A chronological framework for a long and persistent archaeological record: Melka Kunture, Ethiopia

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Abstract
New 40Ar/39Ar geochronological data for several volcanic ash horizons from Melka Kunture, Ethiopia, allow for significantly more precise age constraints to be placed upon the lithostratigraphy, archaeology and paleontology from this long record. Ashes from the Melka Kunture Formation at Gombore yielded the most reliable age constraints, from 1.393 ± 0.162 Ma (millions of years ago) near the base of the section to 0.709 ± 0.013 Ma near the top. Dating the Garba section proved more problematic, but the base of the section, which contains numerous Oldowan obsidian artifacts, may be >1.719 ± 0.199 Ma, while the top is securely dated to 0.869 ± 0.020 Ma. The large ignimbrite from the Kella Formation at Kella and Melka Garba is dated to 1.262 ± 0.034 Ma and pre-dates Acheulean artifacts in the area. The Gombore II site, which has yielded two Homo skull fragments, ‘twisted bifaces,’ and a preserved butchery site, is now constrained between 0.875 ± 0.010 Ma and 0.709 ± 0.013 Ma. Additional ashes from these and other sites further constrain the timing of deposition throughout the section.

Integration with previously published magnetostratigraphy has allowed for the first time a relatively complete, reliable timeline for the deposition of sediments, environmental changes, archaeology, and paleontology at Melka Kunture.

Introduction

History and importance

The site of Melka Kunture includes several localities located on the banks of the Awash River and on the shoulder of the Ethiopian Rift (Figures 1 and 2). The archaeological potential of the area was first recognized by hydrologist Gerard Dekker in 1963 (Chavaillon and Piperno, 2004b) and was first extensively surveyed by Gerard Bailloud in 1963 and 1964 (Bailloud, 1965). Excavations were led by Jean Chavaillon from 1965 to 1995. Since 1999, they have been led by Marcello Piperno (Chavaillon and Piperno, 2004b). Archaeology found at these sites includes artifacts from every major period of the African archaeological record from the Oldowan to the Late Stone Age (Chavaillon and Berthelet, 2004).

Frequently, evidence bearing on human evolution varies both spatially and temporally. Evidence from a particular time period is collected from sites that are hundreds to thousands of kilometers apart and it is relatively rare to find multiple time periods represented within a small area. At Melka Kunture, however, the collection of localities in such close proximity and covering such a wide variety of archaeological technologies (and presumably time) can potentially add a great deal to our understanding of the biological and behavioral evolution of human ancestors over time in this one region. By better constraining the chronology of the localities at Melka Kunture using modern geochronological techniques, the formal lithostratigraphic units (Raynal et al., 2004),

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and the Adindan (Arc) datum. A U.T.M. Zone 37 Grid using a transverse Mercator projection, Clarke 1880 spheroid, Ethiopia (Clark et al., 2003). Artifacts from Kella I, Wofii contain an Acheulean-Middle Stone Age transition and has been excavated since 2007 and still unpublished), Garba XII and Simbiro are considered by some to be too robust to be a Homo habilis, although the latter is much more commonly associated with the Oldowan- or Acheulean-type archaeology from this site (H. erectus is commonly found with Acheulean archaeology). Similarly, the partial mandible of an apparent H. erectus infant has been found at Garba IV, also associated with Oldowan archaeology. Yet two other specimens of H. erectus (skull fragments) have been found at the Gombole II Locality 1, where they are associated with Acheulean archaeology. Three H. sapiens cranial fragments have been found at Garba III, where they are associated with Late Acheulean artifacts.

Vertebrate paleontology (excluding hominids), paleoenvironments, and lithostratigraphy

The vertebrate paleontology at the Melka Kunture sites is dominated by the order Cetartiodactyla (Montgelard et al., 1997) and includes bovids, giraffids, hippopotamids, and suids, as well as primates. With few exceptions, the fossil material is postcranial or dental. Faunal information has also been previously published (Geraads, 1979; Chavaillon and Berthelet, 2004; Geraads et al., 2004). Nearly all of the localities include H. erectus previously described previously (Chavaillon et al., 1974; Chavaillon and Copps, 1975; Chavaillon et al., 1977a, 1977b; Chavaillon and Copps, 1986; Chavaillon et al., 1987; Condemi, 2004; Copps, 2004; Zilberman et al., 2004a, 2004b) and include four apparent Homo erectus (sensu lato) specimens and one probable archaic Homo sapiens. The apparent H. erectus humerus from Gombole I is considered by some to be too robust to be a Homo habilis, although the latter is much more commonly associated with the Oldowan-type archaeology from this site (H. erectus is commonly found with Acheulean archaeology). Similarly, the partial mandible of an apparent H. erectus infant has been found at Garba IV, also associated with Oldowan archaeology. Yet two other specimens of H. erectus (skull fragments) have been found at the Gombole II Locality 1, where they are associated with Acheulean archaeology. Three H. sapiens cranial fragments have been found at Garba III, where they are associated with Late Acheulean artifacts.

Hominids

The hominid fossils found at Melka Kunture have been described previously (Chavaillon et al., 1974; Chavaillon and Copps, 1975; Chavaillon et al., 1977a, 1977b; Chavaillon and Copps, 1986; Chavaillon et al., 1987; Condemi, 2004; Copps, 2004; Zilberman et al., 2004a, 2004b) and include four apparent Homo erectus (sensu lato) specimens and one probable archaic Homo sapiens. The apparent H. erectus humerus from Gombole I is considered by some to be too robust to be a Homo habilis, although the latter is much more commonly associated with the Oldowan-type archaeology from this site (H. erectus is commonly found with Acheulean archaeology). Similarly, the partial mandible of an apparent H. erectus infant has been found at Garba IV, also associated with Oldowan archaeology. Yet two other specimens of H. erectus (skull fragments) have been found at the Gombole II Locality 1, where they are associated with Acheulean archaeology. Three H. sapiens cranial fragments have been found at Garba III, where they are associated with Late Acheulean artifacts.

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particular the $\delta^{13}C$ values of mostly $-2\%$ (PDB) on bovid and equid fossil tooth enamel, support the presence of open C$_4$ grasslands (Bocherens et al., 1996).

The architecture and facies of lithostratigraphic units, particularly the channeling processes and sediment facies (coarse gravels, sands, and clays; largely volcanic), are consistent with fluvial and associated floodplain depositional environments of the paleo-Awash river and its tributaries (Raynal et al., 2004). Recurrent tectonic events, as well as volcanic inputs that are evidenced by several volcanic ashes in primary and sub-primary positions, have
frequently interfered with the climatically-driven sedimentary processes (Raynal and Kieffer, 2004).

The lithostratigraphic, faunal, and isotopic evidence suggests that these floodplains and other areas surrounding the river were likely dry, open savannahs. The presence of evidence of hominin activity is thus not surprising, as hominin fossils and artifacts are often found at the interface between land and freshwater (Hay, 1976).

**Previous geochronology: K–Ar and magnetostratigraphy**

Previous geochronology at Melka Kunture included K–Ar and paleomagnetic analyses. K–Ar data were never formally published but are often attributed to an abstract by Schmitt et al. (1977). The abstract cited does not actually contain K–Ar ages (which were likely reported only orally at the conference), but the apparent results are cited in the monograph edited by Chauchillon and Piperno (2004a). Many of these analyses were performed on glass shards, which are known to yield spurious apparent ages due to post-depositional potassium and/or argon mobility within the glass (Cerling et al., 1985; Morgan et al., 2008). Additionally, the stratigraphic context of the analyzed samples was not well described, further undermining the utility of these previously undocumented K–Ar results. The best estimates for the locations of these samples are shown in Figure 2(a, b, c).

Paleomagnetic analyses were published by Westphal et al. (1979), Cressier (1980), and Tamrat (1997), however correlations between their stratigraphic sections (and associated magnetic polarity stratigraphy) and the more recent sections published by Raynal et al. (2004) are not always clear. When a correlation can be made with confidence, magnetostratigraphic results are shown Figure 2(a, b, c).

The chronostratigraphic significance of paleomagnetic data is difficult to interpret without reliable absolute ages to determine which magnetic reversals are recorded in the sediments, i.e., to facilitate unambiguous correlation of magnetostratigraphy with the geomagnetic polarity time scale (Gradstein et al., 2004). New $^{40}$Ar/$^{39}$Ar geochronological data presented here, when combined with previous paleomagnetic work, thus help to constrain the ages of the artifacts found at several Melka Kunture localities.

**Methods**

**Sample collection**

Tephra samples were collected at Melka Kunture in October 2007 and November 2008, in close collaboration with geologists and archaeologists working on the sites. Care was taken to avoid contamination in the form of root cast infillings and modern roots when possible, although in some cases this was inevitable. Sample locations were recorded with a handheld GPS unit using the WGS 84 reference coordinate system (Table 1). Care was also taken to accurately place and name samples according to the previously published formal lithostratigraphy (Raynal et al., 2004).

**Electron microprobe geochemistry**

The geochemistry of glass shards from volcanic ashes was measured with a Cameca XS-51 electron microprobe in the Department of Earth and Planetary Science at the University of California, Berkeley. A 10 μm rastered beam at 15 nA and 15 kV was used to limit volatilization of mobile elements in glass. Multiple points ($n = 2–5$) were measured on each shard. Multiple shards ($n = 5–15$) were measured from each sample. Obvious outliers, including measurements inadvertently made on mineral grains (feldspars, pyroxenes, etc.) or void-filling epoxy, were omitted from further consideration.

**$^{40}$Ar/$^{39}$Ar geochronology**

Volcanic ash samples were prepared and measured as in Morgan and Renne (2008). Samples were co-irradiated with the Alder Creek sanidine (ACs) (Nomade et al., 2005) standard using the standard and decay constant calibration published by Renne et al. (2010). Values used for nucleogenic production ratios are as in Renne et al. (2005). The atmospheric $^{40}$Ar/$^{39}$Ar ratio of Steiger and Jäger (1977) was used. More recent determinations of atmospheric $^{40}$Ar/$^{39}$Ar give ~1% higher values (Lee et al., 2006; Valkiers et al., 2010), but as shown by Renne et al. (2009) this has negligible impact on age calculations because the same value was used to determine mass discrimination and the air correction. $^{40}$Ar/$^{39}$Ar geochronology was performed at the Berkeley Geochronology Center as in Morgan and Renne (2008). Background values were constrained by measuring blanks every ~ three analyses. Mass discrimination was monitored by measuring air pipette aliquots every ~10–15 analyses. Full data are provided in Supplementary Table 1. Single crystal total fusion (SCTF) was performed on all samples, with the exception of MK27-13, which has sufficiently small crystals that multigrain total fusion analyses were necessary. Finally, MK27-09 and ~20 were subjected to multigrain step-heating experiments in addition to the SCTF.

**Results**

**Electron microprobe geochemistry and potential correlations**

Full data are provided in Supplementary Table 2, including individual shard averages and values for the standard error of the mean (shown in italics). The one exception to this is sample MK27-04, for which it was not possible to visually relocate microprobe points after analysis. Thus, each analysis for this sample is treated individually because the correspondence between analyses and individual shards is ambiguous.

Geochemical data were visualized and analyzed using JMP® version 7.0 (SAS Institute Inc., 2007). A plot of the first two principal components based on correlations of all measured oxides (except relatively volatile oxides Na₂O and K₂O) is shown in Figure 3. Each point represents a single measured shard. Each individual color/shape combination represents a sample. Visual inspection allows for identification of potential correlative units, which are discussed below.

Group A (samples MK27-01, 04, 05, 16) Since samples MK27-04 and MK27-05 were taken from the same outcrop of a non-welded ignimbrite at Kella, their correlation is reliable. Sample MK27-01 was taken from another outcrop of ignimbrite at Melka Garba that was previously believed to be the same lithostratigraphic unit (Raynal and Kieffer, 2004) that forms the Kella Formation (Raynal et al., 2004). The similar geochemistry of these three samples seems to confirm that correlation.

The geochemistry of MK27-16, from a tuff underlying Garba XIII in the Garba gully, overlaps with the others in this group in most oxides, which the exception of Al₂O₃. Although there is only a slight difference, when combined with the mineralogical differences between this tuff and the others, this correlation is tenuous at best. As shown below, MK27-01 and MK27-05 have very similar ages. MK27-16 differs more but is also indistinguishable in age (at the 2σ level) from these two units. An age for MK27-04 was not determined. See Table 2 for details.

Group B (Samples MK27-09, 11, 12, 13, 20) Samples MK27-09 and MK27-20 show very slight differences in SiO₂ concentration, but
Table 1
Sample descriptions, locality name, formation, and unit [Raynal et al., 2004], and GPS coordinates for tephra sampled at Melka Kunture.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Description</th>
<th>Locality</th>
<th>Formation</th>
<th>Unit</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>27–01</td>
<td>Pumice clasts from ignimbrite</td>
<td>Melka Garba</td>
<td>Kella F.</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>27–02</td>
<td>Lithics and pumices from degassing pipe within ignimbrite</td>
<td>Melka Garba</td>
<td>Kella F.</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>27–03</td>
<td>Light gray-brown, fine-grained volcanic ash</td>
<td>Gombore I</td>
<td>Melka Kunture F.</td>
<td>9965–9967</td>
<td>N08 42.333'E</td>
<td>E038 36.094'</td>
</tr>
<tr>
<td>27–04</td>
<td>Pumice clasts from ignimbrite</td>
<td>Kella</td>
<td>Kella F.</td>
<td>N/A</td>
<td>N08 42.881'E</td>
<td>E038 36.602'</td>
</tr>
<tr>
<td>27–05</td>
<td>Base surge of ignimbrite</td>
<td>Kella</td>
<td>Kella F.</td>
<td>N/A</td>
<td>N08 42.881'E</td>
<td>E038 36.602'</td>
</tr>
<tr>
<td>27–06</td>
<td>Volcanic ash ~20 cm thick white fine w/xts</td>
<td>Wofí</td>
<td>—</td>
<td>N/A</td>
<td>N08 43.311'E</td>
<td>E038 34.568'</td>
</tr>
<tr>
<td>27–07</td>
<td>Dark gray indurated volcanic ash</td>
<td>Garba XII</td>
<td>Melka Kunture F.</td>
<td>N/A</td>
<td>N08 42.371'E</td>
<td>E038 33.866'</td>
</tr>
<tr>
<td>27–08</td>
<td>White, fine-grained volcanic ash with xts</td>
<td>Gombore II</td>
<td>Melka Kunture F.</td>
<td>9959</td>
<td>N08 42.314'E</td>
<td>E038 36.098'</td>
</tr>
<tr>
<td>27–09</td>
<td>Crystal- and pumice-rich tuff</td>
<td>Gombore II</td>
<td>Melka Kunture F.</td>
<td>9989</td>
<td>N08 42.284'E</td>
<td>E038 36.098'</td>
</tr>
<tr>
<td>27–10</td>
<td>Crystal-rich bentonite</td>
<td>Gombore II</td>
<td>Melka Kunture F.</td>
<td>9988</td>
<td>N08 42.284'E</td>
<td>E038 36.098'</td>
</tr>
<tr>
<td>27–11</td>
<td>Crystal-rich bentonite</td>
<td>Gombore II</td>
<td>Melka Kunture F.</td>
<td>9988</td>
<td>N08 42.284'E</td>
<td>E038 36.098'</td>
</tr>
<tr>
<td>27–12</td>
<td>Ash flow tuff, sampled just above surge deposit</td>
<td>Gombore I</td>
<td>Melka Kunture F.</td>
<td>9978</td>
<td>N08 42.339'E</td>
<td>E038 36.092'</td>
</tr>
<tr>
<td>27–13</td>
<td>Very fine-grained, light gray-blue volcanic ash (former C tuff)</td>
<td>Garba Gully</td>
<td>Melka Kunture F.</td>
<td>9933</td>
<td>N08 42.322'E</td>
<td>E038 33.852'</td>
</tr>
<tr>
<td>27–14</td>
<td>Very fine-grained, light gray volcanic ash</td>
<td>Simbíro</td>
<td>—</td>
<td>N/A</td>
<td>N08 42.506'E</td>
<td>E038 33.989'</td>
</tr>
<tr>
<td>27–15</td>
<td>Tuffaceous sandstone</td>
<td>Simbíro</td>
<td>—</td>
<td>N/A</td>
<td>N08 42.502'E</td>
<td>E038 33.988'</td>
</tr>
<tr>
<td>27–16</td>
<td>Gray, medium-grained volcanic ash (former B tuff)</td>
<td>Garba Gully</td>
<td>Melka Kunture F.</td>
<td>9928</td>
<td>N08 42.343'E</td>
<td>E038 35.904'</td>
</tr>
<tr>
<td>27–17</td>
<td>White, medium-grained volcanic ash</td>
<td>Kella</td>
<td>Melka Kunture F.</td>
<td>N/A</td>
<td>N08 42.929'E</td>
<td>E038 36.739'</td>
</tr>
<tr>
<td>27–18</td>
<td>White, fine-grained volcanic ash</td>
<td>Kella III</td>
<td>Melka Kunture F.</td>
<td>N/A</td>
<td>N08 42.901'E</td>
<td>E038 36.718'</td>
</tr>
<tr>
<td>27–19</td>
<td>Light gray-brown, fine-grained volcanic ash</td>
<td>Garba Gully</td>
<td>Melka Kunture F.</td>
<td>9918–9923</td>
<td>N08 42.354'E</td>
<td>E038 35.906'</td>
</tr>
<tr>
<td>27–20</td>
<td>Crystal- and pumice-rich tuff</td>
<td>Garba Gully</td>
<td>Melka Kunture F.</td>
<td>N/A</td>
<td>N08 42.920'E</td>
<td>E038 36.677'</td>
</tr>
<tr>
<td>27–21</td>
<td>Crystal-rich bentonite</td>
<td>Garba Gully</td>
<td>Melka Kunture F.</td>
<td>N/A</td>
<td>N08 42.920'E</td>
<td>E038 36.677'</td>
</tr>
<tr>
<td>27–22</td>
<td>Crystal- and pumice-rich tuff</td>
<td>Garba Gully</td>
<td>Melka Kunture F.</td>
<td>N/A</td>
<td>N08 42.920'E</td>
<td>E038 36.677'</td>
</tr>
<tr>
<td>27–23</td>
<td>Very fine-grained, gray volcanic ash</td>
<td>Garba IV</td>
<td>Melka Kunture F.</td>
<td>9911</td>
<td>N08 42.384'E</td>
<td>E038 33.920'</td>
</tr>
<tr>
<td>2005–10</td>
<td>Crystal- and pumice-rich tuff</td>
<td>Simbíro</td>
<td>—</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Other oxides are overlap considerably. When this is considered along with their similar mineralogies and their respective locations near the top of the Melka Kunture Formation at the Gombore II and Kella I sections, this correlation is highly probable. ⁴°Ar/³⁹Ar ages for these two tuffs (provided below) are indistinguishable (Table 2).

Sample MK27-12 shows slight, but clear distinctions from all other sampled units. The ⁴°Ar/³⁹Ar age for this unit is significantly older than those for the other geochemically similar units (Table 2). The possibility remains that this unit formed from an eruptive sequence that also formed the non-welded ignimbrite (MK27-01, MK27-05), as their ages are indistinguishable (Table 2) and their geochemistry is distinct but reasonably similar.

Considering the stratigraphic proximity, and geochemical and mineralogical similarities between MK27-09 and MK27-11, it is highly likely that they are derived from the same volcanic system. MK27-12, MK27-13, and MK27-20 may also derive from this same system, although differences in age suggest that they were erupted over a significant time period. MK27-12 may also contain antecrysts.

Group C (Samples MK27-06, 14) Although in Principal Component space these two samples overlap considerably (Figure 3), several oxides show discrepancies when considered individually (Supplementary Table 2). No correlation is made here.

Group D (samples MK27-07, MK2005-10) These two samples show considerable overlap in both Principal Component space and also in all measured oxides, thus a correlation is likely. ⁴°Ar/³⁹Ar geochronological data for MK27-07 are imprecise, but consistent with this correlation.

⁴°Ar/³⁹Ar geochronology

The tephras intercalated in Melka Kunture strata vary from ignimbritic deposits that are many meters thick to fine distal ashes of only a few centimeters thickness. Some are apparently free of xenocrystic contamination, while others contain significant contamination. This may have occurred during eruption or by post-depositional reworking. Feldspar compositions include mostly anorthoclase and sanidine, although plagioclase is found in some samples. Specifics for each sample, as determined by isotopic ratios...
MK27-06 The inverse isochron here is poorly constrained. The MSWD and P are beyond the acceptable range (defined above) but are slightly better than those for the weighted mean age. Thus, the inverse isochron age is adopted as the more reliable age for this unit.

MK27-07 This sample has no clearly-defined juvenile population. However, since the tuff overlies the archaeology at Garba XII, the youngest crystal can serve as a valid minimum age here.

MK27-09 Due to the presence of a single juvenile population with no apparent xenocrysts, as shown in Figure 5(A, B), multigrain separates from MK27-09 were incrementally heated. Three of the four step-heating experiments yielded plateau ages (Figure 5C). The weighted mean of these is 0.742 ± 0.022 Ma. An isochron age, including steps from the same three aliquots that have >3% of the total 39Ar released, yield an age of 0.740 ± 0.009 Ma (Figure 5D). The slightly higher (in one case distinguishable at 1σ) ages obtained by the multigrain step-heating experiments could be caused by xenocrystic contamination not apparent in the single crystal data. Considering that the age of the unit is a constraint on underlying archaeology and paleontology, the slightly younger, and less well-constrained, weighted mean age of single crystals (0.709 ± 0.013 Ma) is considered a more reliable and valid age for this unit.

MK27-11 The weighted mean model age for this unit differs significantly from the isochron age, although the initial 40Ar/39Ar value is very imprecise (670 ± 160). Since the sample was taken from a tuff directly underlying the tuff from which sample MK27-09 was taken, and since MK27-09 yields a much more reliable age, we do not interpret an age for this unit.

MK27-12 When analyses yielding less than three times the applied background correction are omitted, a juvenile population becomes apparent (Figure 4). An inverse isochron of the juvenile population of crystals yields little spread but similar MSWD and P to the weighted mean age (Figure 4D). The weighted mean age is selected here as more reliable due to superior MSWD and P, as well as the lack of sufficient spread on the isochron.
MK27-13 Individual grains separated from this fine-grained distal ash were too small (\(\sim 180-200 \, \mu m\)) to yield sufficient gas for analysis, so multiple grains (\(n = 50\)) were analyzed in each aliquot. One analysis was omitted for poor ion beam evolution as a function of time, and another is significantly older than the remaining aliquots (Figure 5G). The weighted mean and inverse isochron (Figure 5H) of the potentially juvenile population yield nearly identical ages of 0.870 ± 0.019 and 0.869 ± 0.020 Ma. The possibility of xenocrystic contamination is very high here, especially considering the number of crystals analyzed with no previous single crystal work, but this age is remarkably reproducible, suggesting the presence of little to no contamination.

MK27-16 No obvious juvenile population exists here, although there is a significant xenocrystic population at \(\sim 5\) Ma. The ages of remaining crystals are scattered. The youngest crystal has an age of 1.429 ± 0.029 Ma, which can be considered a maximum age for overlying sediments and archaeology.

MK27-19 This sample contains many xenocrysts and no clear juvenile population. The youngest crystal has an age of 1.429 ± 0.029 Ma, which can be considered a maximum age for overlying sediments and archaeology.

MK27-20 A weighted mean of individual crystals yields a single population with no apparent xenocrysts (Figure 6E, F). Step-heating of four multigrain aliquots a single plateau age of 0.797 ± 0.08 Ma (Figure 6G). An inverse isochron for these data yields an indistinguishable age (Figure 6H). The multigrain aliquots yield slightly older ages than the single crystal data. This could be

Figure 4. Age probability diagrams and inverse isochrons for single crystal total fusion data from (A, B) MK27-03, (C, D) MK27-12, and (E, F) MK27-08. Apparent xenocrysts are shown in gray in age probability diagrams and are not shown on isochrons. These are omitted from all age calculations. Only analyses with sufficient \(^{40}\text{Ar}\) (more than three times blank) are shown here. Isochrons include only analyses from apparent juvenile populations.
Figure 5. Age probability diagrams and inverse isochrons for single crystal total fusion data from (A, B) MK27-09, (E, F) MK27-23, (G, H) MK27-13, and age spectra and inverse isochrons (C, D) for incremental-heating data from MK27-09. Apparent xenocrysts are shown in gray in age probability diagrams and are not shown on isochrones. These are omitted from all age calculations. Incremental heating experiments not resulting in a plateau age are shown in gray in (C). Only analyses with sufficient ⁴⁰Ar (more than three times blank) are shown here. Isochrons (B, D, F, H) include only analyses from apparent juvenile populations. Only steps from plateaux containing more than 3% of the total ³⁹Ar released are shown on isochron from incremental heating data (D).
Figure 6. Age probability diagrams and inverse isochrons for single crystal total fusion data from (A, B) MK27-05, (C, D) MK27-01, (E, F) MK27-20, and inverse isochron and age spectra from (G, H) MK27-20. Apparent xenocrysts are shown in gray in age probability diagrams and are not shown on isochrones. These are omitted from all age calculations. The only incremental heating experiment to yield a plateau age is shown with thicker lines. Only analyses with sufficient $^{39}$Ar (more than three times blank) are shown here. Isochrons (B, D, F) include only analyses from apparent juvenile populations. Steps from plateau containing less than 3% of the total $^{39}$Ar released are shown in gray on the isochron from incremental heating data (H) and are not included in calculations.
explained by alteration more significantly manifest in the single grain total fusion data, but the possibility of xenocrystic contamination in the multigrained aliquots cannot be ruled out. The inverse isochron age for single crystal total fusion experiments (0.726 ± 0.018 Ma) is thus considered the most reliable age for this unit.

**MK27-23** Multiple populations are present, but no conspicuous juvenile population exists. The first set of analyses, as reported in Morgan (2009), did yield an apparent juvenile population, but these runs are inferred to be affected by laboratory contamination (inadvertently loading grains from a different sample) and are not considered here. The presence of a sample of indistinguishable age (MK27-09) to the juvenile population in the same irradiation further supports this conclusion. Subsequent analyses (Figure 5E, F) show the presence of significant xenocrystic contamination and do not yield a consistent juvenile population. However, the youngest crystal with a reasonably well-constrained age (i.e., the uncertainty is < 100% of the age) is dated to 1.414 ± 0.219 Ma. Furthermore, a group of the five youngest crystals yields a weighted mean age of 1.570 ± 0.150 Ma with an MSWD of 0.60 (Figure 5E), and an isochron age of 1.719 ± 0.199 Ma, with an MSWD of 0.73 (Figure 5F). Although these are clearly not ideally determined ages, they provide a reasonable maximum age for this and overlying units, and place useful constraints on paleomagnetic results, as discussed below. If the youngest grains are in fact juvenile, these ages can also place an important minimum age constraint on the obsidian artifacts found immediately underlying this unit.

**Discussion**

**Reconciliation with magnetostratigraphy**

The foregoing results allow us to place constraints on the ages of lithostratigraphic units, archaeology and magnetic reversals, which had previously been ‘hanging’ in time without a reliable absolute date to act as an anchor. Some discrepancies in various paleomagnetic studies have been clarified by new dates. However, difficulty in interpreting the stratigraphic sections that accompany some paleomagnetic studies prevents confident placement of all reversals onto the currently-used lithostratigraphic units. Refer to Figure 2(a, b, c).

At Gombore II (Figure 2b), we now have ages of 0.709 ± 0.013 Ma at the top of the Melka Kunture Formation, where sediments have been found to have normal polarity (Cressier, 1980; Tamrat, 1997), placing these sediments in the Brunhes Chron. Downsection, the polarity reverses (Cressier, 1980), and a tuff within the reverse interval is dated to 0.875 ± 0.010 Ma. Some discrepancy exists here with some paleomagnetic data (Tamrat, 1997) that indicated three reversals in that same section, which would place the lower tuff (MK27-08) in the period between the Jaramillo and Cobb Mountain subchrons by reference to the GPTS (Shackleton et al., 1990; Horng et al., 2002; Gradstein et al., 2004; Lourens et al., 2004). This is highly unlikely considering the 40Ar/39Ar data, and inspection of the paleomagnetic data shows the reversed interval was defined on only two samples (Tamrat, 1997) with opposing inclinations, thus the possibility of sample orientation error or that these reversed samples capture a short excursion within the Brunhes Chron cannot be excluded.

Further down the section in the Gombore I gully, the 40Ar/39Ar age constraints for sample MK27-12 have 2σ uncertainties too high to confidently place units into particular subchrons. However, there appear to be some sediments of normal polarity underlying sample MK27-12, which may have been deposited during either the Jaramillo or Cobb Mountain Subchron. Further downsection, there are parts of the section that seem to reliably indicate reversed polarity; this is in agreement with the age of sample MK27-03.

At Garba (Figure 2a), the top of the Melka Kunture Formation is similarly well constrained. An age of 0.869 ± 0.020 Ma for the uppermost tuff (MK27-13) is consistent with the reverse polarity found there, suggesting placement in the Matuyama Chron (Cressier, 1980). Again, the data become more difficult to interpret downsection, as the 40Ar/39Ar data did not reveal juvenile populations in samples MK27-16 and MK27-19. Since we only have maximum ages for these tuffs, assignment to a subchron cannot be made confidently. Additionally, the sample locations of previously published paleomagnetic studies are difficult to determine, further complicating interpretation. In one case, however, one study seems to capture a normal to reverse transition (Cressier, 1980), which may be the beginning of either the Jaramillo or Cobb Mountain Subchron. Although the age of the sample (MK27-16; 1.037 ± 0.088 Ma) should place this unit in the Jaramillo normal period, this age is within 1σ of Jaramillo time and within 2σ of Cobb Mountain time. Additionally, if the population with an inverse isochron age of 1.719 ± 0.199 Ma in MK27-23 is in fact a juvenile population, the apparently reversed polarity (Westphal et al., 1979; Cressier, 1980) would place it in the earliest portion of the Matuyama Chron, just above the Olduvai Subchron.

At Kella (Figure 2), the only paleomagnetic results are for the ignimbrite from the Kella Formation, which is found both there and at Melka Garba. Numerous paleomagnetic studies on this unit by Cressier (1980) clearly show a reversed polarity. This is in agreement with a 40Ar/39Ar age of 1.281 ± 0.061 Ma for the unit at Melka Garba and 1.253 ± 0.041 Ma at Kella, and places it in the reversed polarity subchron of the Matuyama following the Olduvai.

**Paleoanthropological implications**

These data allow more reliable age constraints to be placed on much of the stratigraphy, and thus archaeology and paleontology, at several localities within Melka Kunture.

Oldowan artifacts, including many made of obsidian, are likely from the Matuyama Chron, between the Jaramillo and Olduvai Subchrons, and thus between 1.072 and 1.778 Ma (Shackleton et al., 1990; Horng et al., 2002; Gradstein et al., 2004; Lourens et al., 2004). Less decisive 40Ar/39Ar geochronology suggests that some Oldowan obsidian artifacts are likely older than 1.393 ± 0.162 Ma (MK27-03) at Gombore I and possibly older than 1.719 ± 0.199 Ma (MK27-23) at Garba IV (Figure 2a, b). These dates also place constraints on the age of vertebrate fauna, including Homo specimens, from each of these localities.

Although less than ideal, results for sample MK27-23 suggest that the Oldowan obsidian artifacts found in levels E and F of the Garba IV excavation are the oldest known case of intensive (here > 100 artifacts) exploitation of obsidian as a raw material for tool making. As noted in the introduction, the previously known earliest intensive use of obsidian is at Kariandusi, Kenya, which likely reaches back only to ~ 1 Ma (Gowlett and Crompton, 1994). Other, less intensive use (generally < 10 artifacts) possibly pre-dates 1.48 Ma in the Acheulean at Gadeb locality 8E (Clark, 1979; Williams et al., 1979) but this is based on an unpublished K–Ar age on an alluvial unit, which are often plagued by xenocrystic contamination. As demonstrated in many studies (e.g., Morgan and Renne, 2008), K–Ar data from volcanic ashes with xenocrystic contamination are often shown to be unreliable by grain-specific 40Ar/39Ar work. Occasional obsidian artifacts are also found in several other localities, but they are exclusively in an Acheulean context and rarely, if ever, predate ~ 1 Ma. Here, then, we may have increased the known time period of well-dated obsidian exploitation by ~ 700 ka. As Piperno et al. (2009) discussed, it is unsurprising that the earliest use of obsidian would occur in such close proximity to the excellent source of obsidian at
Balchit. Whether earlier hominids eschewed obsidian or were simply unaware of it remains a question that may have fairly profound implications for the evolution of hominin cognitive skills; as obsidian gained increasing popularity in subsequent industries, its suitability for making specialized tools was increasingly recognized.

Additional age constraints can be assigned to the artifacts and vertebrate fauna found at Gombore II (Figure 2b), including the ‘twisted bifaces’ and Homo partial cranium from the Gombore II Locality 1 and the overlying possible butcherly site at Locality 2. 

\[40Ar/39Ar\] ages for Acheulean artifacts at Garba XIII (Figure 2a) are found between volcanic ashes with ages \(<0.772\pm0.091\) Ma and \(0.875\pm0.020\) Ma, while archaeological horizons from Garba XII underlie a tuff dated to \(0.772\pm0.091\) Ma. Early Acheulean artifacts at Simbiro III are older than \(0.875\pm0.020\) Ma and \(0.709\pm0.013\) Ma (MK7-08). As these are the only known ages for twisted bifaces in Africa, the potential importance of these dates cannot yet be assessed.

At Gombore I, a tuff dated to \(1.20\pm0.07\) Ma in the earliest portion of the Matuyama Chron, above the Olduvai Subchron, post-dates the Developed Oldowan from Gombore I and constrains the beginning of the Acheulean at Melka Kunture. At Gabeb, on the east Main Ethiopian Rift border, the Developed Oldowan/early Acheulean sites recently revisited are dated to possibly \(>1.48\) Ma and at least \(>0.7\) Ma by the K–Ar method (Williams et al., 1979; Clark, 1979, 1987; de la Torre, 2011).

\[40Ar/39Ar\] ages for Acheulean artifacts at Barba XII (Figure 2a) are found between volcanic ashes with ages \(<1.037\pm0.088\) Ma and \(0.869\pm0.020\) Ma, while archaeological horizons from Garba XII underlie a tuff dated to \(<0.772\pm0.091\) Ma. Early Acheulean artifacts at Simbiro III are older than \(0.878\pm0.014\) Ma. At Kella III (Figure 2c), Oldowan artifacts are younger than \(1.666\pm0.009\) Ma (Tables 1, 2). The large ignimbrite of the Kella Formation at Kella and Melka Garba is dated to \(1.26\pm0.07\) Ma. This pre-dates classical Acheulean artifacts in the area. These dates form a unique record for the classical Acheulean of the high Ethiopian Plateau.

Conclusions

New \[40Ar/39Ar\] data presented here allow, for the first time, significantly more precise age constraints to be placed upon the lithostratigraphy, archaeology and paleontology from Melka Kunture. Though some of the units could not be dated with the full current potential precision of the \[40Ar/39Ar\] technique due to geologic complications, the new chronostratigraphy reifies dependence on previous magnetostratigraphic studies whose results are somewhat inconsistent.

This work helps constrain the timing of the tool manufacture using Oldowan, Acheulean, Middle Stone Age, and Late Stone Age technologies in this region. This allows for the first time a reliable and relatively complete timeline for the stratigraphic sequence, environmental changes, archaeology, and paleontology of this unique area. This contributes toward our understanding of the timing of human biological and behavioral evolution on the shoulder of the Ethiopian Rift.

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Appendix. Supplementary Data

Supplementary data related to this article can be found online at doi:10.1016/j.jhevol.2011.10.007.

References


