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Magnetostratigraphy of the Fossil-Rich Shungura Formation, southwest Ethiopia

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ABSTRACT

Three hundred eighty-six oriented block samples were collected from the lower 334 m of Pliocene and Pleistocene fluvial strata of the Shungura Formation in two field seasons. Paleomagnetic polarity of these was determined on samples from these blocks, using a routine of 8–13 steps for AF demagnetization, and 15–20 steps for thermal demagnetization. Rock magnetic properties revealed titanomagnetite with subordinate maghemite as the dominant magnetic minerals with pseudo-single domain magnetic grain sizes. Directional analyses indicate one or two components of magnetization both in AF and thermal techniques. The first component is mostly removed by 5–10 mT AF fields or heating to 300 °C. The magnetization component after these steps generally defined straight-line segments directed towards the origin which are interpreted as the Characteristic Remanent Magnetization (ChRM). ChRM directions so determined and averaged at the site level revealed both normal and reversed polarities. The directions of the normal and reversed polarities are respectively Dec = 357°, Inc = −0.1 (N = 36, α_{95} = 3.7°) and Dec = 176°, Inc = −3.4 (N = 55, α_{95} = 3.1°) and are antipodal. A sequence of R4-N3-R3-N2-(R2)-N1-R1 polarities was identified with R2 being an anomalous direction within N2/N1. Published weighted mean ^{40}Ar/^{39}Ar ages on volcanic ash layers in this part of the section with height from the base and ages in parentheses are: Tuff A (34 m; 3.60 ± 0.02 Ma), Tuff B-α (65 m; 3.43 ± 0.01 Ma), Tuff B-δ (77 m; 3.41 ± 0.01 Ma), Tuff in B-10-1 (150 m; 2.97 ± 0.01 Ma), Tuff C (170 m; 2.99 ± 0.09 Ma), Tuff D (252 m; 2.53 ± 0.01 Ma), Tuff D-3-2 (272 m; 2.47 ± 0.01 Ma), and Tuff F (228 m; 2.32 ± 0.01 Ma). These direct age results imply that the identified polarity zones correspond to the Gilbert Chron, lower Gauss Chron, Mammoth Subchron, upper Gauss Chron, and lower Matuyama Chron, respectively. No new paleomagnetic data are available for the Usno Formation, but tephrostratigraphic work results in reinterpretation of the stratigraphy suggesting that only the Mammoth Subchron is preserved in the upper part of this formation. In the Shungura, Usno and Koobi Fora formations, the thickness represented by the lower Gauss and Mammoth Subchron is very similar, but the Kaena Subchron is either not recorded in the type area of the Shungura Formation, or only incompletely revealed.

1. Introduction

Earth's geomagnetic field has reversed polarity repeatedly in the geologic past, and polarity reversals are used as a tool for correlation of stratigraphic logs between distant localities. Brunhes (1906) and Matuyama (1929) first reported polarity reversals of the geomagnetic field. Hospers (1951) first described and realized the potential use as a correlative tool while Khramov (1958) realized that a single geochronological paleomagnetic time scale valid for the entire world might be developed (cf. Langereis et al., 2010). Cox et al. (1963, 1964) described the first geomagnetic polarity time scale (GPTS) combining K/Ar dates with measured polarities on volcanic rocks. The GPTS has now been extended to the late Jurassic through magnetic anomaly profiles recorded on the spreading seafloor (e.g., Harland et al., 1989). More recently, times of polarity transitions in the later part of the GPTS have been estimated through astronomical calibrations (e.g., Horng et al., 2002; Gradstein et al., 2004), as well as through ^{40}Ar/^{39}Ar dating of terrestrial sections (e.g., McDougall et al., 1992).

In the early development of the GPTS, many workers suggested that short polarity intervals might be missing in the reference GPTS

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because of the limited resolving power of marine magnetic profiles (e.g., Watkins, 1968; Blakely and Cox, 1972). Only detailed magnetostratigraphic records from sedimentary sequences or lava flows on continents provide sufficient resolution to detect magnetic intervals, often termed excursions, with durations of only a few thousands of years. At least 15 short magnetic polarity features with precise radio isotopic ages have been proposed for the last 4 Ma (Singer et al., 2002; Singer, 2004; Laj and Channel, 2007).

Magnetostratigraphy relies on the assumption that the geomagnetic field direction is globally recordable at the Earth's surface without significant time gap between different sites. As such it is a powerful tool to constrain the timing of sedimentary sequences. Since the pioneering work of Opdyke et al. (1977), the method has been used to correlate and determine numerical ages at particular levels in stratigraphic sections (e.g., Butler et al., 1981). Magnetostratigraphy is widely used in continental sections and in deep-sea sediment cores to determine details of their chronology. Long, continuous sedimentary sections with high sedimentation rates or thick volcanic sections with many lava flows providing snapshots of the past geomagnetic field are required for successful application of magnetostratigraphy as a dating technique.

The Shungura Formation in the Omo-Turkana Basin is thick (~765 m), and was deposited relatively rapidly, although paleosols record breaks in sedimentation. Magnetostratigraphic correlations between sections elsewhere in the Omo–Turkana Basin (e.g., Usno Formation, Koobi Fora Formation) allow comparison between them, providing insight into the depositional and tectonic history of the basin.

Mixed polarities had been reported at some levels of the Shungura Formation (Shuey et al., 1974; Brown et al., 1978), and these needed to be resolved. These mixed polarities occurred principally in Members D through G, and have been discussed by Kidane et al. (2007). We attribute the much cleaner results in the present work to use of both thermal demagnetization and higher AF demagnetization in our procedures than were used by Shuey et al. (1974) and Brown et al. (1978). In addition we wanted to determine the magnetic mineralogy to put the magnetostratigraphic work on a more solid basis. Also, many new $^{40}Ar/^{39}Ar$ results had become available in the Shungura Formation since the early work of Shuey et al. (1974), and Brown et al. (1978). Kidane et al. (2007) reported the magnetostratigraphy of the Shungura Formation between Tuff F and Tuff H, which contributed towards the objectives described above. Here we report magnetostratigraphic results on samples collected from the lower part of the section; the Basal Member and Members from A to E in July 2008 and June 2011.

2. Geological and tectonic setting

The Omo–Turkana depression is characterized by N–S oriented Cenozoic fault bounded basins, and also by buried NW–SE oriented basins formed in connection to the breakup of Gondwana during the Mesozoic (e.g., the Anza graben; Morley et al., 1999b). Thick piles of fluvio-lacustrine sediment and sandstones, shales and mudstones fill these rift basins. The geometry of the basins is generally considered to be half-grabens (Morley et al., 1999a; Tiercelin et al., 2004). The thickness of these sediments reaches up to7 km in the Cenozoic Lokichar Basin (Morley et al., 1999a)and at least 9 km of Cretaceous to Recent rocks in the Anza Graben (Morley et al., 1999b). In the lower Omo valley, the Shungura Formation with a total measured thickness of 760 meters outcrops only west of the Omo River, which itself follows a N–S oriented fault (Fig. 1; Brown and de Heinzelin, 1983; Mammo, 2012).

A N–S oriented fault system that parallels the Omo River and the Korath Range (a late Pleistocene volcano; Jicha and Brown (2013)), cuts the Shungura Formation and juxtaposes strata of different ages throughout the outcrop area (see inset Fig. 1). Thus, there is stratigraphic omission or repetition along any E–W oriented cross-section through the outcrops (see inset Fig. 1). Recent geophysical surveys in the region have provided information on the 2D and 3D basin architecture and sediment thickness. A magnetotelluric (MT) study east of the Omo River estimated sediment thickness of about 4 km (Hautot et al., 2007). Mammo (2012) interprets the Omo basin on the basis of gravity surveys as an asymmetric graben with N–S oriented faults and shows that sediment thickness exceeds 4 km. Moreover, the deepest parts of the basin are situated east of the Omo River and in Sanderson's Gulf west of outcrops of the Shungura Formation. It is likely that the horst on which the Shungura Formation is now exposed developed in part during the time of deposition, and accumulated less sediment than the basins to the east and west (Mammo, 2012). In addition the asymmetric half-graben geometry means that strata are thicker in areas of rapid subsidence near bounding faults and thinner away from such faults (Mammo, 2012).

The Shungura Formation is the principal formation of the Omo Group (Brown and de Heinzelin, 1983), and has excellent exposures of well-dated Plio-Pleistocene fluvial and lacustrine strata of the group in the lower Omo-Turkana Basin, but its base is not exposed. North of the Shungura Formation older strata exist in the Mursi, Usno, Koobi Fora, and Nkalabong formations. Tephrostratigraphic correlations between the Shungura and Usno formations (Haileab, 1995) require reinterpretation of the magnetostratigraphy of the Usno Formation as presented by Brown et al. (1978). These are dealt with below.

The Shungura Formation is exposed in beds that strike N–S and dip gently (~10°) to the west, and is divided into thirteen members named for the tuff that occurs (Tuff A to Tuff L, excluding I) at the base of each (de Heinzelin and Haesaerts, 1983a), with the Basal Member below Tuff A. Members are further divided into submembers according to a generalized cyclic patterns of fining-upward sequences (de Heinzelin and Haesaerts, 1983a). These submembers are numbered sequentially from the base to the top of each member, and may correspond to separate climatic cycles, reflecting times of sedimentary deposition and times of soil formation. Alternatively the fining upward cycles may result from autocyclic meandering in a subsiding basin. In the ensuing text we omit the term "submember" before numbered submembers (e.g. we say "B-7" instead of "submember B-7" because no confusion should result.)

3. Paleomagnetism

3.1. Paleomagnetic sampling

Rocks of the Shungura Formation are not highly compacted so we collected oriented blocks along two sections. In one section that began in outcrops of the Basal Member and extended upward to Tuff E we collected 254 oriented block samples from 64 paleomagnetic sites. We also collected 72 block samples from 18 paleomagnetic sites from Members C and Member D in a parallel section at Nakuloi at L. 9 (L. # refers to locality numbers of the Omo Research Expedition; de Heinzelin, 1983), to thoroughly investigate Member D where previous work had suggested a short normal polarity event.

A second field season (June 9–June 15, 2011) was conducted to collect samples with denser spacing from Member B which should record the Kaena Subchron, but for which no evidence had yet been found. The upper part of Member B is temporally bounded by a K/Ar date of 2.95 Ma in B-10, and by the top of the Mammoth Subchron (3.20 Ma) in B-2. Accordingly, we recollected all units from B-3 to B-8 (15 sites; 60 oriented block samples).