ~ 0.18 wt. %) (Fig. 6).

418 *Bimodal tuff sequence*

419 Bimodal pumice lapillistone tuff is present at the Waki-Mille confluence, <65 cm
420 above the MLT sequence (Deino et al., 2010), and in the same stratigraphic position at
421 Mesgid Dora and Aralee Issie (Figs. 2, 3, and 4). In each of these areas bimodal tuff is
422 below WT, a vitric ash, though in some exposures there is intervening pumice lapillistone
423 tuff. At the Waki-Mille confluence, the bimodal tuff is 25 cm thick and compositionally
424 stratified, with a scoria-dominated lower half that grades upward to a rhyolitic upper half.
425 Across Mesgid Dora, exposures of bimodal tuff vary from 25 cm thick and
426 compositionally banded to >1 m of mixed rhyolitic pumice and scoria gravel that fills
427 fluvial channels. At ARI-5, there is a bed of discontinuous basaltic conglomerate <1
428 meter above the top of the MLT sequence. The conglomerate, which consists of cobbles,
429 10 cm and greater across, of basalt and scoria, passes laterally into discontinuous lenses,
430 a few tens of centimeters thick, of rhyolitic pumice lapillistone, basaltic scoria, and
431 vesicular basalt. Across the Mille River from Aralee Issie, a wedge of basalt in this same
432 stratigraphic position, above the MLT sequence, expands to several meters thick.

433 The distinctive character and position of bimodal tuff make it a useful marker
434 layer previously referred to, informally, as the basalt-rhyolite tuff (Deino et al., 2010). At
435 some locations across the Waki-Mille area, however, there are clearly multiple bimodal
436 tuffs at different levels in the same section (for example between layers of MLT).
437 Because only two samples of bimodal tuff were analyzed for this study, one basaltic and
438 one rhyolitic, more work is needed to characterize the geochemical similarity and
439 distribution of these tuffs and no formal name is assigned to this tuff sequence.

WMC-08-3, the rhyolitic upper part of bimodal tuff at the Waki-Mille confluence, is broadly similar in glass composition to the underlying MLT sequence, though it differs in CaO abundance (0.56 wt. % versus 0.46 wt. %) (Fig. 6 and Table 3). WMC-08-3 glass is also broadly similar to the felsic mode of glass in the bimodal Middle Awash tuff ERV-036, though this, too, differs in CaO abundance (0.35 %) (Table 2). Fe-enriched glass in MSD-08-3, the mafic, lower part of bimodal tuff at MSD-5, is basaltic in composition ($\text{Fe}_2\text{O}_3 = 14$ wt. %, $\text{SiO}_2 = 50.7$ wt. %) and differs from the intermediate composition of Fe-enriched glass in ERV-036 ($\text{Fe}_2\text{O}_3 = 8$ wt. %, $\text{SiO}_2 = 69.69$ wt. %) (Tables 2 and 3). Still, these tuffs - the MLT sequence, bimodal tuff in the Waki-Mille area, and ERV-036 - are more similar to each other than to any other tuffs in the region. They are also close in age and stratigraphic position. ERV-036 is overlain by a geochemical correlate of the Lomogol Tuff (Table 1, Haileab and Brown, 1992) and the bimodal tuff at Aralee Issie, Waki-Mille confluence, and Mesgid Dora is overlain by WT, shown below to also be a geochemical correlate of this same widespread Omo-Turkana Basin tuff. The bimodal tuffs, both in the Waki-Mille area and in the Middle Awash, and the MLT sequence clearly do not all represent a single, unique eruptive event, but they may be genetically related.

Araskimiro Tuff (AKT)

At Aralee Issie (ARI-5) and locally across Mesgid Dora there is pumice lapillistone tuff above the bimodal tuff, between it and the next higher vitric ash, the WT. This lapillistone tuff (ARI-13-1) is well exposed along the Araskimiro drainage near the bottom of the ARI-5 section. There it is as much as 3 m thick with locally abundant

pebbles, lithic fragments, and cross-bedding. WM-MD-5 and MSD-08-3a are duplicate samples of a 15 cm thick pumice lapillistone tuff found 10 cm above bimodal tuff and 20 cm below WT in the MSD-5 section (Fig. 3). WM-MD-5 has an anorthoclase age of 3.77 ± 0.04 Ma (Deino et al., 2010). MSD-11-2 is a lithic, pumice lapillistone tuff exposed as a bedding plane north of the MSD-2 section, on the west side of MSD (Fig. 2). The tuff has rounded pumice fragments, up to 1 cm across, in a matrix of silt, finer pumice, and lithic fragments, and is partially altered. It contains in-place vertebrate fossils and is a source for surface finds of tuff-encrusted fossils. This bed is traceable southward over tens of meters to small drainages and hummocks, which reveal its position between bimodal tuff and WT.

Attempts to isolate and analyze volcanic glass from ARI-13-1 have been unsuccessful due to devitrification. MSD-11-2, however, meets the threshold for geochemical correlation with both WM-MD-5 (SC = 0.95) and MSD-08-3a (SC = 0.92), which, as expected for duplicates from the same bed, are geochemically similar to each other (SC = 0.96). However, comparison with samples of MDT, a lapillistone tuff above WT (ARI-08-01, MSD-08-5, and MKM-08-5), yields comparably high measures of similarity (S.C. = 0.91 to 0.94). Although these tuffs are difficult to differentiate geochemically, they are at demonstrably different stratigraphic levels, above and below a key stratigraphic marker, the WT. The name Araskimiro Tuff (AKT) is assigned to the pumice lapillistone tuff below WT.

484 *Waki Tuff (WT)*

485 The Waki Tuff (WT) is a 25 cm thick, fine vitric ash that lies 70 cm above
486 bimodal tuff and 50 cm below MDT at the Waki-Mille confluence (Fig. 3) (Deino et al.,
487 2010). It forms a distinctive blue-gray, resistant marker layer that is recognized across
488 Aralee Issie and Mesgid Dora, locally above the AKT (Figs. 2 and 4B). Samples of WT
489 from Mesgid Dora (MSD-09-3), Waki-Mille confluence (WMC-08-4), and Aralee Issie
490 (ARI-08-2) have high similarity to each other ($SC > 0.97$) supporting local stratigraphic
491 correlations. Relatively high Fe_2O_3 abundances (~4.5 wt. %) and low Al_2O_3 (~10.6
492 wt. %) and CaO (~0.18 wt. %) abundances distinguish WT glass from lapillistone tuffs in
493 the area and from ARI-09-1 (Figs. 6A, B). WT glass overlaps in composition with the
494 high Fe mode of KT, which lies 20 m above it at Aralee Issie (Fig. 4), but lacks KT's low
495 Fe mode, distinguishing it geochemically from this similar vitric ash (Fig. 6A).

496 The KT has been correlated based on age and glass geochemistry with the
497 Lokochot Tuff of the Omo-Turkana Basin (Deino et al., 2010). The WT is geochemically
498 similar to the Turkana Basin's Lomogol Tuff ($SC = 0.94$ to 0.97), which is in a similar
499 stratigraphic position beneath the KT-equivalent Lokochot Tuff (Feibel et al., 1989;
500 Brown et al., 1992). Like the Lomogol Tuff, which is below the Gauss-Gilbert transition
501 (Hillhouse et al., 1986), the position of WT below KT places it in a reverse chronozone
502 interpreted as part of Gilbert subchron C2Ar (Deino et al., 2010; Haile-Selassie et al.,
503 2012) (Fig. 4).

504 Three samples of WT were dated at the Berkeley Geochronology Center (BGC)
505 by the laser-fusion, single-crystal $^{40}Ar/^{39}Ar$ method. Sample WM09/MD-1 is from the
506 base of a 20-30 cm medium to fine grained massive vitric tuff exposed at Mesgid Dora

(Figs. 2 and 3). WM09/W-1 and WM09/W-2 are from a similar, 30-50 cm thick tuff exposed for approximately a half-kilometer along the banks of the Mille River near the Waki confluence (Figs. 2 and 3).

A total of 98 analyses were performed (32 for WM09/MD-1; 35 for WM09/W-1, and 25 for WM09/W-2; six additional analyses were either analytical failures or not feldspars, and are omitted from further discussion) (Fig. 7). Many ($n = 33$) of the feldspars were older than 4.5 Ma, and based on the overall distribution and modes of ages, these were considered to be detrital contaminants. The most common ages occurring within this detrital material, ~30.5, 27-26, 7.3, and 4.7 Ma, are the same as detrital feldspar ages reported previously for other $^{40}\text{Ar}/^{39}\text{Ar}$ dated Waki-Mille area tuffs (Deino et al., 2010). After excluding these obvious older contaminants, a robust median filter technique ('normalized deviation from the median', where $n\text{Mad} = 1.5$) was applied to the individual sample populations to exclude additional outliers. Age-probability density spectra calculated for the samples (Fig. 7) are simple near-Gaussian populations for WM09/MD-1 and WM09/W-2, but show significant, broad tails to either side of the age distribution for WM09/W-1 (due to the probability distribution being dominated by just two relatively high precision analyses). The greater scatter, typically higher analytical uncertainty (due to smaller grain size), and low number of analyses indicate that this sample is of lesser reliability than the other samples (weighted mean age of WM09/W-1 is 3.782 ± 0.032 at 1s, $\text{MSWD} = 0.6$, $n = 9$). Excluding this sample, samples WM09/MD-1 and WM09/W-2 yield congruent ages at 3.642 ± 0.028 Ma ($\text{MSWD} = 0.1$, $n = 19$), and 3.674 ± 0.019 Ma ($\text{MSWD} = 1.0$, $n = 18$). The weighted-mean age of these two samples, 3.664 ± 0.016 Ma, is taken as the reference age for the WT. Regionally, this new date on

the WT is significantly older than the astronomically tuned age (3.62 ± 0.01 Ma; deMenocal and Brown, 1999) for the geochemically similar and potentially correlative Lomogol Tuff (Table 1). The resolution of this apparent age discrepancy may lie in an overestimation of the age or underestimation of the uncertainties reported here for the WT, the assumptions underlying the astronomical tuning of ODP Site 721/722 in this interval of the Pliocene, or in the validity of the correlation of the Lomogol and the WT. More dating and geochemistry, either within an astronomically tuned drill-core context, or from land-based outcrops, are needed to resolve this problem.

Mesgid Dora Tuff (MDT)

The Mesgid Dora Tuff (MDT), as first described in the MSD-5 section (MSD-08-5), is a massive, coarse, pumice lapillistone tuff, 1 m thick and less than 2 m above WT (Deino et al., 2010). It is the highest tuff in the section at WMC and across much of Mesgid Dora, but has KT above it at Makah Mera (MKM-08-1) (Figs. 2 and 3). Across the Mesgid Dora area, the MDT cuts down section along the margins of a large fluvial channel from as much as 8 m above WT to directly on MLT; the character of the tuff varies across the channel from airfall to fluvially reworked. MDT is present between WT and KT in the ARI-5 section (ARI-08-1) and in isolation, across a steep normal fault, at ARI-1, where it is exposed as a bedding plane (ARI-09-2, WM-ut-1) (Fig. 4). The tuff at ARI-1 is a fluvially reworked pumice lapillistone interpreted to correlate with the MDT fluvial channel (Deino et al., 2010). AMA-12-1 is from a meter thick pumice lapillistone tuff on basalt, locally on bimodal tuff, at the bottom of the section at Am-Ado, about 8 m below KT (Fig. 4). KSD-13-1 is a lapillistone tuff, which, based on geologic mapping

and correlation across fault blocks at Korsi Dora, is interpreted to be about 10 m below KT (Figs. 1 and 4) (Haile-Selassie et al., 2012; Saylor et al., 2016).

High similarity coefficients ($SC \geq 0.96$) for samples ARI-08-01, MSD-08-5, and MKM-08-1, combined with similarity of position above WT and below KT, support stratigraphic correlation of these tuffs across the WMC-MSD-MKM composite section and between that section and Aralee Issie (Figs. 3 and 4). ARI-09-2, AMA-12-1, and KSD-13-1 also have high similarity ($0.92 < SC < 0.98$) to MDT and slightly lower similarity ($0.89 < SC < 0.94$) to AKT, below WT. These tuffs are not present in section with WT and thus their positions relative to this marker bed are less clear. Still, fieldwork between Am-Ado and Aralee Issie has found WT below a tuff that physically resembles AMA-12-1 and, like AMA-12-1, locally rests on Am-Ado basalt. In addition, individual glass shards with compositions similar to WT were found and excluded from the sample average of ARI-09-2 and MSD-08-5 (Table 3, excluded). These shards are likely detrital in origin, reworked from underlying WT. Taken together, the geologic and geochemical evidence favors interpreting all the above samples as MDT.

Previously, an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 3.72 ± 0.03 Ma (2σ) was reported for the MDT at ARI-1 (WM-ut-1) (Fig. 3B); however due to limitations imposed by the virtually aphyric nature of the tuff, and the presence of extensive detrital contamination, it could only be considered with certainty to be a maximum age (Deino et al., 2010). It is now apparent, based on the more definitive age determination for the underlying WT, that the MDT postdates 3.664 ± 0.016 Ma.

The MDT is enriched in Al_2O_3 , CaO, and MgO compared to the MLT sequence and depleted in these oxides relative to other, higher lapillistone tuffs in the Waki-Mille

area (Fig. 6). MDT glass compositions overlap with the stratigraphically lower ARI-09-1 and AKT tuffs, and also are broadly similar to the Maka Sand and Arbosh tuffs of the Awash Valley. They are more similar to these apparently older (>3.77 Ma) and younger tuffs (~ 3.42 Ma) than to any other tuffs in the Waki-Mille area or elsewhere in the Awash Valley.

AMA-09-1 tuff

AMA-09-1 is a meter-thick, massive, pumice lapillistone tuff, 2 m above basalt at Am-Ado (Fig. 4A). It is 6 m below the KT, with intervening, altered, fossiliferous, pumice lapillistone tuff. With its large white pumice fragments, AMA-09-1 physically resembles other lapillistone tuffs in the area, but its glass geochemistry differs. It has higher CaO (~ 0.9 wt. %), TiO_2 (~ 0.3) and MgO (0.26) abundances than all but the AAT and also is geochemically dissimilar to regional tuffs (Fig. 6).

Kilaytoli Tuff (KT)

The Kilaytoli Tuff (KT) is a fine, white, laminated vitric ash, first described in the Kilaytoli drainage at KSD where it has a $^{40}\text{Ar}/^{39}\text{Ar}$ age of 3.570 ± 0.014 Ma (Deino et al., 2010) (Figs. 1C and 4). Glass geochemical data have been used to correlate the dated samples (WM-KSD-1&3) with exposures of KT at the top of the ARI-5 section (ARI-08-5), at Makah Mera (MKM-08-13), and across different fault blocks at Korsi Dora (KSD-09-8, WM-KSD-1&3), and also to correlate these samples with the Lokochot Tuff of the Turkana Basin (Deino et al., 2010; Saylor et al., 2016).

New data are reported for vitric ash beds at Am-Ado and Kerare. AMA-09-4 is from a 1.3 m thick vitric ash above a succession of pumice lapillistone tuffs that includes MDT (AMA-12-1) and AMA-09-1 (Fig. 4A). This vitric ash crops out widely across Am-Ado, where it exhibits planar lamination, ripple cross stratification and massive bedding, and contains accretionary lapilli ~1 cm across. KER 13-3 is a 0.5 m thick, faintly laminated vitric ash at Kerare (Fig. 1). It is the highest tuff there, 2 to 4 m above bimodal tuff, and is cut out laterally by a fluvial channel. Sandstone and conglomerate above the vitric ash are overlain by two distinct basaltic flows, part of the Kerare-Korsi Dora-Burtele basalts, which constitute a low-relief ridge traceable from Kerare to Burtele (Fig. 1C). Both KER-13-3 and AMA-09-4 have bimodal rhyolitic glass with compositions similar to KT (and to the Lokochot Tuff) and distinguishable from WT (Fig. 6 and Table 3).

Am-Ado Tuff (AAT) sequence

The Am-Ado Tuff (AAT) is a 25 cm pumice lapillistone tuff, 5 m above the KT at Am-Ado (AMA-09-5). It has buff to pinkish matrix with white pumice clasts 0.1 cm to 0.5 cm across. It is immediately underlain by siltstone and a 10 cm thick lapillistone tuff, 1 m below. Similar lapillistone tuffs are recognized at this stratigraphic level, above KT, across the Waki-Mille area. MSD-09-5 is a lapillistone tuff above KT on topographical flats that constitute the short MSD-9 section. MKM-11-1 is the upper of two pinkish lapillistone tuffs traceable across conglomerate covered hilltops directly south of those flats (Figs. 2 and 3). WM09/KSD-1 is a 3.6 ± 0.03 Ma tuff found below the partial skeleton of *Au. afarensis* at Korsi Dora (Haile-Selassie et al., 2010a), which, based on

paleomagnetic data and geologic mapping, is interpreted to be positioned above KT (Saylor et al., 2016). ESC-11-4 is from a pumice lapillistone tuff near the bottom of the Guda escarpment, above a 2.5 m thick bed of laminated vitric ash that is physically similar to KT.

The ashy matrix of WM09/KSD-1, the dated tuff at Korsi Dora, is devitrified, but glass from the other lapillistone tuffs at this level are geochemically similar to AMA-09-5, and to each other ($SC \geq 0.97$), and distinct from other Waki-Mille area tuffs as well as regional tuffs. They have the highest TiO_2 (~0.33 wt. %), CaO (~1.07 wt. %), and MgO (~0.32 wt. %) abundances of any of the local or regional tuffs.

Sidi Hakoma Tuff (SHT)

The highest tuffs for which data are reported here are from above basalt flows at the northern and southern margins of the Waki-Mille area. ESC-11-5 is a 70 cm thick lens of white, fine vitric ash in the lower part of the escarpment to Guda Plateau. It rests on basalt that, traced laterally, overlies AAT (AMA-09-5) (Fig. 1C). BDB-09-1 is from south of Korsi Dora, above the ridge of Kerare-Korsi Dora-Burtele basalts (Fig. 1C). It is a 3.4 m thick vitric ash above 10 m of claystone, siltstone and sandstone. The bottom meter of the ash consists of massive, coarser and finer beds, 10 cm to 40 cm thick, and the upper part is finer grained with climbing ripple cross-stratification, low angle and planar lamination, and soft sediment deformation. Both tuffs, ESC-11-5 and BDB-09-1, are stratigraphically higher than, and therefore postdate, the ~3.57 Ma KT. They are physically and geochemically similar to the ~3.41 Ma Sidi Hakoma Tuff of the Hadar

Formation and its correlate, the β - Tulu Bor Tuff (S.C.= 0.93 and 0.96) of the Omo-Turkana Basin.

Discussion

WORMIL has become one of the most important middle Pliocene sites in eastern Africa and promises to help resolve some of the outstanding questions related to middle Pliocene hominin taxonomic diversity, locomotor adaptations, and their paleoecological contexts. Moreover, it is also yielding new information on the timing of major shifts in dietary adaptations and inter-relationships between morphology and behavior across various vertebrate taxa. For example, recent stable isotope analyses of hominins and associated mammalian fossil teeth from the area show that hominins and some papionins expanded their diets to include C4 plants as early as 3.76 Ma (Levin et al., 2015). Most importantly, however, the data show that while morphological changes preceded behavioral changes among hominins during the middle Pliocene, it appears that the opposite was true for some other primate groups such as *Theropithecus* (Levin et al., 2015). These novel discoveries not only highlight the significance of WORMIL, but also add new data to our understanding of middle Pliocene hominin evolution and the associated paleoecological context. Therefore, precise stratigraphic placement using geochronology and tephrostratigraphy is of paramount significance.

Volcanic tuffs in the Waki-Mille area break out into at least ten chemically distinct glass compositions, recognition of which support field-based mapping of tuffs and correlations of stratigraphic sections across the area, and also identify potential correlates of widespread regional tuffs. The mapping and correlations demonstrate that

strata in the Waki-Mille area contain multiple layers of basalt, including below the ~3.77 Ma MLT sequence and above the ~3.57 Ma KT and overlying AAT sequence. Although not clearly present in any of the measured sections (Figs. 3 and 4), there is also at least one layer of basalt between the MLT sequence and KT, as evidenced by exposures along the Mille River, across from Aralee Issie, where the MLT sequence is overlain by basalt. Basalt at Am-Ado also may be positioned above the MLT sequence, accounting for the absence in that section of this otherwise prominent stratigraphic unit (Figs. 1 and 4).

Strata in the Waki-Mille area are offset by high-angle faults and dip gently eastward such that older tuffs (e.g., the Mille Tuff sequence and below) are exposed most extensively in the western part of the area, near the Waki-Mille confluence, while younger tuffs (e.g., KT and AAT) are exposed most extensively in the eastern part of the area, near Makah Mera, and southeast of there at Korsi Dora (Figs. 1 and 4). An older tuffaceous section (>3.82 Ma), below the Mille basalt, is exposed west of the Waki-Mille confluence, along the Mille and Waki rivers, and a younger, primarily sedimentary section (< 3.46 Ma) is present east of Korsi Dora, above the Kerare-Korsi Dora-Burtele basalts at Burtele (Haile-Selassie et al., 2012). Most tuffs in these older and younger sections are altered and unsuitable for glass geochemical analysis.

The youngest tuffs for which oxide abundance data are reported (ESC-11-5 and BDB-09-1) are geochemical correlates of the ~3.41 Ma SHT, which defines the base of the Sidi Hakoma Member of the Hadar Formation in the Lower Awash Valley. These tuffs are from plateaus on the northern and southern margins of the Waki-Mille area, and on both margins are above basalt flows that overlie the highest tuffs (KT and AAT sequence) of the WMC-MSD-MKM composite section. Thus, the Waki-Mille area is

encircled by plateaus, which are topped by basalts and younger strata (Fig. 1). Older strata, comparable to the WMC-MSD-MKM section, are exposed across the interior of the Waki-Mille area, where erosion along the Mille River and its tributaries has created a window into lower stratigraphic levels, down to and below the ~3.82 Ma Mille basalt. The strata of the Waki-Mille area are comparable in age and stratigraphic position to the Hadar Formation's Basal Member, below the SHT, and may form the most laterally extensive exposures of fossiliferous strata of this age in the Awash Valley.

Inter-basinal correlation, tephra sources and the connectivity of sedimentary basins

Tuffs of the Waki-Mille area include fine vitric ash deposits and coarser lapillistone tuffs, which, because of the grain-size dependence of settling velocity, have potentially very different source areas and distribution patterns. Out of four vitric ash layers in the area, three, the WT, KT, and SHT, are similar in glass geochemistry and stratigraphic position to widespread, regional tuffs, respectively the Lomogol, Lokochot, and β -Tulu Bor tuffs of the Omo-Turkana Basin. These fine, homogeneous, glassy tuffs have extra-basinal origins, potentially from very distal source areas in the Main Ethiopian Rift (WoldeGabriel et al., 1992; Walter and Aronson, 1993; WoldeGabriel et al., 2000, 2013), and have dispersal areas that extend northward from Kenya and southern Ethiopia to the Red Sea and the Gulf of Aden (Sarna-Wojcicki et al., 1985; Brown et al., 1992; deMenocal and Brown, 1999), including, as documented here, widespread accumulations across the Waki-Mille area. Despite the wide distribution of these tuffs, however, neither the Lomogol nor Lokochot tuffs has been identified in the neighboring field areas of the Lower Awash Valley, and, although a geochemical correlate of the

Lomogol Tuff is present at Middle Awash, it is recognized only very locally. The Lokochot Tuff is claimed to be present at Asa Issie in Middle Awash, but without published geochemical data (WoldeGabriel et al., 2013).

Lapillistone tuffs in the Waki-Mille area have relatively high abundances of Al_2O_3 and CaO , and low abundances of SiO_2 (Fig. 6), which differentiate them geochemically from the vitric ash deposits that correlate with widespread Omo-Turkana Basin tuffs. There are broad similarities between Waki-Mille area lapillistone tuffs and the more locally distributed tuffs of the Awash Valley, which also have relatively high abundances of Al_2O_3 and CaO , but none is a match in terms of geochemistry and age, and most are clearly different. The greatest overlap in glass compositions between tuffs in the different areas is between the MLT sequence and bimodal tuffs of the Waki-Mille area and ERV-036 of Middle Awash, and also between the MDT and AKT tuffs and ARI-09-1 of the Waki-Mille area and the Arbosh/Maka Sand tuffs of the Lower and Middle Awash Valley. Because these tuffs are at multiple stratigraphic levels and span as much as 400 thousand years (between the age of ARI-09-1, <3.77 Ma, and the Maka Sand Tuff, ~3.42 Ma), the similarities in oxide abundances are significant primarily as a caution against correlations based on geochemistry alone.

It is noteworthy that so few Waki-Mille area tuffs are recognized in the Lower and Middle Awash Valley field areas and that those present are limited to widespread, distally-sourced tuffs (Table 1). Lapillistone tuffs in the Waki-Mille area are predominantly airfall deposits, locally fluvially reworked. Large pumice clasts, in many cases exceeding 1 to 4 cm, require local derivation from a source area within 20 to 30 km (Carey and Sparks, 1986). Reasonable sources for these tephra deposits include the Gura

Ale and Ide Ale volcanic centers, located northwest and southeast of the Waki-Mille confluence, respectively. Gura Ale is favored by the increasing number and thickness of tuffs northward across the Waki-Mille area. For example, lapillistone tuffs at Am-Ado, including AMA-09-1 and others between MDT and KT, are not found at comparable stratigraphic levels in Waki-Mille sections further south and east. They may represent the southernmost geographic limits of fallout for their eruptive events, which may have been small, low-altitude, and of limited aerial extent. Monsoonal winds over the Horn of Africa vary with season and altitude, but are generally directed toward the west, east, or north (Feakins et al., 2007). These may have further hindered southward transport of locally sourced lapillistone tuffs toward the field areas of the Awash Valley. Fluvial transport also may not have been favorable. A large and long-lived paleochannel trends northwest-southeast across much of Mesgid Dora. Paleocurrent measurements on trough azimuths in sandstone and fluvially reworked tuffs within this channel point away from the Awash Valley field areas (Fig. 2).

East-directed winds may have transported tephra from volcanic centers near the Waki-Mille area as far as the Gulf of Aden. Microshard counts in a core from Deep Sea Drilling Project site 231 identified 68 discrete micro-tephra layers in addition to visible tephra horizons with compositions matching the widespread Omo-Turkana Basin tuffs (Feakins et al., 2007). A concentration of microlayers between ~3.58 Ma and ~ 3.8 Ma, between correlates of the Lokochot and Wargolo Tuffs, represents a period of increased frequency of volcanic eruptions corresponding in time with the period of volcanic activity in the Waki-Mille area. This cannot be the only source, however. Tephrochemical data

are available for only one layer in the core interval (20-6-135-150, Feakins et al. 2007), and it is unlike any of the Waki-Mille area tuffs.

Unfavorable transport is insufficient to explain the limited presence in the Awash Valley of the Lomogol and Lokochot tuffs because tephra from these eruptions clearly extended across the Awash region leaving deposits that are thick and well developed in the Waki-Mille area. It may be that there are few or no exposures of the appropriate age. In most areas of the Lower Awash Valley only the top few meters of the Basal Member are exposed, and, where the Basal Member is thicker, as in Dikika, exposures lack age constraints or are older than studied sections of the Waki-Mille area (Wynn et al., 2006, 2008). The As Duma area on the western margin of Gona has a section that spans the age of Waki-Mille area strata and also contains several tuffs (Quade et al., 2008), but no glass geochemical data are available. Formation “W” in Middle Awash (White et al., 1993), which in one section preserves a geochemical correlate of the Lomogol Tuff (Haileab and Brown, 1992) and in another has a correlate of the Lokochot Tuff (WoldeGabriel et al., 2013), has an unconformity that may include much of the time represented by the Waki-Mille area strata. Thus, in addition to limited exposure in the field areas of the lower and middle Awash Valley, the relative paucity and discontinuity of strata comparable in age to those of the Waki-Mille area may reflect discontinuous accumulation due to faulting, erosion, and geographically disconnected depocenters (Quade et al., 2008).

The lack of common, identifiable, volcanic tuffs makes it difficult to fit the section in the Waki-Mille area into stratigraphic nomenclatures developed for the Awash Valley. Although provisionally part of the Hadar Formation (Deino et al., 2010), the interbedded thick tuffs, coarse fluvial clastic deposits, and multiple, discontinuous layers

of basalt bear little resemblance to the fine lacustrine deposits of the Basal Member of the Hadar Formation (Wynn et al., 2008). There is also no evidence that the strata in the Waki- area represent deposits on the margin of the Hadar lake (Wynn et al., 2008), or even, necessarily, that they were deposited as part of the same drainage system or basin. Work is continuing to understand the geographic and vertical extent of the volcanic and sedimentary strata around the Waki-Mille area as well as the relation of sedimentation to the volcanic and tectonic evolution of the area.

The age of fossil horizons

The 3.664 ± 0.016 Ma age for the WT and the recognition that it is similar in geochemistry and stratigraphic position to the Lomogol Tuff refine understanding of the distribution of time in the strata of the Waki-Mille area and the ages of fossil horizons there. Deino et al. (2010) calculated an average sediment accumulation rate of 11 cm/kyr between the Mille basalt and KT in the WMC-MSD-MKM composite section. This estimate holds, on average, though it must be noted that significant lateral variations in thicknesses between marker tuffs make these kinds of calculations less useful than in areas with more “layer cake” stratigraphy. However, almost half the time in the section (106 thousand years) is represented by the 4 m between the AKT (~3.77 Ma) and the WT (3.664 Ma). This constraint yields a sediment accumulation rate of 4 cm per thousand years for those 4 m, which contrasts with as much as ~35 cm/kyr below the AKT and as much as 23 cm/kyr year above the WT, and suggests the presence of a condensed section or cryptic unconformity.

802 Hominin fossils have been described from several stratigraphic levels between the
803 MLT and KT in the Waki-Mille area (Haile-Selassie, 2010; Haile-Selassie et al., 2010b;
804 Haile-Selassie and Melillo, 2015). These fossils are significant because, together with
805 fossils from the Laetoli beds in Kenya and Tanzania, they partially fill a gap in the fossil
806 record between about ~3.6 and ~3.8 Ma (Haile-Selassie et al., 2010b; Harrison, 2011).
807 The ages of the Waki-Mille area fossils can now be refined within this timeframe. The
808 oldest published hominin fossils are from below WT. Localities MSD-VP-1, 3 and 5 have
809 fossils at this level, many of which are derived from the AKT and are about 3.77 Ma. The
810 specimens from this time interval are morphologically more similar to *Au. anamensis*
811 than they are to *Au. afarensis* (e.g., MSD-VP-5/16, MSD-VP-5/50; see Haile-Selassie,
812 2010, for details). Most described fossils are derived from horizons above the WT and are
813 between 3.66 Ma and 3.57 Ma. These include fossils from above and within the MDT in
814 locality ARI-VP-1, MKM-VP-1, and at AMA-VP-2, and those from just below the MDT
815 in locality ARI-VP-3. The hominin specimens from these localities also show a mosaic of
816 dental features shared by both *Au. anamensis* and *Au. afarensis*. Some of the teeth are *Au.*
817 *anamensis*-like in having occlusally sloping buccal walls on lower molars and lingual
818 walls on upper molars, and long canine roots, while others have vertical buccal and
819 lingual walls on their molars as in *Au. afarensis*. Other fossils, including the partial
820 skeleton KSD-VP-1 are from above the KT and AAT and are younger than ~3.6 Ma and
821 assigned to *Au. afarensis*, but are below the Kerare-Korsi Dora-Burtele basalts (Haile-
822 Selassie et al., 2012; Saylor et al., 2016). Dentognathic fossils reported from Burtele and
823 assigned to *Australopithecus deyiremeda* are part of this time-stratigraphic interval. This
824 species was interpreted as indicating the presence of at least two contemporaneous

825 hominin species at Woranso-Mille during the middle Pliocene (Haile-Selassie et al.,
826 2015)

827 The youngest hominin fossils described thus far from the WORMIL project are
828 the partial foot from Burtele, whose taxonomic affinity has not been determined yet, and
829 a partial mandible at the adjacent Waytaleyta locality at the eastern edge of the Waki-
830 Mille area, which is recognized as one of the paratypes of *Au. deyiremeda* (Haile-Selassie
831 et al., 2012, 2015) (Fig. 1). These fossils are younger than the Kerare-Korsi Dora-Burtele
832 basalts and are younger than the 3.469 ± 0.008 Ma Burtele Tuff (Haile-Selassie et al.,
833 2012). Their age and stratigraphic positions relative to the ~3.41 Ma SHT (a
834 geochemical correlate of which is shown here to lie above the same ridge of basalts, 8 km
835 to the west) are as yet unclear because the SHT is not present in the Burtele section. SHT
836 crops out as a laterally discontinuous channel-fill deposit in many of its exposures across
837 the Hadar Basin and is also laterally discontinuous in parts of the Waki-Mille area. It is
838 possible that the Burtele section extends up to the stratigraphic level of the SHT but the
839 tuff is absent due to vagaries of deposition and preservation. Alternatively, given the 59
840 thousand years between the eruptions of the Burtele Tuff and the SHT, a sediment
841 accumulation rate of 47 cm/kyr or more would be required for the SHT to be above the
842 top of the measured Burtele section, 27.5 m above the Burtele Tuff (Haile-Selassie et al.,
843 2015). This rate is high compared to the older strata in WMC-MSD-MKM section in the
844 core of the Waki-Mille area. It is also high relative to the Hadar Formation, above the
845 SHT, at Hadar, where typical rates are 30 cm/kyr (Campisano and Feibel, 2007), but is
846 low compared to Middle Ledi, where rates for the same stratigraphic zone are 82 cm/kyr
847 to 95 cm/kyr (Dupont-Nivet et al., 2008). It is, therefore, not unreasonable for the

stratigraphic level of the SHT to be above the fossils and exposures at Burtele, though such a position would likely reflect a change in basin dynamics relative to lower sediment accumulation rates of the WMC-MSD-MKM section at the core Waki-Mille area.

Conclusions

Pliocene volcanic and sedimentary strata in the Waki-Mille area of the WORMIL paleoanthropological study area lie mostly below the SHT of the Hadar Formation and range in age from >3.41 Ma, the astronomically tuned model age of the SHT and its correlate the β -Tulu Bor, to >3.82 Ma, the radioisotopic age of the Mille basalt. These strata are distinctive in their abundance of volcanic tuffs and the presence of multiple levels of interbedded basalts compared to strata of similar age elsewhere in the Awash Valley.

Tephrochemistry and stratigraphic position identify at least 14 unique tephra beds and ten geochemically distinct tuffs or tuff sequences, which are correlated across the study area. $^{40}\text{Ar}/^{39}\text{Ar}$ sanidine ages for four of these tuffs and underlying basalt, including a new age of 3.664 ± 0.016 Ma for the WT, identify a ~ 106 thousand year condensed section or cryptic unconformity in the middle of the section and tightly constrain the ages of three fossiliferous levels within the core of the Waki-Mille area, as well as a younger fossiliferous level at Burtele, at the edge of the Waki-Mille area.

In addition to the SHT, which is shown to overlie the Waki-Mille area strata, two other tuffs from the area correlate with tephra layers in the Omo-Turkana Basin and in deep-sea cores. The 3.570 ± 0.014 Ma Kilaytoli Tuff (KT) was previously correlated, based on geochemistry and age, with the Lokochot Tuff, and the WT is here correlated,

based on geochemistry and stratigraphic position, with the Lomogol Tuff, though its $^{40}\text{Ar}/^{39}\text{Ar}$ age of 3.664 ± 0.14 Ma differs significantly from the astronomically-tuned model age of 3.62 Ma. These fine vitric ashes represent the widely disseminated deposits of immense, distant volcanic eruptions.

Others tuffs in the Waki-Mille area are not recognized elsewhere. Most are pumice lapillistone tuffs that must be derived from within a few tens of kilometers of the area, most likely the nearby Ida Ale or Gura Ale volcanic centers. Limited exposures, unconformities, unfavorable fluvial and wind transport directions, and paleotopographic barriers may account for the absence or scarcity of these tuffs in neighboring and nearby paleoanthropological research areas of the Lower and Middle Awash Valley.

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894 **References**

- 895 Acocella, V., 2010. Coupling volcanism and tectonics along divergent plate boundaries:
896 Collapsed rifts from central Afar, Ethiopia. *Geol. Soc. Am. Bull.* 122, 1717-1728.
- 897 Asfaw, B. 1987. The Belohdelie frontal: new evidence of early hominid cranial
898 morphology from the Afar of Ethiopia. *J. Hum. Evol.* 16, 611-624.
- 899 Beyene, A., Abdelsalam, M.G., 2005. Tectonics of the Afar Depression: a review and
900 synthesis. *J. Afr. Earth Sci.* 41, 41-59.
- 901 Borchardt, G.A., Harward, M.E., Schmitt, R.A., 1971. Correlation of volcanic ash
902 deposits by activation analysis of glass separates. *Quatern. Res.* 1, 247-260.
- 903 Borchardt, G.A., Aruscavage, P.J., Millard, H.T., Jr., 1972. Correlation of the Bishop
904 Ash, a Pleistocene marker bed, using instrumental neutron activation analysis. *J.*
905 *Sed. Petrol.* 42, 301-306.
- 906 Brown, F.H., Sarna-Wojcicki, A.M. , Meyer, C.E. , Haileab, B., 1992. Correlation of
907 Pliocene and Pleistocene tephra layers between the Turkana Basin of East Africa
908 and the Gulf of Aden. *Quatern. Int.* 13-14, 55-67.
- 909 Brown, F.H., McDougall, I., Gathogo, P.N., 2013. Age ranges of *Australopithecus*
910 species, Kenya, Ethiopia, and Tanzania. In: Reed, K.E., Fleagle, J.G., Leakey,
911 R.E. (Eds.), *The Paleobiology of Australopithecus*. *Vertebrate Paleobiology and*
912 *Paleoanthropology*. Springer, New York, pp. 7-20.

- 913 Campisano, C, Feibel, C., 2007. Connecting local environmental sequences to global
914 climate patterns: evidence from the hominin-bearing Hadar Formation, Ethiopia. *J.*
915 *Hum. Evol.* 53, 515-527.
- 916 Campisano, C.J., Feibel, C.S., 2008. Tephrostratigraphy of the Hadar and Busidima
917 formations at Hadar, Afar depression, Ethiopia. In: Quade, J., Wynn, J. (Eds.),
918 *The Geology of Early Humans in the Horn of Africa. Geol. S. Am. S.* 446, pp.
919 135-162.
- 920 Carey, S., Sparks, R., 1986. Quantitative models of the fallout and dispersal of tephra
921 from volcanic eruption columns. *Bull. Volcanol.* 48, 109-125.
- 922 Cerling, T.E., Brown, F.H., 1982. Tuffaceous marker horizons in the Koobi Fora region
923 and the Lower Omo Valley. *Nature* 299, 216-221.
- 924 Deino, A., Scott, G., Saylor, B., Alene, M., Angelini, J., Haile-Selassie, Y., 2010.
925 $^{40}\text{Ar}/^{39}\text{Ar}$ dating, paleomagnetism, and tephrochemistry of Pliocene strata of the
926 hominid-bearing Woranso-Mille area, West-central Afar Rift, Ethiopia. *J. Hum.*
927 *Evol.* 58, 111-126.
- 928 deMenocal, P.B., Brown, F.H., 1999. Pliocene tephra correlations between East African
929 hominid localities, the Gulf of Aden, and the Arabian Sea. In: Agusti, J., Andrews,
930 P. (Eds.), *Hominid evolution and climate change in Europe, Volume 1.*
931 Cambridge University Press, Cambridge, pp. 23-54.

- 932 Donovan, J., Kremser, D., Fournelle, J., Goemann, K., 2015, Probe for EPMA – User’s
933 Guide and Reference Manual, Probe Software, 429 pages.
- 934 Dupont-Nivet, G., Sier, M., Campisano, C.J., Arrowsmith, J.R., DiMaggio, E., Reed, K.,
935 Lockwood, C., Franke, C., Hüsing, S., 2008. Magnetostratigraphy of the eastern
936 Hadar Basin (Ledi-Geraru research area, Ethiopia) and implications for hominin
937 paleoenvironments. In: Quade, J., Wynn, J. (Eds.), *The Geology of Early Humans*
938 *in the Horn of Africa. Geol. S. Am. S.*, 446, pp. 67-85.
- 939 Feakins, S.J., Brown, F.H., deMenocal, P.B., 2007. Plio-Pleistocene microtephra in
940 DSDP site 231, Gulf of Aden. *J. Afr. Earth Sci.* 48, 341-352.
- 941 Feibel, C.S., Brown, F.H., McDougall, I., 1989. Stratigraphic context of fossil hominids
942 from the Omo Group deposits: northern Turkana Basin, Kenya. *Am. J. Phys.*
943 *Anthropol.* 78, 595-622.
- 944 Fleagle, J.G., Rasmussen, D.T., Yirga, S., Bown, T.M., Grine, F.E., 1991. New hominid
945 fossils from Fejej, southern Ethiopia. *J. Hum. Evol.* 21, 145-152.
- 946 Frogatt, P.C., 1992. Standardization of the chemical analysis of tephra deposits. *Quatern.*
947 *Int.* 13/14, 93-96.
- 948 Gathogo, P.N., Brown, F.H., 2006. Stratigraphy of the Koobi Fora Formation (Pliocene
949 and Pleistocene) in the Ileret region of northern Kenya. *J. Afr. Earth Sci.* 45, 369-
950 390.

- 951 Haile-Selassie, Y., 2010. Phylogeny of early *Australopithecus*: new fossil evidence from
952 the Woranso-Mille (central Afar, Ethiopia). Phil. Trans. R. Soc. B, 365, 3323-
953 3331.
- 954 Haile-Selassie, Y., Melillo, S.M., 2015. Middle Pliocene hominin mandibular fourth
955 premolars from Woranso-Mille (central Afar). J. Hum. Evol. 78, 44-59.
- 956 Haile-Selassie, Y., Deino, A., Saylor, B., Umer, M., Latimer, B., 2007. Preliminary
957 geology and paleontology of new hominid-bearing Pliocene localities in the
958 central Afar region of Ethiopia. Anthropol. Sci. 115, 215-222.
- 959 Haile-Selassie, Y., Latimer, B.M., Alene, M., Deino, A.L., Gibert, L., Melillo, S.M.,
960 Saylor, B.Z., Scott, G.R., Lovejoy, C.O., 2010a. An early *Australopithecus*
961 *afarensis* postcranium from Woranso-Mille, Ethiopia. Proc. Natl. Acad. Sci. 107,
962 12121-12126.
- 963 Haile-Selassie, Y., Saylor, B.Z., Deino, A., Alene, M., Latimer, B.M., 2010b. New
964 hominid fossils from Woranso-Mille (central Afar, Ethiopia) and taxonomy of
965 early *Australopithecus*. Am. J. Phys. Anthropol. 141, 406-417.
- 966 Haile-Selassie, Y., Saylor, B., Deino, A., Levin, N., Alene, M., Latimer, B., 2012. A new
967 hominin foot from Ethiopia shows multiple Pliocene bipedal adaptations. Nature
968 483, 565-569.

- 969 Haile-Selassie, Y., Gibert, L., Melillo, S.M., Ryan, T.M., Alene, M., Deino, A., Levin,
 970 N.E., Scott, G.R., Saylor, B.Z., 2015. New species from Ethiopia further expands
 971 Middle Pliocene hominin diversity. *Nature* 521, 483-488.
- 972 Haileab, B., Brown, F.H., 1992. Turkana Basin-Middle Awash Valley correlations and
 973 the age of the Sagantole and Hadar formations. *J. Hum. Evol.* 22, 453-468.
- 974 Harrison, T., 2011. Hominins from the Upper Laetoli and Upper Ndolanya beds, Laetoli.
 975 In: Harrison, T. (Ed.), *Paleontology and Geology of Laetoli: Human Evolution in*
 976 *Context*. Springer, Netherlands, pp. 141-188.
- 977 Hart, W.K., Walter, R.C., WoldeGabriel, G., 1992. Tephra sources and correlations in
 978 Ethiopia: application of elemental and neodymium isotope data. *Quatern. Int.* 13-
 979 14, 77-86.
- 980 Hillhouse, J.W., Cerling, T.E., Brown, F.H., 1986. Magnetostratigraphy of the Koobi
 981 Fora Formation, Lake Turkana, Kenya. *J. Geophys. Res. B: Solid Earth* 91(B11),
 982 11581-11595.
- 983 Kappelman, J., Swisher III, C.C., Fleagle, J.G., Yirga, S., Bown, T.M., Feseha, M., 1996.
 984 Age of *Australopithecus afarensis* from Fejej, Ethiopia. *J. Hum. Evol.* 30, 139-
 985 146.
- 986 Kimbel, W.H., Lockwood, C.A., Ward, C.V., Leakey, M.G., Rak, Y., Johanson, D.C.,
 987 2006. Was *Australopithecus anamensis* ancestral to *A. afarensis*? A case of
 988 anagenesis in the hominin fossil record. *J. Hum. Evol.* 51, 134-152.

- 989 Kuiper, K.F., Deino, A., Hilgen, F.J., Krijgsman, W., Renne, P.R., Wijbrans, J.R., 2008.
990 Synchronizing rock clocks of Earth history. *Science* 320, 500-503.
- 991 Leakey, M.G., Feibel, C.S., McDougall, I., Walker, A., 1995. New four-million-year-old
992 hominid species from Kanapoi and Allia Bay, Kenya. *Nature* 376, 565–571.
- 993 Leakey, M.G., Feibel, C.S., McDougall, I., Ward, C., Walker, A. 1998. New specimens
994 and confirmation of an early age for *Australopithecus anamensis*. *Nature* 393, 62–
995 66.
- 996 Lee, J.Y., Marti, K., Severinghaus, J.P., Kawamura, K., Yoo, H.S., Lee, J.B., Kim, J.S.,
997 2006. A redetermination of the isotopic abundances of atmospheric Ar. *Geochim.*
998 *Cosmochim. Acta.* 70, 4507-4512.
- 999 Levin, N.E., Haile-Selassie, Y., Frost, S.R., Saylor, B.Z., 2015. Dietary change among
1000 hominins and cercopethicids in Ethiopia during the early Pliocene. *Proc. Natl.*
1001 *Acad. Sci.* 112(40), 12304-12309. McDougall, I., Brown, F.H., 2008.
1002 Geochronology of the pre-KBS Tuff sequence, Omo Group, Turkana Basin. *J.*
1003 *Geol. Soc. London*, 165, 549-562.
- 1004 McDougall, I., Brown, F.H., Vasconcelos, P.M., Cohen, B.E., Thiede, D.S., Buchanan,
1005 M.J., 2012. New single crystal $^{40}\text{Ar}/^{39}\text{Ar}$ ages improve time scale for deposition of
1006 the Omo Group, Omo–Turkana Basin, East Africa. *J. Geol. Soc. London*, 169,
1007 213-226.

1008 Min, K., Mundil, R., Renne, P.R., Ludwig, K.R., 2000. A test for systematic errors in
1009 $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology through comparison with U/Pb analysis of a 1.1-Ga
1010 rhyolite. *Geochim. Cosmochim. Acta.* 64, 73-98.

1011 Morgan, G.B., London, D.L., 1996. Optimizing the electron microprobe analysis of
1012 hydrous alkali aluminosilicate glasses. *Am. Mineral.* 81, 1176-1185.

1013 Morgan, G.B., London, D.L., 2005. Effect of current density on the electron microprobe
1014 analysis of alkali aluminosilicate glasses. *Am. Mineral.* 90, 1131-1138.

1015 Nash, W., 1992. Analysis of oxygen with the electron microprobe: applications to
1016 hydrated glass and minerals. *Am. Mineral.* 77, 453-457.

1017 Quade, J., Levin, N.E., Simpson, S.W., Butler, R., McIntosh, W.C., Semaw, S.,
1018 Kleinsasser, L., Dupont-Nivet, G., Renne, P., Dunbar, N., 2008. The geology of
1019 Gona, Afar, Ethiopia. in: Quade, J., Wynn, J. (Eds.), *The Geology of Early*
1020 *Humans in the Horn of Africa*. *Geol. Soc. of Am. Special Papers*, 446, pp. 1-32.

1021 Renne, P.R., WoldeGabriel, G., Hart, W.K., Heiken, G., White, T.D., 1999.
1022 *Chronostratigraphy of the Miocene–Pliocene Sagantole Formation, Middle*
1023 *Awash Valley, Afar rift, Ethiopia*. *Geol. Soc. Am. Bull.* 111, 869-885.

1024 Renne, P. R., Mundil, R., Balco, G., Min, K., Ludwig, K. R., 2010. Joint determination of
1025 ^{40}K decay constants and $^{40}\text{Ar}^*/^{40}\text{K}$ for the Fish Canyon sanidine standard, and
1026 improved accuracy for $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology. *Geochim. Cosmochim. Acta.* 74,
1027 5349-5367.

- 1028 Roman, D., Campisano, C., Quade, J., DiMaggio, E., Arrowsmith, J., Feibel, C., 2008.
1029 Composite tephrostratigraphy of the Dikika, Gona, Hadar, and Ledi-Geraru
1030 project areas, northern Awash, Ethiopia. in: Quade, J., Wynn, J. (Eds.), The
1031 Geology of Early Humans in the Horn of Africa. Geol. S. Am. S. 446, pp. 119-
1032 134.
- 1033 Sarna-Wojcicki, A.M., Meyer, C.E., Roth, P.H., Brown, F.H., 1985. Ages of tuff beds at
1034 East African early hominid sites and sediments in the Gulf of Aden. Nature 313,
1035 306-308.
- 1036 Saylor, B.Z., Alene, M., Deino, A., Gibert, L., Haile-Selassie, Y., Melillo, S.M., Scott, G.,
1037 2016. The geologic context of Korsi Dora and the KSD-VP-1/1 partial skeleton.
1038 In: Haile-Selassie, Y., Su, D.F. (Eds.), The Postcranial Anatomy of
1039 *Australopithecus afarensis*: New Insights from KSD-VP-1/1. Springer, New York.
- 1040 Spell, T.L., McDougall, I., 2003. Characterization and calibration of $^{40}\text{Ar}/^{39}\text{Ar}$ dating
1041 standards. Chem. Geol., 198, 189-211.
- 1042 Steiger, R.H., Jäger, E., 1977. Subcommittee on geochronology: conventions on the use
1043 of decay constants in geo- and cosmochemistry. Earth Plan. Sci. Lett. 36, 359-
1044 362.
- 1045 Taieb, M., Johanson, D.C., Coppens, Y., Aronson, J.L., 1976. Geological and
1046 paleontological background of Hadar hominid site, Afar, Ethiopia. Nature 260,
1047 289-293.

- 1048 Walter, R.C., Aronson, J.L., 1993. Age and source of the Sidi Hakoma Tuff, Hadar
1049 Formation, Ethiopia. *J. Hum. Evol.*, 25, 229-240.
- 1050 Walter, R.C., Hart, W.K., Westgate, J.A., 1987. Petrogenesis of a basalt-rhyolite tephra
1051 from the West-central Afar, Ethiopia. *Contrib. Mineral. Petrol.* 95, 462-480.
- 1052 Ward, C.V. 2014. Taxonomic affinity of the Pliocene hominin fossils from Fejej,
1053 Ethiopia. *J. Hum. Evol.* 73, 98-102.
- 1054 White, T.D., Suwa, G., Hart, W.K., Walter, R.C., WoldeGabriel, G., Deheinzelin, J.,
1055 Clark, J.D., Asfaw, B., Vrba, E., 1993. New discoveries of *Australopithecus* at
1056 Maka in Ethiopia. *Nature* 366, 261-265.
- 1057 White, T.D., WoldeGabriel, G., Asfaw, B., Ambrose, S., Beyene, Y., Bernor, R.L.
1058 Boissarie, J.R., Currie, B., Gilbert, H., Haile-Selassie, Y., Hart, W.K., Hlusko,
1059 L.J., Howell, F.C., Kono, R.T., Lehmann, T., Louchart, A., Lovejoy, C.O., Renne,
1060 P.R., Saegusa, H., Vrba, E.S., Wesselman, H., Suwa, G., 2006. Asa Issie, Aramis
1061 and the origin of *Australopithecus*. *Nature* 440, 883-889.
- 1062 WoldeGabriel, G., Walter, R.C., Aronson, J.L., Hart, W.K., 1992. Geochronology and
1063 distribution of silicic volcanic rocks of Plio-Pleistocene age from the central
1064 sector of the Main Ethiopian Rift. *Quatern. Int.* 13/14, 69-76.
- 1065 WoldeGabriel, G., Heiken, G., White, T., Asfaw, B., Hart, W.K., Renne, P., 2000.
1066 Volcanism, tectonism, sedimentation, and the paleoanthropological record in the
1067 Ethiopian Rift system. In: McCoy, F.W., Heiken, G. (Eds.), *Volcanic Hazards and*

1068 Disasters in Human Antiquity, Geol. S. Am. S. 345, pp. 83-99. WoldeGabriel, G.,
 1069 Endale, T., White, T., Thouveny, N., Hart, W.K., Renne, P.R., Asfaw, B., 2013.
 1070 The role of tephra studies in African paleoanthropology as exemplified by the Sidi
 1071 Hakoma Tuff. J. Afr. Earth Sci. 77, 41-58.

1072 Wolfenden, E., Ebinger, C., Yirgu, G., Deino, A., Ayalew, D., 2004. Evolution of the
 1073 northern main Ethiopian rift: birth of a triple junction. Earth Planet. Sci. Lett. 224,
 1074 213-228.

1075 Wynn, J., Alemseged, Z., Bobe, R., Geraads, D., Reed, D., Roman, D., 2006. Geological
 1076 and palaeontological context of a Pliocene juvenile hominin at Dikika, Ethiopia.
 1077 Nature 443, 332-336.

1078 Wynn, J.G., Roman, D.C., Alemseged, Z., Reed, D., Geraads, D., Munro, S., 2008.
 1079 Stratigraphy, depositional environments, and basin structure of the Hadar and
 1080 Busidima formations at Dikika, Ethiopia. In: Quade, J., Wynn, J. (Eds.), The
 1081 Geology of Early Humans in the Horn of Africa. Geol. S. Am. S. 446, pp. 87-118.

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Figure Captions

Figure 1: Location maps. A) Location of the Woranso-Mille paleoanthropological research project (WM) and the Awash Valley relative to the Omo-Turkana Basin and deep-sea cores around the Horn of Africa. B) Location of the Waki-Mille area (box) of WORMIL relative to nearby volcanic centers and paleoanthropological field areas of the Lower and Middle Awash Valley, including G: Gona, H: Hadar, L: Ledi-Geraru, D: Dikika, and MA: Middle Awash. C) Locality (plain text), section (bold text), and sample (white box) locations in the Waki-Mille area, including AMA: Am-Ado, ARI: Aralee Issie, KER: Kerare, KSD: Korsi Dora, MSD: Mesgid Dora, MKM: Makah Mera, and WMC: Waki-Mille confluence, and the location of the 3.469 ± 0.008 Ma (Deino et al., 2010) Burtele Tuff (BT) at Burtele (BRT). White symbols show locations of named tuffs for which tephrochemical data are presented here, MLT: Mille Tuff sequence, WT: Waki Tuff, MDT: Mesgid Dora Tuff, KT: Kilaytoli Tuff, and SHT: Sidi Hakoma Tuff. Box shows location of Figure 2.

Figure 2: Map showing outcrops of named tuffs and section and sample locations across the Waki-Mille confluence (WMC), Mesgid Dora (MSD), and Makah Mera (MKM). Rose diagram shows paleocurrent directions based on trough azimuths measured across MSD. Abbreviations for named tuffs are as in Figure 1, AKT is Araskimiro Tuff. See Figure 3 for measured sections.

1107 Figure 3: Measured sections across the Waki-Mille confluence (WMC), Mesgid Dora
1108 (MSD), and Makah Mera (MKM). See Figure 2 for section and sample locations.
1109 $^{40}\text{Ar}/^{39}\text{Ar}$ ages are from Deino et al. (2010) except the age for the WT (samples
1110 WM09/W-2 and WM09/MD-1), which is from this paper.

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1112 Figure 4: Measured and composite stratigraphic sections in the Waki-Mille area
1113 identifying positions of tephra samples with EPMA glass compositional data and
1114 $^{40}\text{Ar}/^{39}\text{Ar}$ radiometric ages. Sections B and C are after Deino et al. (2010). Section D
1115 is after Haile-Selassie et al. (2012) and Saylor et al. (2016). Bold lines indicate
1116 correlations of tuffs for which there is high tephrochemical similarity. Sample
1117 numbers and positions for C are shown in Figures 2 and 3.

1118

1119 Figure 5: Bivariate plots of normalized A) Fe_2O_3 vs. Al_2O_3 , B) TiO_2 vs. CaO , C) MnO vs.
1120 SiO_2 , and D) MgO vs. SiO_2 for eastern African tephra samples between 4.0 Ma and 3.4
1121 Ma. Widespread Turkana Basin tuffs and their correlates in the Lower and Middle
1122 Awash Valley and in deep-sea cores are indicated by open symbols. Tephra samples
1123 from the Awash Valley that are not recognized in the Turkana Basin are indicated by
1124 closed symbols. See Table 2 for data and references.

1125

1126 Figure 6: Bivariate plots of normalized A) Fe_2O_3 vs. Al_2O_3 , B) TiO_2 vs. CaO , C) MgO vs.
1127 SiO_2 , and D) MnO vs. SiO_2 for Waki-Mille area tephra samples overlain on the
1128 compositional fields of eastern African tuffs from Figure 5. Samples of vitric ash are
1129 indicated with open symbols as opposed to samples of lapillistone tuff, which are

indicated by closed symbols. D.L. shows detection limit. See Table 3 for data and excluded values.

Figure 7: Age probability-density spectra for single-crystal $^{40}\text{Ar}/^{39}\text{Ar}$ dating results of the WT tuff. The results are divided for each of the three samples at an arbitrary age criterion of 4.5 Ma, representing a demarcation between grains attributed to detrital contamination, and younger grains considered more likely to be juvenile phenocrysts of the WT tuff. Weighted-mean ages of the juvenile population are shown, calculated after outlier deletion using a robust deviation from the median procedure. Closed symbols in the upper plot represent analyses included in the mean, whereas open symbols represent excluded grains. All errors are shown at 1σ . Not shown are several analyses at ~ 27 and 30 Ma (Table 4).

Table 1: Weighted-mean or ^ simple mean alkali feldspar ages adjusted to 28.198 Ma reference (Kuiper et al. 2008) and astronomically tuned model ages for eastern African tuffs between 4.0 Ma and 3.4 Ma from 1) deMenocal and Brown, 1999, 2) White et al., 1993, 3) McDougall and Brown, 2008, 4) Renne et al., 1999, 5) Walter and Aronson, 1993, 6) Deino et al., 2010, 7) Haile-Selassie et al., 2010a, 8) Haile-Selassie et al., 2012, 9) McDougall et al. 2012, 10) this study.

Omo-Turkana Basin (1σ)	Arabian Sea (Model)	Middle Awash (1σ)	Lower Awash	WORMIL (2σ)
^Tuff B, 3.424 ± 0.033 ⁹				
^β-Tulu Bor, <3.45 ± 0.023 ³	722A-11-1, 3.41 ± 0.01 ¹	Sidi Hakoma, 3.45 ± 0.02 ⁵ , 3.44 ± 0.04 ²	Sidi Hakoma	Sidi Hakoma
			Maka Sand	Arbosh
			Sidi Hakoma	?
				Burtele (BT) - 3.469 ± 0.008 ⁸
				Am-Ado (AAT) - 3.60± 0.03 ⁷
^Lokochot, 3.609 ± 0.045 ³	722A-11-4, 3.58 ± 0.01 ¹			Kilaytoli (KT) - 3.570 ± 0.014 ⁶
				AMA-09-1
				Mesgid Dora (MDT)
			Lomogol	Waki (WT), 3.664 ± 0.016 ¹⁰ (1σ)
			?	Araskimiro (AKT), 3.77 ± 0.04 ⁶
		ERV-036		Bimodal sequence
		?		Mille seq. (MLT), 3.76 ± 0.03 ⁶
				ARI-09-1
Wargolo	721C-13-3, 3.80 ± 0.01 ¹	VT3, 3.80± 0.02 ²	Ikini	?
				Cindery, 3.91 ± 0.08 ⁴ , 3.92 ± 0.01 ² , plag.
				ERV-046
				VT2
^Moiti, 3.984 ± 0.032 ³	722A-12-4, 3.96 ± 0.01 ¹	VT1, 3.94 ± 0.03 ² , 3.924 ± 0.010 ⁴		

Table 2: Abundances of oxides used for correlation of eastern African tuffs between 4.0 Ma and 3.4 Ma, normalized to 100%.

1 Sarna-Wojcicki et al., 1985		5 White et al., 1993		9 Feakins et al., 2007		AS Arabian Sea		LA Lower Awash										
2 Brown et al., 1992		6 deMenocal and Brown, 1999		10 Campisano & Feibel 2008		IO Indian Ocean		MA Middle Awash										
3 Wynn et al., 2006		7 Hart et al., 1992		11 WoldeGabriel et al., 2013		GoA Gulf of Aden												
4 Haileab & Brown, 1993		8 Gathogo & Brown, 2006				OTB Omo-Turkana Basin												
		Ref.		SiO ₂	1s	Al ₂ O ₃	1s	Fe ₂ O ₃	1s	CaO	1s	TiO ₂	1s	MgO	1s	MnO	1s	O.Total
Moiti/VT-1	K81-602	2	OTB	77.03		11.19		2.81		0.22		0.16				0.10		93.79
low Fe	231-22-1-82	1	GoA	77.02		11.11		2.74		0.21		0.17		0.01		0.09		93.60
	ERV-057	4	MA	78.60		11.10		2.95		0.21		0.17		0.01		0.14		94.26
	A81-42	7	MA	77.17		11.11		3.00		0.20		0.21		0.01		0.05		
	722A 12-4 (90-120)	6	AS	76.01		11.11	0.03	2.92	0.14	0.23		0.21	0.01	0.01		0.11	0.02	96.07
high Fe	231-22-1-82	1	GoA	75.95		10.23		4.60		0.28		0.35		0.01		0.15		92.10
	83-2 ANU	2	IO	74.41		11.01		4.61		0.30		0.32		0.01		0.18		95.85
	83-1 ANU	2	IO	74.31		11.11		4.65		0.30		0.36				0.17		95.44
	722A 12-4 (90-120)	6	AS	75.83	0.88	10.57	0.24	4.64	0.13	0.28	0.06	0.30	0.03	0.03	0.03	0.17	0.04	96.18
VT-2	A81-25	7	MA	75.72		11.85		3.42		0.33		0.25		0.01		0.06		
ERV046	ERV-046	4	MA	76.20		13.30		2.20		0.51		0.19		0.13		0.06		94.26
Cindery Tuff	A81-1	7	MA	75.44		12.26		3.01		1.00		0.21						
	A81-42	7	MA	75.54		12.30		2.94		1.00		0.22						
	ERV-049	4	MA			12.28		3.10		1.04		0.23						
Wargolo/VT-3/Ikini	721C 13-3 (90-120)	6	AS	76.12	0.58	11.48	0.23	2.61	0.07	0.19	0.01	0.16	0.04	0.03	0.01	0.07	0.04	95.67
	K81-485	2	OTB	77.91	0.43	11.42	0.26	2.48	0.06	0.20	0.02	0.14	0.02	0.03	0.02	0.08	0.03	92.49
	231-21-2 (15-17)	1	GoA	76.87	0.68	11.44	0.24	2.42	0.06	0.18	0.01	0.13	0.02	0.07	0.01	0.18	0.01	93.20
	EO2-1110	3	LA	77.18	0.55	12.21	0.38	2.11	0.13	0.18	0.04	0.08	0.09	0.03				93.95
	EO2-2004	3	LA	77.45	0.88	12.31	0.26	2.46	0.13	0.16	0.03	0.11	0.04	0.02	0.04			91.99
	ERV-053	4	MA	78.87		11.27		2.64	0.00	0.19		0.14		0.02		0.07		94.62
	MA90-29	5	MA	77.90		11.28		2.34	0.00	0.14		0.12		0.02		0.02		92.07
	MA90-30A	5	MA	77.16		11.07		2.33	0.00	0.17		0.13		0.02		0.07		93.50
	MA90-45A	5	MA	77.03		11.16		2.38	0.00	0.20		0.13				0.07		92.12
	TW91-3	5	MA	77.82		11.19		2.43	0.00	0.18		0.13		0.01		0.04		91.92
	A81-70	7	MA	77.40		11.33		2.57	0.00	0.13		0.12		0.02		0.04		
ERV036	ERV-036a	4	MA	80.54		12.26		2.20		0.35		0.14		0.02		0.03		91.83
	ERV-036b	4	MA	69.69		13.29		8.19		2.72		0.62		0.11		0.24		92.16

Lomogol/ERV032	722A 11-5(60-90)	6	AS	74.84		10.22	0.30	4.61	0.47	0.21	0.02	0.24	0.04	0.02	0.02	0.17	0.03	90.67
	232A-1-5(25-27)	1	GoA	75.39	0.79	10.53	0.45	4.14	0.37	0.19	0.02	0.24	0.04	0.16	0.02	0.19	0.02	92.68
	K82-742	2	OTB	77.85	0.68	10.62	0.24	4.62	0.12	0.21	0.03	0.25	0.03	0.02	0.01	0.19	0.02	95.48
	ERV-032	4	MA	80.83		10.70		4.83		0.21		0.30		0.20		0.05		91.28
Lokochot	K80-293	2	OTB	76.89		11.06		3.14		0.19		0.17		0.03		0.10		93.70
low Fe	K81-532	2	OTB	78.01		11.30		3.20		0.17		0.17		0.03		0.10		92.30
	K80-295	2	OTB	77.43	0.80	11.12	0.19	3.19	0.10	0.19	0.02	0.18	0.04	0.03	0.02	0.11	0.01	91.45
	722A 11-4 (60-90)	6	AS	75.62	0.37	10.99	0.10	3.27	0.06	0.22	0.05	0.19	0.05	0.04	0.02	0.09	0.04	95.03
	232-16-4-10	2	GoA	76.34		11.13		3.06		0.18		0.19		0.02		0.09		93.50
high Fe	IL02-194	8	OTB	80.01	0.40	11.40	0.13	2.94	0.17	0.21	0.01	0.24	0.07	0.03	0.02	0.10	0.07	95.34
	231-20-1(20-30) M19	9	GoA	77.82	0.50	11.34	0.12	3.07	0.07	0.20	0.01	0.20	0.04	0.03	0.01	0.09	0.02	92.24
	231-20-1(20-30) M29	9	GoA	78.02	0.79	11.19	0.10	3.14	0.06	0.18	0.01	0.19	0.02	0.03	0.04	0.10	0.02	94.03
	231-20-1(20-30) M39	9	GoA	77.86	0.66	10.49	0.08	4.50	0.04	0.23	0.01	0.24		0.01	0.01	0.14	0.01	92.81
	K80-293	2	OTB	77.74		10.37		4.59		0.21		0.22		0.02		0.15		91.40
	K81-532	2	OTB	78.76		10.63		4.67		0.19		0.23		0.00		0.14		90.00
	IL02-194	8	OTB	80.03	0.38	10.67	0.10	4.21	0.26	0.20	0.03	0.28	0.10	0.02	0.01	0.21	0.06	94.38
sub-Arbosh SHT	231-20-2 (25-28)	1	GoA	76.65	0.66	10.62	0.35	4.06	0.35	0.19	0.02	0.23	0.03	0.16	0.02	0.19	0.02	92.48
	722A 11-4 (60-90)	6	AS	75.99	1.34	10.42	0.24	4.57	0.20	0.22	0.01	0.23	0.08	0.03	0.01	0.13	0.03	96.42
	K80-295	2	OTB	77.33	0.61	10.41	0.23	4.43	0.06	0.20	0.03	0.21	0.05	0.02	0.01	0.15	0.03	90.60
	E03-3017	3	LA	77.24		12.93		1.52		0.26		0.14		0.06				93.99
Maka Sand/Arbosh	E03-3018	3	LA	77.73		13.25		1.76		0.31		0.18		0.06				93.39
	E03-3019	3	LA	78.66		13.38		1.55		0.27		0.13		0.05				90.67
	MA90-16 Lo Fe	5	MA	76.25		12.87		1.61		0.51		0.11		0.07				93.77
α -Tulu Bor	MA90-16 HI Fe	5	MA	75.48		12.92		2.30		0.80		0.15		0.02				91.69
	E02-2005	3	LA	75.08		13.67		2.09		0.67		0.14		0.06				91.49
	K82-851	2	OTB	76.67		13.67		1.54		0.58		0.23		0.06		0.03		90.70
β -Tulu Bor/	II02-116	8	OTB	77.39	0.45	13.53	0.20	1.36	0.12	0.58	0.04	0.25	0.04	0.04	0.02	0.13	0.02	93.66
	E02-2003	3	LA	77.71		13.24		1.67		0.31		0.13						91.58

SHT	E03-3020	3	LA	78.00	13.20	1.52	0.29	0.23	0.10								90.34
	MA90-14	5	MA	76.52	12.68	1.54	0.31	0.13	0.05	0.08							92.64
	MA90-28	5	MA	76.69	12.32	1.61	0.30	0.13	0.02	0.03							92.64
	MA90-39	5	MA	77.85	12.44	1.57	0.31	0.11	0.03	0.07							91.63
	HE01-207	10	LA	78.76	0.30 12.55	0.08	1.67	0.08	0.30	0.03	0.16	0.03	0.04	0.01	0.06	0.03	93.00
	HE01-208	10	LA	78.35	0.31 12.51	0.11	1.64	0.03	0.30	0.01	0.14	0.03	0.06	0.01	0.04	0.01	94.23
	HE01-140	10	LA	78.67	0.20 12.56	0.06	1.68	0.01	0.29	0.03	0.17	0.04	0.05	0.01	0.04	0.02	92.86
	82-869	2	OTB	76.80	0.21 12.73	0.10	1.69	0.06	0.30	0.02	0.16	0.06	0.06	0.01	0.05	0.01	3.09
	722A 11-1 (30-60)	6	AS	76.96	0.50 12.74	0.20	1.76	0.03	0.33	0.02	0.14	0.01	0.06	0.01	0.08	0.01	92.07
	231-19-2 (33-34)	1	GoA	76.43	0.60 12.50	0.23	1.57	0.06	0.31	0.06	0.14	0.01	0.05	0.01			94.31
	IL02-118	8	OTB	78.48	0.39 12.71	0.15	1.67	0.08	0.32	0.05	0.17	0.05	0.05	0.02	0.05	0.02	94.97
	TB05-024	8	OTB	78.20	0.37 12.89	0.11	1.64	0.06	0.33	0.02	0.17	0.04	0.06	0.01	0.05	0.01	93.78
	E02-2006	3	LA	76.66	13.13	1.60	0.31	0.17	0.07								92.48
	IL02-118	8	OTB	78.48	0.39 12.71	0.15	1.67	0.08	0.32	0.05	0.17	0.05	0.05	0.02	0.05	0.02	94.97
	TB05-024	8	OTB	78.20	0.37 12.89	0.11	1.64	0.06	0.33	0.02	0.17	0.04	0.06	0.01	0.05	0.01	93.78
	E02-2006	3	LA	76.66	13.13	1.60	0.31	0.17	0.07								92.48
	MA-05-05	11	MA	76.73	12.34	1.80	0.32	0.15	0.05	0.06							94.89
	MA-06-41	11	MA	77.49	12.69	1.63	0.32	0.15	0.05	0.05							93.83
	MA-06-43	11	MA	77.42	12.73	1.74	0.32	0.16	0.12	0.05							94.82
	MA-07-23	11	MA	78.01	12.66	1.68	0.32	0.15	0.08	0.05							94.44
	MA-05-39	11	MA	77.17	12.76	1.66	0.31	0.15	0.05	0.06							94.2
	MA-93-33	11	MA	76.65	12.38	1.58	0.30	0.14	0.04	0.05							94.85
	MA-94-50	11	MA	76.84	12.67	1.64	0.31	0.16	0.05	0.04							94.01
	231-19-2-26	2	GoA	76.37	12.64	1.578	0.31	0.15	0.08	0.05							93.13
	ET-128	2	OTB	78.16	12.74	1.438	0.29	0.16	0.04	0.04							91.79
	ET-19	2	OTB	78.01	12.78	1.605	0.3	0.15	0.05	0.04							90.94
high Fe	231-19-2	2	GoA	73.06	13.85	2.947	0.55	0.28	0.12	0.11							92.98
	ET-128	2	OTB	75.38	14.3	2.993	0.74	0.39	0.2	0.1							89.22
	ET-19	2	OTB	75.63	13.87	3.013	0.54	0.3	0.1	0.09							88.95

Table 3. Oxide abundances for Waki-Mille area tuffs normalized for differences in water measured as halogen corrected excess oxygen (O*). Italics < detection limits.

	N	Na ₂ O	1s	MgO	1s	Cl	1s	CaO	1s	K ₂ O	1s	SiO ₂	1s	Al ₂ O ₃	1s	TiO ₂	1s	MnO	1s	Fe ₂ O ₃	1s	Total	Total-O*
Sidi Hakom Tuff (SHT) (β-Tulu Bor correlate)																							
ESC 12-5	12	2.90	0.29	0.08	0.02	0.09	0.01	0.35	0.02	6.56	0.41	75.85	0.70	12.31	0.07	0.18	0.05	0.04	0.03	1.62	0.10	100.75	95.82
BDB-09-1	12	2.37	0.18	0.07	0.05	0.10	0.02	0.31	0.02	5.54	0.63	76.42	0.70	12.64	0.14	0.15	0.05	0.06	0.03	1.58	0.12	101.36	95.31
Am Ado Tuff sequence (AAT)																							
AMA 09-5	6	2.25	0.44	0.32	0.01	0.08	0.01	1.07	0.05	5.59	0.34	74.09	0.67	13.96	0.17	0.33	0.08	0.04	0.04	1.98	0.16	101.10	93.37
MKM11-1P	14	2.28	0.43	0.33	0.03	0.09	0.01	1.08	0.03	5.58	0.91	74.52	0.40	13.92	0.14	0.33	0.08	0.05	0.03	1.82	0.17	100.69	92.21
MSD 09-5 P excluded	13 1.0	2.38 1.46	0.37	0.31 0.06	0.05	0.08 0.13	0.01	1.05 0.25	0.11	5.66 4.12	0.52	74.56 78.64	0.65	13.68 10.78	0.30	0.34 0.18	0.07 0.13	0.03 0.13	0.04	1.90 4.24	0.14	100.15 98.36	92.42 90.06
ESC-12-4	5	2.15	0.13	0.33	0.03	0.08	0.01	1.12	0.04	5.57	0.57	74.47	0.31	13.83	0.14	0.36	0.06	0.04	0.03	1.90	0.16	98.63	92.37
Kilaytoli Tuff (KT) (Lokochot correlate)																							
WM-KSD-1 Lo Fe	11	2.67	0.52	0.04	0.02	0.14	0.02	0.19	0.01	5.11	0.30	77.14	1.03	11.34	0.12	0.19	0.06	0.07	0.03	3.11	0.17	99.88	92.99
WM-KSD-3 Lo Fe	8	2.42	0.34	0.02	0.01	0.13	0.02	0.20	0.02	4.53	0.36	78.04	0.66	11.27	0.21	0.17	0.03	0.09	0.03	3.13	0.14	99.90	92.66
WM-KSD-3 Hi Fe	11	2.30	0.33	0.04	0.03	0.19	0.02	0.21	0.02	4.41	0.44	77.38	0.97	10.59	0.15	0.28	0.06	0.15	0.04	4.45	0.31	99.67	92.76
ARI-08-5 Low Fe	13	2.34	0.44	0.03	0.01	0.13	0.02	0.20	0.02	5.01	0.56	77.32	0.82	11.24	0.25	0.22	0.08	0.12	0.04	3.40	0.41	99.82	92.82
ARI-08-5 Hi Fe	5	1.77	0.25	0.04	0.02	0.17	0.05	0.22	0.04	4.40	0.39	77.86	0.46	10.64	0.29	0.27	0.02	0.14	0.03	4.48	0.30	99.63	91.57
MSD-08-13 Lo Fe	9	2.02	0.30	0.04	0.02	0.12	0.02	0.19	0.03	4.84	0.38	77.92	0.65	11.41	0.19	0.20	0.07	0.09	0.03	3.16	0.27	99.89	92.76
MSD-08-13 Hi Fe	3	1.53	0.37	0.04	0.03	0.19	0.02	0.19	0.02	4.21	0.60	78.75	0.97	10.19	0.25	0.22	0.05	0.15	0.02	4.53	0.08	100.0	93.26
AMA-09-4 Lo Fe	4	2.26	0.68	0.03	0.01	0.14	0.01	0.20	0.03	6.13	0.31	76.57	0.44	11.39	0.10	0.17	0.05	0.13	0.05	2.99	0.22	100.6	93.41
AMA-09-4 Hi Fe	5	2.21	0.75	0.03	0.01	0.18	0.01	0.19	0.02	5.54	0.66	76.41	0.79	10.71	0.22	0.21	0.04	0.15	0.05	4.36	0.31	100.1	92.61
KSD 09-8 Lo Fe	2	2.63	0.86	0.03	0.01	0.14	0.02	0.20	0.02	4.52	0.45	78.14	0.38	11.04	0.05	0.18	0.01	0.06	0.04	3.07	0.00	100.1	91.13

KSD 09-8 1Hi Fe	2	2.12	0.16	0.05	0.06	0.20	0.03	0.22	0.05	4.11	0.06	77.98	0.85	10.30	0.23	0.19	0.12	0.19	0.03	4.64	0.13	99.0	89.23
KER-13-3 Lo Fe	4	2.514	1.3	0.02	0.03	0.15	0.0	0.20	0.02	4.78	0.57	77.27	0.79	11.1	0.12	0.16	0.03	0.09	0.02	3.41	0.13	99.93	90.1825
KER-13-3 Hi Fe	2	3.288	0.66	0.04	0.00	0.16	0.0	0.24	0.02	4.19	0.23	76.61	0.07	10.61	0.46	0.24	0.07	0.14	0.06	4.70	0.32	101.1	90.7881
AMA 09-1																							
AMA 09-1	3	1.50	1.20	0.29	0.03	0.05	0.00	0.94	0.06	3.33	2.38	77.62	1.97	13.58	0.24	0.31	0.01	0.04	0.03	2.32	0.08	99.35	88.6003
excluded	1	3.0		0.12		0.06		0.39		3.59		78.76		12.0		0.30		0.05		1.758		99.17	88.52
Mesgid Dora Tuff (MDT)																							
ARI-08-1	10	2.90	0.37	0.18	0.02	0.07	0.01	0.74	0.04	5.54	0.46	74.82	0.62	13.51	0.14	0.21	0.06	0.07	0.03	1.96	0.16	100.1	93.62
MKM-08-1	9	2.69	0.56	0.17	0.02	0.07	0.01	0.73	0.03	6.12	0.31	74.41	0.61	13.52	0.10	0.23	0.03	0.06	0.02	1.99	0.10	100.7	93.08
MSD-08-5	12	2.81	0.64	0.16	0.07	0.07	0.02	0.75	0.08	6.02	0.57	74.36	0.54	13.54	0.22	0.25	0.05	0.06	0.03	1.98	0.22	100.2	94.68
excluded	1	1.46		0.01		0.13		0.16		4.29		78.59		10.66		0.27		0.18		4.26		99.23	92.70
ARI-09-2 P 5/09	4	2.42	0.16	0.18	0.02	0.08	0.01	0.75	0.03	6.31	0.09	74.58	0.51	13.58	0.14	0.23	0.04	0.06	0.04	2.11	0.07	100.5	93.30
ARI-09-2 P 5/11	7	2.01	0.80	0.20	0.03	0.07	0.02	0.76	0.03	4.91	1.08	76.26	1.25	13.54	0.07	0.22	0.10	0.05	0.04	1.97	0.21	99.9	91.33
excluded	1	1.48		0.01		0.19		0.18		4.29		78.16		10.04		0.21		0.16		5.27		101.33	91.59
AMA-12-1 P	11	2.49	0.40	0.18	0.02	0.07	0.07	0.74	0.02	5.96	0.48	75.01	0.99	13.26	0.13	0.24	0.05	0.06	0.03	2.05	0.20	100.0	94.23
KSD-13-1 P	7	4.01	0.55	0.21	0.02	0.07	0.01	0.75	0.04	3.53		75.62	0.81	13.39	0.07	0.25	0.06	0.08	0.02	2.02	0.18	100.6	94.90
Waki Tuff (Lomogol correlate)																							
ARI-08-2	19	1.80	0.44	0.03	0.01	0.15	0.04	0.18	0.04	4.76	0.52	77.57	0.78	10.52	0.35	0.24	0.05	0.18	0.03	4.58	0.41	100.0	92.11
WMC-08-4	16	2.21	0.28	0.03	0.01	0.14	0.04	0.19	0.04	4.35	0.71	77.70	0.92	10.57	0.31	0.24	0.07	0.16	0.04	4.41	0.41	100.5	92.68
MSD-09-3	21	1.83	0.44	0.04	0.08	0.16	0.04	0.18	0.03	4.78	0.75	77.45	1.19	10.50	0.39	0.22	0.04	0.16	0.04	4.47	0.37	99.2	91.51

Araskimiro Tuff (AMT)

WM-MD5 P	10	1.93	0.32	0.15	0.02	0.08	0.02	0.77	0.03	5.19	0.42	76.18	0.76	13.13	0.13	0.20	0.09	0.08	0.02	2.29	0.26	100.2	91.58
MSD 11-2 P	7	1.90	0.42	0.18	0.02	0.06	0.02	0.84	0.12	4.92	0.54	76.62	1.00	13.32	0.25	0.20	0.05	0.06	0.03	2.28	0.40	100.5	92.43
MSD 08-3R	12	2.51	0.52	0.13	0.01	0.07	0.02	0.75	0.03	5.55	0.46	75.21	0.90	13.15	0.09	0.22	0.05	0.07	0.02	2.34	0.11	99.1	90.60

Bimodal tuff sequence

MSD-08-3B P	10	2.38	0.14	5.69	0.16	0.02	0.01	9.96	0.10	0.82	0.04	50.68	0.47	13.38	0.10	2.88	0.12	0.23	0.02	13.96	0.44	99.3	98.38
WMC 08-3 P	16	2.46	0.21	0.09	0.02	0.07	0.01	0.56	0.03	5.97	0.52	76.62	0.90	12.35	0.10	0.13	0.04	0.05	0.03	1.75	0.07	100.1	95.59

Mille Tuff Sequence (MLT sequence)

MSD-08-2	10	2.67	0.24	0.02	0.01	0.04	0.01	0.46	0.03	5.72	0.36	76.67	0.42	12.29	0.09	0.12	0.07	0.04	0.02	1.96	0.12	101	93.47
ARI-08-3	12	2.90	0.38	0.03	0.02	0.05	0.02	0.46	0.05	5.60	0.31	76.37	0.92	12.33	0.17	0.15	0.07	0.05	0.02	2.07	0.21	100.7	93.62
ARI-08-4	11	2.89	0.48	0.03	0.03	0.04	0.02	0.45	0.04	5.05	0.68	77.07	1.27	12.18	0.29	0.15	0.07	0.06	0.03	2.08	0.28	101.2	94.52

ARI-09-1

ARI-09-1	10	3.19	0.56	0.05	0.01	0.04	0.02	0.75	0.03	5.08	0.44	74.61	0.61	12.89	0.20	0.16	0.05	0.10	0.02	2.81	0.24	100.7	94.93
excluded	1	5.29		0.04		0.01		0.37		3.60		76.90		13.17		0.11		0.02		0.49		100.3	97.75

Table 4.

Lab ID#	<i>J</i> (X 10 ⁻³) ± 1s		Relative Isotopic Abundances										Derived Results						
			⁴⁰ Ar ±1s	³⁹ Ar ±1s	³⁸ Ar ±1s	³⁷ Ar ±1s	³⁶ Ar ±1s	³⁹ Ar Mol × 10 ⁻¹⁵	Ca/K ±1s	% ⁴⁰ Ar ⁺	Age (Ma) ±1s	w/± <i>J</i> ±1s							
WM09/MD-1 (Ages < 4.5 Ma)																			
25328-01	1.836	0.002	0.326248	0.001419	0.279584	0.000772	0.003298	0.000112	0.018159	0.000313	0.000075	0.000026	0.306	0.495	0.010	94.8	3.661	0.094	0.094
25328-02	1.836	0.002	0.044837	0.001087	0.074644	0.000316	0.000884	0.000065	0.002716	0.000259	0.000028	0.000024	0.082	0.277	0.027	83.2	1.653	0.320	0.320
25328-03	1.836	0.002	0.046502	0.001096	0.076975	0.000438	0.000888	0.000050	0.002524	0.000279	-0.000003	0.000024	0.084	0.250	0.028	103.4	2.067	0.310	0.310
25328-04	1.836	0.002	0.131389	0.001193	0.118462	0.000345	0.001368	0.000070	0.059930	0.000370	0.000066	0.000025	0.130	3.870	0.052	99.1	3.640	0.211	0.211
25328-05	1.836	0.002	0.068284	0.001105	0.062160	0.000320	0.000803	0.000049	0.029224	0.000313	0.000058	0.000025	0.068	3.600	0.060	87.9	3.198	0.402	0.402
25328-06	1.836	0.002	0.049315	0.001062	0.044005	0.000237	0.000568	0.000040	0.021845	0.000289	0.000044	0.000025	0.048	3.803	0.070	87.2	3.235	0.568	0.568
25328-07	1.836	0.002	0.259074	0.001362	0.232988	0.000762	0.002624	0.000099	-0.000723	0.000250	0.000004	0.000024	0.255	-0.024	0.008	99.4	3.656	0.106	0.106
25328-09	1.836	0.002	0.294452	0.001421	0.265298	0.000782	0.003121	0.000103	-0.000361	0.000254	0.000006	0.000025	0.291	-0.011	0.007	99.4	3.648	0.095	0.095
25328-10	1.836	0.002	0.139020	0.001176	0.108200	0.000344	0.001372	0.000072	0.046041	0.000476	0.000130	0.000026	0.119	3.273	0.052	82.4	3.504	0.244	0.244
25328-11	1.836	0.002	0.077166	0.001087	0.065666	0.000315	0.000802	0.000063	0.000318	0.000249	0.000000	0.000024	0.072	0.037	0.029	100.2	3.894	0.370	0.370
25328-12	1.836	0.002	0.032380	0.001055	0.030273	0.000179	0.000331	0.000032	0.014669	0.000333	0.000007	0.000025	0.033	3.732	0.098	107.5	3.807	0.821	0.821
25328-13	1.836	0.002	0.030238	0.001002	0.025470	0.000198	0.000336	0.000039	0.012750	0.000307	0.000009	0.000026	0.028	3.858	0.108	104.3	4.099	0.997	0.997
25328-14	1.836	0.002	0.166922	0.001174	0.151110	0.000374	0.001723	0.000070	-0.000189	0.000261	-0.000012	0.000025	0.166	-0.010	0.013	102.1	3.731	0.167	0.167
25328-15	1.836	0.002	0.217431	0.001215	0.195311	0.000523	0.002250	0.000064	-0.000164	0.000261	0.000011	0.000024	0.214	-0.007	0.010	98.5	3.626	0.126	0.126
25328-16	1.836	0.002	0.058984	0.001051	0.053587	0.000296	0.000568	0.000043	0.026050	0.000340	0.000006	0.000026	0.059	3.755	0.069	110.6	4.030	0.477	0.477
25328-18	1.836	0.002	0.058512	0.001069	0.053308	0.000314	0.000623	0.000043	0.024461	0.000340	0.000025	0.000026	0.058	3.549	0.068	100.3	3.644	0.488	0.488
25328-20	1.836	0.002	0.177985	0.001210	0.161824	0.000404	0.002052	0.000058	-0.000339	0.000249	0.000003	0.000027	0.177	-0.017	0.012	99.5	3.619	0.168	0.168
25328-21	1.836	0.002	0.205223	0.001240	0.182793	0.000543	0.002243	0.000085	0.000126	0.000249	0.000022	0.000028	0.200	0.005	0.011	96.9	3.597	0.152	0.152
25328-22	1.836	0.002	0.128326	0.001111	0.115150	0.000404	0.001506	0.000061	-0.000073	0.000253	-0.000007	0.000027	0.126	-0.005	0.017	101.6	3.743	0.231	0.231
25328-23	1.836	0.002	0.045722	0.001033	0.037613	0.000237	0.000370	0.000043	0.019686	0.000313	0.000038	0.000028	0.041	4.068	0.084	88.4	3.560	0.730	0.730
25328-24	1.836	0.002	0.347368	0.001229	0.314567	0.000961	0.003555	0.000098	-0.000344	0.000265	0.000001	0.000027	0.345	-0.009	0.007	99.9	3.648	0.089	0.089
25328-25	1.836	0.002	0.167897	0.001193	0.078487	0.000304	0.000995	0.000051	0.040266	0.000377	0.000265	0.000031	0.086	3.993	0.061	60.4	4.276	0.396	0.396
25328-27	1.836	0.002	0.049554	0.001041	0.028840	0.000178	0.000290	0.000038	0.055331	0.000493	0.000130	0.000028	0.032	15.012	0.238	56.8	3.245	0.956	0.956

25328-28	1.836	0.002	0.588797	0.001632	0.522806	0.001401	0.006000	0.000112	-0.000220	0.000254	0.000059	0.000027	0.573	-0.004	0.004	97.0	3.612	0.054	0.054
25328-30	1.836	0.002	0.161145	0.001163	0.143527	0.000812	0.001751	0.000054	0.000128	0.000257	-0.000010	0.000026	0.157	0.007	0.014	101.8	3.780	0.180	0.180
25328-31	1.836	0.002	0.411876	0.001462	0.373449	0.001101	0.004364	0.000090	0.000222	0.000251	0.000005	0.000026	0.409	0.004	0.005	99.7	3.636	0.072	0.072
25328-32	1.836	0.002	0.040545	0.001010	0.035942	0.000180	0.000427	0.000038	0.018108	0.000333	0.000010	0.000025	0.039	3.941	0.088	106.6	3.980	0.705	0.705
WM09/MD-1 (Ages > 4.5 Ma)																			
25328-08	1.836	0.002	0.268555	0.001412	0.039085	0.000247	0.000568	0.000037	0.017944	0.000347	0.000729	0.000032	0.043	3.526	0.083	21.1	4.791	0.866	0.866
25328-17	1.836	0.002	2.067133	0.003544	0.222485	0.000672	0.002709	0.000087	0.000695	0.000269	-0.000001	0.000028	0.244	0.024	0.009	100.0	30.514	0.195	0.198
25328-19	1.836	0.002	0.163373	0.001195	0.044840	0.000225	0.000708	0.000043	0.021227	0.000326	0.000293	0.000031	0.049	3.663	0.073	50.4	6.082	0.691	0.691
25328-26	1.836	0.002	2.041167	0.003055	0.219487	0.000642	0.002536	0.000089	0.000434	0.000260	-0.000005	0.000028	0.241	0.015	0.009	100.1	30.556	0.194	0.197
25328-29	1.836	0.002	0.056277	0.001035	0.013624	0.000169	0.000188	0.000034	0.058496	0.000409	0.000143	0.000028	0.015	33.868	0.628	56.9	7.865	2.040	2.040
WM09/W-2 (Ages < 4.5 Ma)																			
25331-02	1.837	0.002	0.123651	0.001292	0.048835	0.000198	0.000707	0.000054	0.149888	0.000582	0.000459	0.000032	0.054	28.090	0.360	33.6	2.845	0.666	0.666
25331-04	1.837	0.002	0.938942	0.001564	0.829981	0.001901	0.010120	0.000162	0.008297	0.000279	0.000003	0.000028	0.910	0.090	0.003	100.2	3.750	0.038	0.038
25331-06	1.837	0.002	0.088730	0.001307	0.079715	0.000314	0.000942	0.000047	0.024341	0.000320	0.000043	0.000028	0.087	2.779	0.050	95.5	3.518	0.356	0.356
25331-07	1.837	0.002	0.090218	0.001341	0.050845	0.000247	0.000544	0.000043	0.125932	0.000619	0.000295	0.000030	0.056	22.725	0.305	53.6	3.174	0.601	0.602
25331-08	1.837	0.002	0.505406	0.001632	0.454793	0.001102	0.005288	0.000142	0.000152	0.000249	0.000014	0.000027	0.498	0.003	0.005	99.2	3.644	0.062	0.062
25331-09	1.837	0.002	0.150207	0.001355	0.130517	0.000434	0.001560	0.000078	0.040784	0.000417	0.000088	0.000028	0.143	2.851	0.045	92.4	3.522	0.216	0.216
25331-10	1.837	0.002	0.393315	0.001534	0.350450	0.001002	0.004322	0.000112	-0.000032	0.000249	-0.000011	0.000027	0.384	-0.001	0.006	100.8	3.742	0.079	0.079
25331-11	1.837	0.002	0.506169	0.001582	0.448302	0.001202	0.005311	0.000112	0.000079	0.000253	0.000077	0.000028	0.491	0.001	0.005	95.5	3.565	0.064	0.065
25331-12	1.837	0.002	0.593854	0.001720	0.534185	0.001302	0.006113	0.000172	0.000009	0.000265	0.000016	0.000028	0.585	0.000	0.005	99.2	3.648	0.055	0.055
25331-13	1.837	0.002	0.536796	0.001708	0.480302	0.001102	0.005734	0.000079	0.000216	0.000258	0.000031	0.000027	0.526	0.004	0.005	98.3	3.634	0.060	0.060
25331-15	1.837	0.002	0.079649	0.001009	0.071252	0.000274	0.000809	0.000052	0.022319	0.000347	0.000058	0.000024	0.078	2.946	0.058	89.0	3.295	0.331	0.331
25331-16	1.837	0.002	0.084167	0.001005	0.074767	0.000285	0.000935	0.000043	0.031571	0.000417	0.000059	0.000023	0.082	3.975	0.071	93.2	3.475	0.307	0.307
25331-18	1.837	0.002	0.476508	0.001316	0.262934	0.000842	0.003192	0.000112	0.000090	0.000252	0.000620	0.000028	0.288	0.003	0.010	61.2	3.666	0.118	0.118
25331-20	1.837	0.002	0.216694	0.001188	0.196452	0.000562	0.002373	0.000086	-0.000301	0.000254	0.000013	0.000022	0.215	-0.016	0.013	98.2	3.582	0.111	0.111
25331-21	1.837	0.002	0.125622	0.000891	0.105487	0.000842	0.001251	0.000063	0.033342	0.000417	0.000045	0.000023	0.116	3.164	0.059	100.1	3.946	0.218	0.218
25331-22	1.837	0.002	0.117196	0.000991	0.104801	0.000383	0.001281	0.000059	0.038727	0.000409	0.000064	0.000024	0.115	3.703	0.059	97.1	3.594	0.226	0.226
25331-23	1.837	0.002	0.067788	0.000873	0.058997	0.000274	0.000649	0.000048	0.015180	0.000274	0.000039	0.000023	0.065	2.578	0.057	92.1	3.502	0.391	0.391
25331-24	1.837	0.002	0.305426	0.001117	0.278293	0.000762	0.003316	0.000122	-0.000274	0.000259	0.000001	0.000023	0.305	-0.010	0.009	99.9	3.626	0.083	0.084

25331-25	1.837	0.002	0.361253	0.001252	0.323749	0.001001	0.004053	0.000112	-0.000476	0.000265	0.000031	0.000023	0.355	-0.015	0.008	97.4	3.594	0.073	0.073
25331-26	1.837	0.002	0.400315	0.001334	0.329588	0.000851	0.003911	0.000112	0.010380	0.000274	0.000080	0.000024	0.361	0.316	0.009	95.1	3.819	0.076	0.076
25331-27	1.837	0.002	0.345225	0.001172	0.307433	0.000881	0.003833	0.000101	-0.000097	0.000254	0.000023	0.000024	0.337	-0.004	0.008	98.0	3.638	0.079	0.079
25331-28	1.837	0.002	0.287751	0.001261	0.255729	0.000881	0.002966	0.000112	-0.000169	0.000248	-0.000005	0.000022	0.280	-0.007	0.010	100.5	3.739	0.090	0.090
WM09/W-2 (Ages > 4.5 Ma)																			
25331-05	1.837	0.002	1.422704	0.002025	0.517020	0.001201	0.006222	0.000103	0.000498	0.000279	0.000925	0.000036	0.566	0.008	0.005	80.6	7.330	0.088	0.088
25331-14	1.837	0.002	0.070462	0.001168	0.061300	0.000314	0.000761	0.000065	0.019127	0.000320	-0.000042	0.000028	0.067	2.856	0.060	127.9	4.864	0.454	0.454
25331-17	1.837	0.002	0.984154	0.001679	0.441674	0.001001	0.005242	0.000112	0.000048	0.000255	0.000015	0.000024	0.484	0.001	0.005	99.6	7.330	0.062	0.063
WM09/W-1 (Ages < 4.5 Ma)																			
25336-08	1.844	0.003	0.912851	0.001903	0.784801	0.002002	0.009523	0.000233	0.001620	0.000063	0.000066	0.000027	10.435	0.013	0.001	97.9	3.782	0.040	0.040
25336-14	1.844	0.003	0.027018	0.000897	0.024499	0.000181	0.000237	0.000052	0.080316	0.000440	0.000068	0.000024	0.326	21.005	0.345	101.1	3.729	0.983	0.983
25336-17	1.844	0.003	0.506445	0.001512	0.448132	0.001202	0.004814	0.000092	0.001015	0.000058	-0.000012	0.000024	5.958	0.014	0.001	100.8	3.782	0.056	0.057
25336-20	1.844	0.003	0.130838	0.000946	0.097592	0.000414	0.000999	0.000094	0.040550	0.000410	0.000121	0.000022	1.298	2.654	0.046	80.3	3.579	0.231	0.231
25336-22	1.844	0.003	0.066223	0.000841	0.057802	0.000315	0.000665	0.000083	0.016567	0.000191	0.000070	0.000021	0.769	1.831	0.034	75.0	2.856	0.368	0.368
25336-24	1.844	0.003	0.029021	0.000790	0.024849	0.000198	0.000233	0.000041	0.014607	0.000221	0.000010	0.000020	0.330	3.764	0.082	102.6	3.986	0.821	0.821
25336-29	1.844	0.003	0.073839	0.000961	0.046626	0.000239	0.000447	0.000060	0.013273	0.000362	0.000072	0.000024	0.051	2.874	0.086	78.1	4.113	0.518	0.518
25336-34	1.844	0.003	0.078212	0.001075	0.066655	0.000366	0.000852	0.000053	0.023450	0.000327	0.000001	0.000024	0.073	3.591	0.068	111.8	4.362	0.368	0.368
25336-35	1.844	0.003	0.030844	0.000940	0.026586	0.000199	0.000268	0.000044	0.009889	0.000290	0.000031	0.000024	0.029	3.800	0.123	83.2	3.208	0.902	0.902
25336-38	1.844	0.003	0.071404	0.001014	0.059853	0.000297	0.000794	0.000066	0.022967	0.000362	0.000059	0.000025	0.066	3.928	0.079	88.4	3.508	0.424	0.424
WM09/W-1 (Ages > 4.5 Ma)																			
25336-02	1.844	0.003	1.321053	0.002073	0.592077	0.001602	0.006965	0.000183	0.000872	0.000043	0.000033	0.000029	7.872	0.009	0.000	99.3	7.349	0.062	0.063
25336-03	1.844	0.003	1.543819	0.002057	0.685226	0.001602	0.008044	0.000242	0.002378	0.000078	0.000076	0.000028	9.112	0.021	0.001	98.6	7.368	0.056	0.057
25336-04	1.844	0.003	2.725999	0.004112	1.212588	0.003001	0.014517	0.000242	0.002255	0.000083	0.000034	0.000029	16.122	0.011	0.000	99.6	7.433	0.045	0.046
25336-05	1.844	0.003	0.791858	0.001491	0.558065	0.001802	0.006833	0.000213	0.002105	0.000099	-0.000012	0.000028	7.421	0.023	0.001	100.5	4.735	0.056	0.056
25336-06	1.844	0.003	1.807482	0.002364	1.278954	0.002102	0.014145	0.000471	0.006936	0.000141	0.000022	0.000028	17.005	0.034	0.001	99.7	4.680	0.031	0.032
25336-07	1.844	0.003	0.745325	0.001640	0.417634	0.001203	0.004266	0.000154	0.001263	0.000059	0.000065	0.000027	5.552	0.019	0.001	97.4	5.772	0.073	0.074
25336-09	1.844	0.003	1.101361	0.001907	0.495955	0.001202	0.005655	0.000164	0.000810	0.000056	0.000023	0.000026	6.593	0.010	0.001	99.4	7.325	0.065	0.066
25336-10	1.844	0.003	0.441996	0.001565	0.192755	0.000545	0.002398	0.000100	0.000720	0.000050	-0.000004	0.000026	2.562	0.023	0.002	100.3	7.631	0.141	0.141
25336-12	1.844	0.003	1.403949	0.002175	0.973580	0.001601	0.010732	0.000392	0.004024	0.000111	0.000122	0.000026	12.945	0.026	0.001	97.5	4.667	0.036	0.037

25336-13	1.844	0.003	0.843530	0.001547	0.381972	0.001401	0.004448	0.000164	0.001076	0.000055	0.000046	0.000026	5.079	0.017	0.001	98.4	7.210	0.079	0.080
25336-15	1.844	0.003	0.652062	0.001700	0.464170	0.001401	0.004911	0.000233	0.001732	0.000064	0.000002	0.000023	6.171	0.023	0.001	100.0	4.662	0.057	0.057
25336-16	1.844	0.003	0.837458	0.001517	0.379271	0.001002	0.004223	0.000154	0.001248	0.000064	-0.000008	0.000023	5.043	0.021	0.001	100.3	7.350	0.072	0.073
25336-18	1.844	0.003	3.076490	0.003978	0.979702	0.001601	0.011810	0.000401	0.003356	0.000151	0.003179	0.000032	13.027	0.021	0.001	69.2	7.208	0.093	0.093
25336-19	1.844	0.003	0.910495	0.001785	0.405365	0.001002	0.004618	0.000134	0.000396	0.000050	0.000128	0.000023	5.390	0.006	0.001	95.8	7.141	0.070	0.071
25336-21	1.844	0.003	0.744557	0.001684	0.331852	0.000962	0.003813	0.000125	0.001257	0.000053	0.000018	0.000023	4.412	0.024	0.001	99.3	7.394	0.079	0.080
25336-23	1.844	0.003	1.131096	0.001942	0.804895	0.001701	0.008983	0.000144	0.003874	0.000065	0.000114	0.000022	10.701	0.030	0.001	97.1	4.530	0.037	0.037
25336-25	1.844	0.003	0.743569	0.001561	0.331235	0.001201	0.003356	0.000076	0.001941	0.000095	0.000095	0.000021	4.404	0.037	0.002	96.3	7.170	0.077	0.078
25336-26	1.844	0.003	0.397552	0.001246	0.180841	0.000464	0.002080	0.000100	0.000154	0.000043	0.000028	0.000020	2.404	0.005	0.002	97.9	7.144	0.118	0.118
25336-27	1.844	0.003	2.107193	0.002530	0.260066	0.000863	0.002964	0.000085	0.001489	0.000081	0.000043	0.000021	3.458	0.036	0.002	99.4	26.587	0.168	0.172
25336-28	1.844	0.003	0.780872	0.001650	0.358145	0.000891	0.003933	0.000112	0.000194	0.000261	0.000019	0.000023	0.393	0.005	0.007	99.3	7.181	0.073	0.073
25336-31	1.844	0.003	2.046808	0.002949	0.243016	0.000943	0.002675	0.000095	0.016893	0.000348	0.000061	0.000027	0.266	0.707	0.017	99.5	27.641	0.187	0.191
25336-32	1.844	0.003	0.791605	0.001591	0.352921	0.001004	0.004230	0.000082	0.000144	0.000265	0.000052	0.000025	0.387	0.004	0.008	98.1	7.297	0.079	0.080
25336-33	1.844	0.003	0.873480	0.001835	0.376225	0.001103	0.004444	0.000152	0.001362	0.000260	0.000156	0.000026	0.412	0.036	0.007	94.7	7.297	0.081	0.081
25336-36	1.844	0.003	1.080493	0.001915	0.488095	0.001102	0.006191	0.000090	0.000226	0.000251	0.000031	0.000025	0.535	0.004	0.005	99.2	7.282	0.062	0.062
25336-37	1.844	0.003	0.478291	0.001409	0.342739	0.001001	0.003847	0.000112	-0.000269	0.000254	-0.000078	0.000025	0.376	-0.008	0.008	104.9	4.857	0.075	0.076

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5ab

Figure 5cd

Figure 6ab

Figure 6cd

Figure 7