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PALEOMAGNETIC DATING OF THE ENTICHO SANDSTONE AT NEGASH LOCALITY (TIGRAI REGION, NORTHERN ETHIOPIA): IMPLICATION FOR QUATERNARY REMAGNETIZATION

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ABSTRACT: New paleomagnetic result is reported from the Enticho Sandstone (Late Paleozoic age) at Negash locality in Northern Ethiopia. Twenty-three paleomagnetic core samples were collected from three sites for paleomagnetic investigations. Specimens were subjected either to progressive alternating field (AF) or thermal (TH) demagnetization techniques. Rock magnetic experiments revealed major magnetization carriers to be titano-magnetite and titano-hematite. Well-defined viscous remanent magnetizations (VRM) components are removed by intermediate AF fields of between 20–30 mT and heating above 600°C. These magnetizations defining straight-line segments are directed towards the origin and interpreted as the Characteristic Remanent Magnetization (ChRM). Directions of magnetizations and site-mean directions in the *in-situ* coordinate results in Dec = 356.7°, Inc = 24.9° (N=23, K = 43, α_{95} = 4.7°). Paleomagnetic stability tests confirmed that the ChRMs identified are secondary and postdate age of deposition and tectonic tilting. The paleomagnetic pole position Long = 296.6°E, Lat = 86.7°N (A_{95} = 5.0°, N = 23) obtained from these data when plotted with the Apparent Polar Wander Path (APWP) of Africa (Besse and Courtillot, 1991, 2003; Cogné, 2003) gives a Quaternary age for the magnetization of Enticho Sandstone at Negash locality. Comparison of this result with that of Enticho Sandstone at Enticho locality, which had primary magnetization fingerprints (Tesfaye Kidane *et al*., 2013) with ages of between 260 Ma and 270 Ma (Late Carboniferous – Early Permian) implies that the Quaternary age for the Enticho Sandstone at Negash is a recent remagnetization.

Key words/phrases: African Permian paleogeography, Ethiopia, paleomagnetism, primary magnetization, remagnetization

INTRODUCTION

Background

For more than four decades now, the fundamental question in Late Palaeozoic Era has been the paleogeographic configuration of continents within Pangaea supercontinet, (*e.g.*, Van der Voo, 1993; McElhinny and McFadden, 2000; Muttoni *et al*., 2003; Domeier *et al*., 2012). Although there is a broad consensus on the paleogeographic configuration of Pangaea in the Early Jurassic to be that of Pangaea 'A' (Van der Voo, 1993), there is ongoing debate regarding the exact configuration of Pangaea 'A' during Late Carboniferous and Late Triassic since Pangaea 'B' was introduced by Irving (1977). Reconstruction of type 'A' (Bullard *et al*., 1965; Van der Voo and French, 1974) is minor modification of Wegener's (1915) original reconstruction and represents a model accepted by most geoscientists as the likely configuration, just before the opening of the Atlantic Ocean in the Early Jurassic (Van der Voo, 1993). However, it is incompatible with available paleomagnetic data triggering alternative reconstructions. Reconstruction model 'B' was then proposed and follow-up paleomagnetic studies supported this reconstruction and asserted its validity for Carboniferous to Triassic Periods (Kanasewich *et al*., 1978; Morel and Irving, 1981). Pangea 'B' configuration encountered another problem; it requires dextral – slip of Gondwana farther to the east by the order of ~3000 km with respect to Laurasia, on the basis of this paleomagnetic data. This scenario was disputed for scarcity of geological evidences supporting such a mega shear. This alternative model is, therefore, discarded on the suspicion that the paleomagnetic interpretation relied on poor quality data included from sediments with known geomagnetic inclination error and poor age control inserting latitudinal artifacts (Rochette and Vandamme, 2001; Muttoni *et al*., 2003). Domeier *et al*. (2012), after detailed re-analyses of late Paleozoic early Mesozoic paleomagnetic data concluded that, existing paleomagnetic data could be reconciled with Pangaea during early Mesozoic and late Permian. Recent high-resolution paleomagnetic study from the Paleozoic Tillite of Northern Ethiopia brought new hopes of rectifying this on-going debate (Tesfaye Kidane *et al.*, 2013) about Pangaea paleogeography. This work underlined the need for more paleomagnetic study on rocks of similar ages from this part of Africa. It also invites more comprehensive Paleozoic paleomagnetic investigations to be made in different outcrops and discriminate rock types at various localities recording primary and secondary magnetizations. Accordingly the paleomagnetic results from the glacial sandstone named Enticho Sandstone from the Negash locality, northern Ethiopia are presented here (Fig. 1A).

Geological setting

The Paleozoic sediments in northern Ethiopia were first described by Dow *et al.* (1971) and Beyth (1972a and b). The two works differentiated two facies: Glacigenic Sandstone and tillite, described and named "Enticho Sandstone" and "Edaga Arbi Tillite", respectively.

The Enticho Sandstone is the lowermost sedimentary unit exposed in different areas of Tigrai Region: along the margins of the Mekele Basin, along the Adigrat – Adwa ridge and also along the Astbi horst; it unconformably overlies the Precambrian basement rocks. This unit has a variable thickness in different places but is believed to be less than 160 meters. It generally has white colour and of medium grain size with silt laminations and thin flat-lying bedding. In the sampling site, Belessa area of Negash locality (Fig. 1), the sandstone outcrops along a major E–W oriented fault and is coarse-grained, white coloured, cross bedded (120°/12°E) and steeply tilted (095°/16°SW). In this particular outcrop, iron encrustations and ferruginous layers are present along the bedding plane (Fig. 1B).

Attempts have been made to determine the exact age of these sediments. However, because age diagnostic fossils (see Tesfaye Kidane *et al.*, 2013 and references therein) are missing, no precise age could be determined. Bussert and Schrank (2007) have extracted Palynomorphs from these sediments at the upper part and had assigned an Upper Ordovician age for the lower part of the Enticho sandstone and concluded this later part to be equivalent to those in Eritrea. Recent and reliable paleomagnetic age estimation for the Edaga Arbi Glacials (Tesfaye Kidane *et al.*, 2013) and for the Enticho sandstone at Enticho yielded a Late Carboniferous – Early Permian age. However, more robust spatially distributed paleomagnetic data are required in order to constrain the paleogeographic position of Pangaea configuration. For this sustained effort, it has become imperative to collect samples of the sandstones from different places. In this study, samples of Enticho sandstones from Negash locality are analyzed in detail and results are then compared with those of the Enticho Sandstone from Enticho locality reported in the work of Tesfaye Kidane *et al.* (2013).

MATERIALS AND METHODS

Paleomagnetism

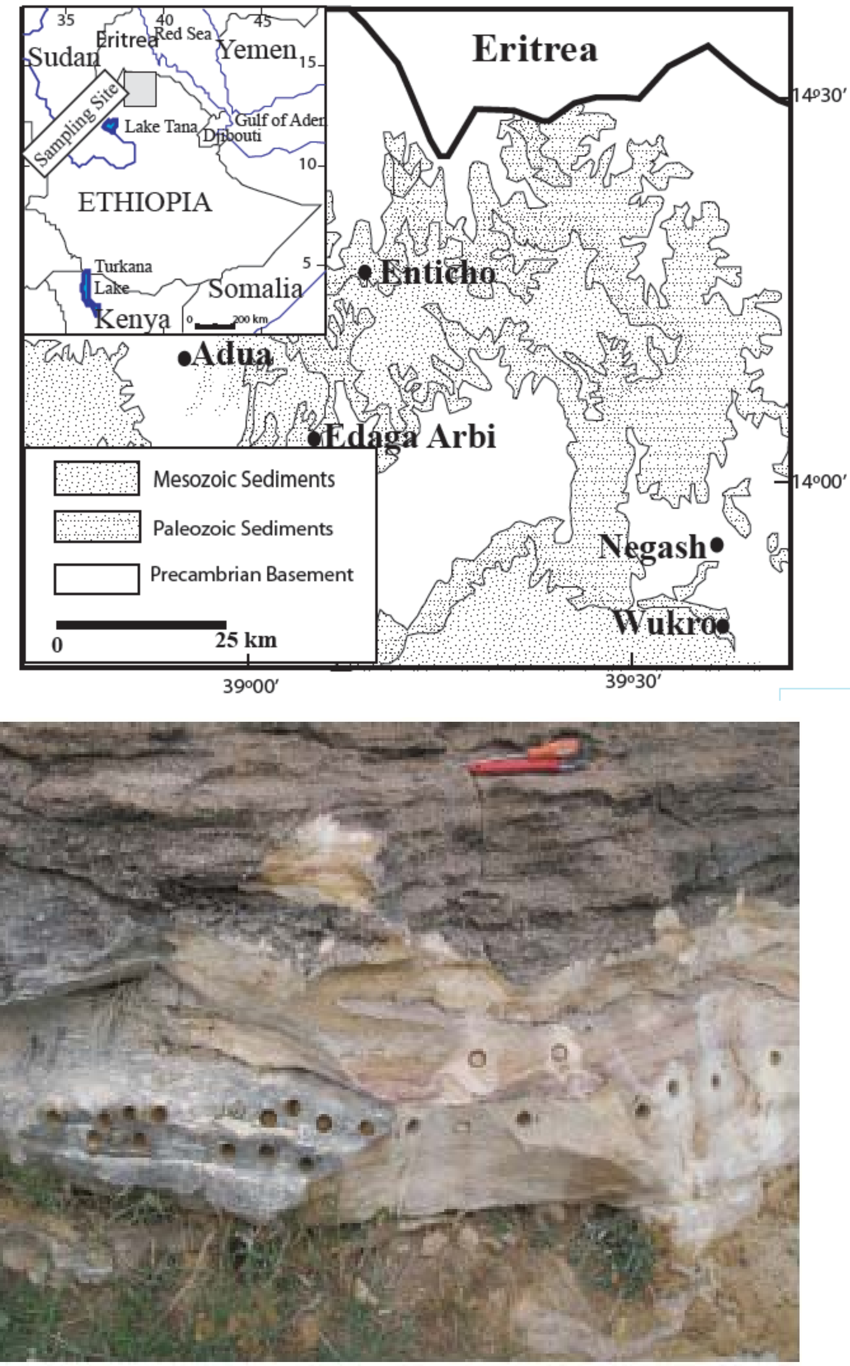
Sampling

A total of 23 paleomagnetic core samples from the Enticho Sandstone outcrops at Negash locality (Fig. 1) were collected at three paleomagnetic sites using a pomeroy portable drill. Core samples were oriented with an orienting fixture mounted with standard magnetic compass following the routine of paleomagnetism. Each paleomagnetic site is defined as a different stratigraphic level within the Enticho Sandstone layers. Exposures of the Enticho Sandstone are observed north of a prominent E-W trending normal fault overlying the basement rocks. The existence of the fault is recognized mainly because of a creek that developed later along this fault line that juxtaposes sediments to the south and basement to the north. The Enticho Sandstone exposures here are characterized by being cross-bedded (120°/12°NE) medium to coarse-grained whitish coloured and tilted (095°/16°SW).

Laboratory analyses

At least one specimen per core sample drilled was used to measure directional behavior while 5 additional specimens were used to characterize their magnetic properties. In most of the cases both thermal (TH) or alternating field (AF) demagnetization techniques were used in order to resolve the directional spectrum in these samples. For most of the samples TH technique was used more than the AF. The paleomagnetic and rock–magnetic experiments were done in the paleomagnetic laboratory facility at Ludwig–Maximilians–Universität München, Germany.

A.

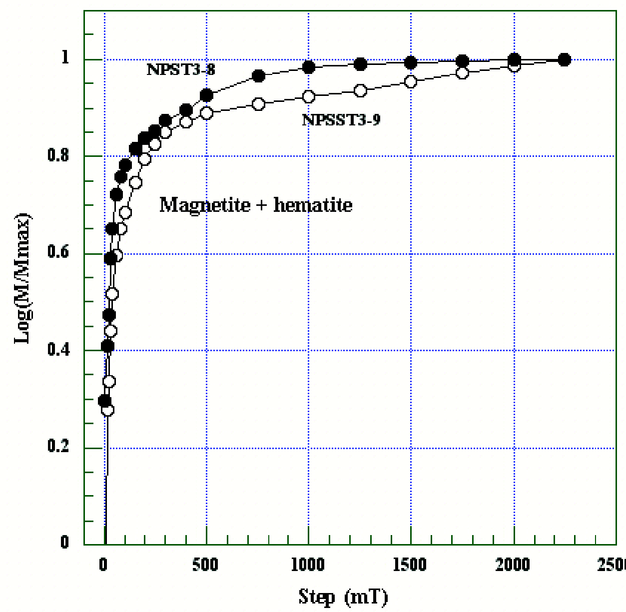


B.

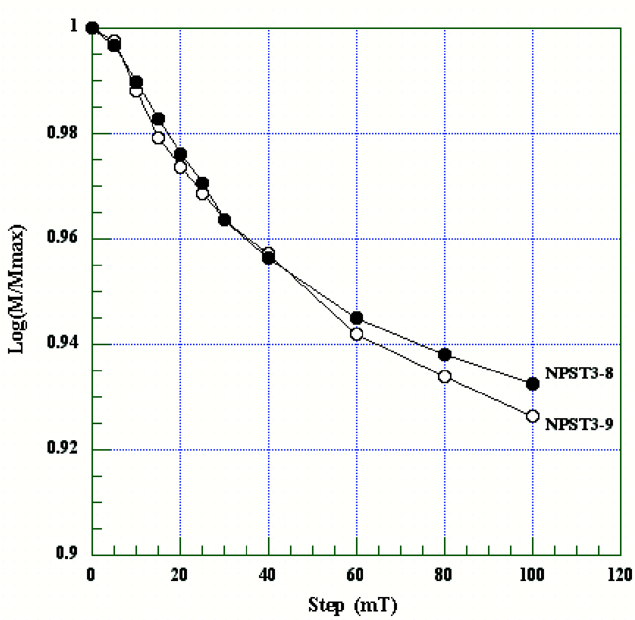
Figure 1. (A) General geological map of the studied area in Tigrai Region Ethiopia. (B) A picture showing outcrop of the sampled Enticho Sandstone at Negash locality.

Rock magnetic properties

Two representative specimens from the Enticho Sandstone at Negash locality were chosen for Isothermal Remanent Magnetization (IRM) experiments (Fig. 2A). An initial steep rise in IRM up to an applied field of 300 mT was observed in both samples. Further, the samples show a gentle slope (300 mT – 500 mT) followed by gradual increase in magnetization in fields up to 2000 mT. The magnetization of one of the samples (NPSST3–9) couldn't attain saturation at the highest applied field of 2250 mT. The steep increase in magnetization in fields up to 300 mT followed by a more gradual increase without reaching saturation is diagnostic of magnetic assemblages containing both magnetically soft (*e.g.*, titano-magnetite) and hard (*e.g.*, titano-hematite) minerals. The corresponding AF demagnetizations of these IRM results show that ~90% of the IRM could not be demagnetized (Fig. 2B) using the maximum available laboratory alternating field (100 mT), indicating predominance of magnetically hard (high coercive) materials. The NRM intensity decay curves show the contribution from the low coercive or soft magnetic materials could go as high as 50% (Figs 3A and B). These generally indicate the Enticho sandstone at Negash is characterized by ferromagnetic assemblages with both magnetically soft (titano-magnetite) and hard materials (titano-hematite) and probably with minor contribution from iron oxyhydroxides or ironsulfides (Fig. 2B).



A.



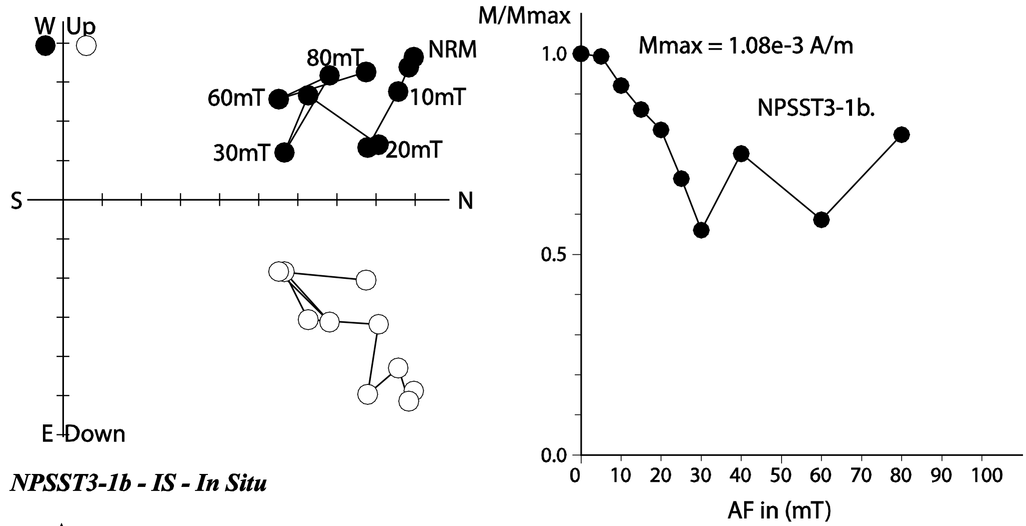
B.

Figure 2. (A) IRM acquisition experiment for representative specimens from Enticho Sandstone at Negash. (B) AF demagnetization curve of the IRM experiment in A; the corresponding specimen names are given.

RESULTS

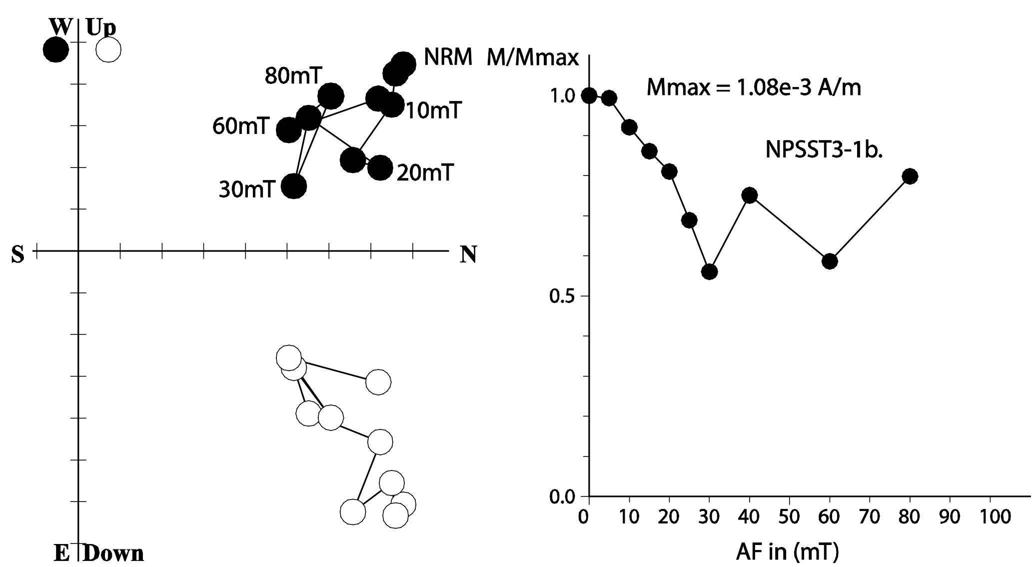
Paleomagnetic directions

The paleomagnetic directions obtained from the Enticho Sandstone at Negash using the AF and thermal techniques are different. When AF technique is used more than 50 percent of the total Natural Remanent Magnetization (NRM) remains after the maximum field available in the laboratory is applied (Figs 3A and B). The component of magnetization directions obtained at intermediate AF fields between 20–30 mT, in the *in–situ* coordinates are subparallel to the present geomagnetic field at Negash (Fig. 3B). For AF fields below and above the given interval paleomagnetic directions are erratic. This progressive AF demagnetization removed only 40–50 percent of the total NRM indicating that magnetic materials of high coercivity are predominant.



NPSST3-1b - IS - In Situ

A.

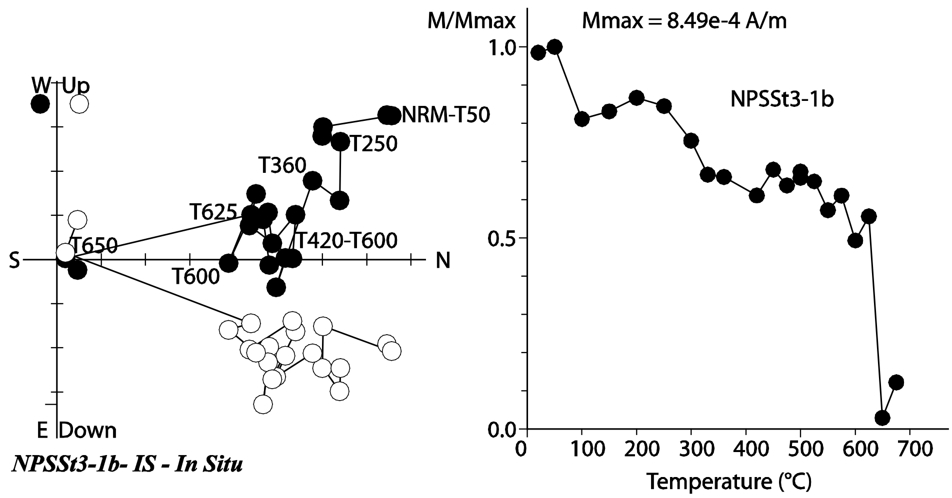


NPSSt3-1b-TC - Tectonic Corrected

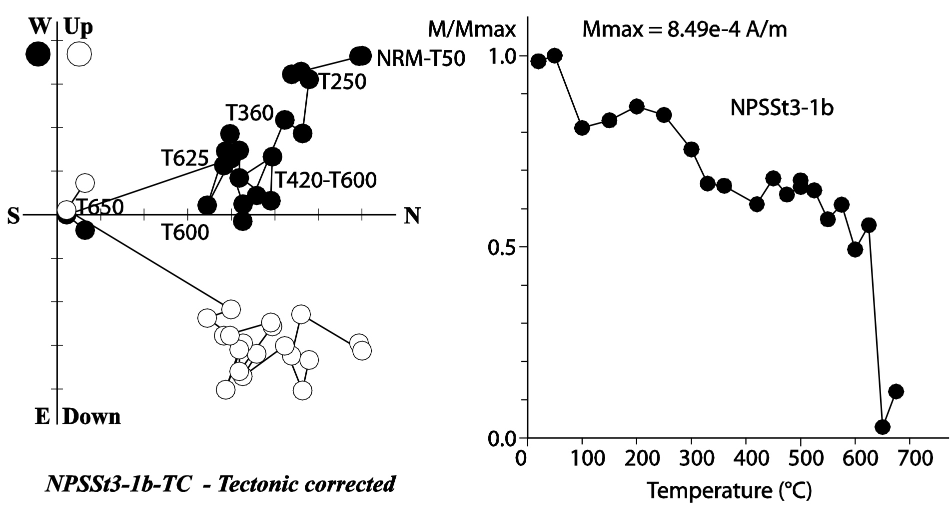
B.

Figures 3 A and B. Examples of Zijderveld diagrams for specimens from the Enticho Sandstone at Negash area one treated by Alternating Field (AF) and another by thermal demagnetization techniques. A represents the *in-situ* coordinate; B represents the tectonic corrected coordinates. (The magnetic polarity is down and pointing north consistent with normal configuration for the location).

The results of progressive TH demagnetizations of the Enticho Sandstone at Negash village indicate an erratic behavior until a temperature of 625ºC and further stepwise heating to 650ºC removed all the NRM components. The high stability component defines a straight-line segment directed towards the origin and is considered as the Characteristic Remanent Magnetization (ChRM) directions (Figs 3C and D). But the directions in the *in-situ* coordinate, like the AF equivalent, are sub parallel to the present geomagnetic field at Negash (Fig. 3D) suggesting probably it is a Viscous Remanent Magnetization (VRM). The AF and TH progressive demagnetization results are consistent and agree very well. The directions of magnetization for specimens resulting in stable straight line segments is determined by the best-fit line using the least square technique of Kirschvink (1980) for specimens with overlapping spectra and unblocking temperatures, direction of magnetization is determined by remagnetization circles of Halls (1976; 1978).



C.



D.

Figures 3 C and D. Examples of Zijderveld diagrams for specimens from the Enticho Sandstone at Negash area one treated by Alternating Field (AF) and another by thermal demagnetization techniques. C represents the *in-situ* coordinate where as D represents the tectonic corrected coordinates. (The magnetic polarity is down and pointing north consistent with normal configuration for the location)

Site mean directions

The directions of magnetization determined in either best-fit line or remagnetization circles techniques are plotted on stereogram (Fig. 4). The distribution of ChRM for all specimens of the Enticho Sandstone at Negash village is given both for *in-situ* and tectonic corrected coordinates (Fig. 4). A mean direction is then calculated for all specimens in the *in-situ* and tectonic corrected coordinates resulting in Dec = 356.7°, Inc = 24.9° (N=23, K = 43, α_{95} = 4.7°), and Dec = 352.6°, Inc = 37.3° (N=23, K = 37.3, α_{95} = 5.0°), respectively. The *in-situ* and tectonic corrected coordinates differ slightly with the distribution being more clustered in the *in-situ* coordinates and showing a bit of scatter after the correction. All specimens of Enticho Sandstone at Negash village have ChRM directions of normal polarity configuration that is not related and not antipodal to the reversed polarities described for Enticho area above.

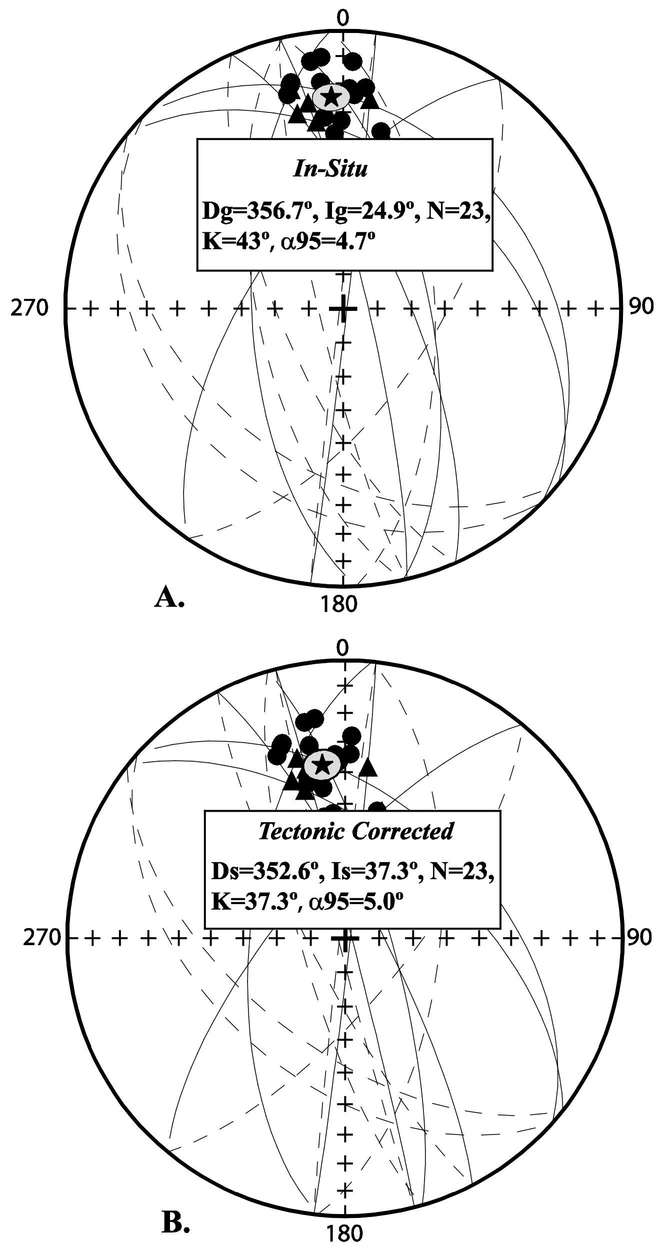


Figure 4. Streographic projection showing the Characteristic Remanent Directions (ChRM) as determined by both remagnetization circles of Halls (1976; 1978) and least–square technique of Kirschvink (1980); A) *in-situ* coordinates (prior to tilt correction); B) after tectonic correction and restoration to the pre-tilting position. In both cases the corresponding overall mean directions with 95 percent confidence circles are shown by star symbols and circles.

Site mean directions are calculated by using Fisher (1953) statistics for those having stable endpoints and McFadden and McElhinny (1988) statistics for combined stable endpoints and great circles employing the PaleoMac software package of Cogné (2003). These site mean directions of Enticho Sandstone in the *in-situ* and tectonic corrected coordinates are compared (Fig. 5). The site mean directions in both coordinates have positive inclinations with the tectonic corrected coordinate value steeper than the *in-situ* one and declinations being sub-parallel to the Earth's axis of rotation, consistent with current geomagnetic field direction at sampling locality. This suggests that the ChRM direction is VRM acquired after sedimentation or a recent remagnetization. The mean ChRM direction becomes consistent with the current geomagnetic field only with *in-situ* coordinates and diverges from it when tectonic correction is applied, indicating ChRM postdating the tilting of the sandstone at Negash (Fig. 6).

DISCUSSION

Age estimation

Paleomagnetic pole positions were calculated from the Virtual Geomagnetic Pole (VGP) of the specimens of Enticho Sandstone at Negash locality. This resulted in: Lon = 296.6°E, Lat = 86.7°N (A_{95} = 5.0°, N = 23) and Lon = 355.4°E, Lat = 80.0°N (A_{95} = 5.9°, N = 23), respectively for the *in-situ* and tectonic corrected coordinates (Fig. 6). The paleopole position of the Enticho Sandstone at Negash locality was then compared with the Apparent Polar Wander Path (APWP) of Africa (Fig. 6; Besse and Courtillot, 1991; 2003; Cogné, 2003). The full star and full diamond symbols, respectively represent the *in-situ* and tectonic corrected coordinates. Evidently, the *in-situ* pole position coincides with the North Geographic Pole coordinate whereas the tectonic corrected coordinates has no relation to the APWP. This observation, together with the better grouping of

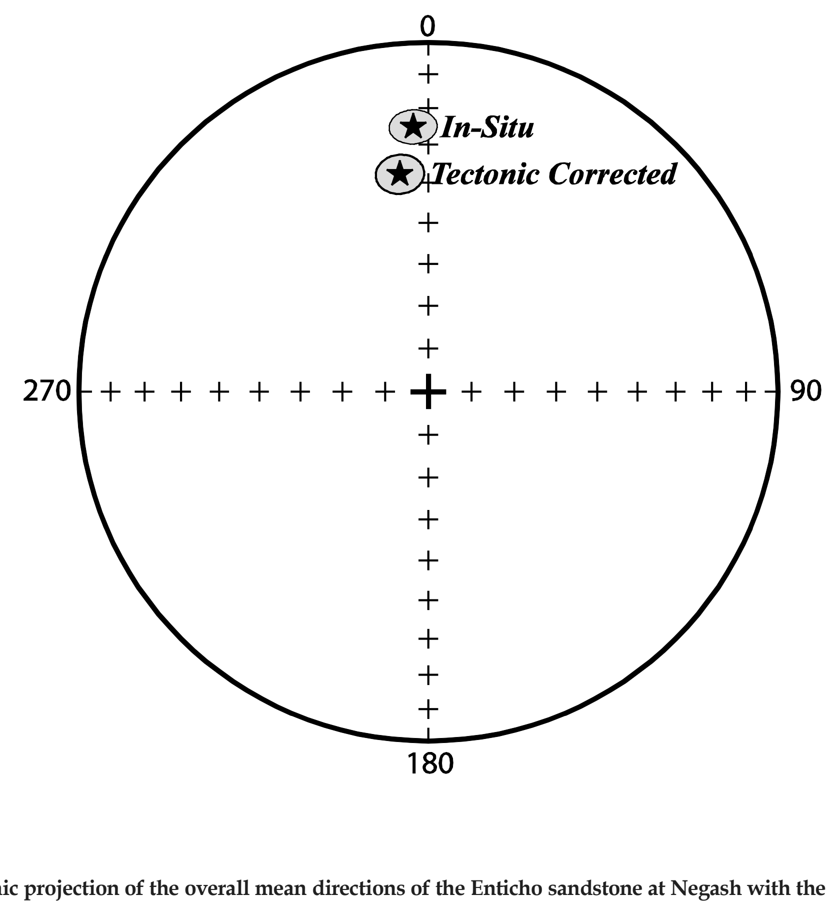


Figure 5. Stereographic projection of the overall mean directions of the Enticho sandstone at Negash with the corresponding 95% confidence indicated as circles around the star in *in-situ* and restored or tectonic corrected coordinates.

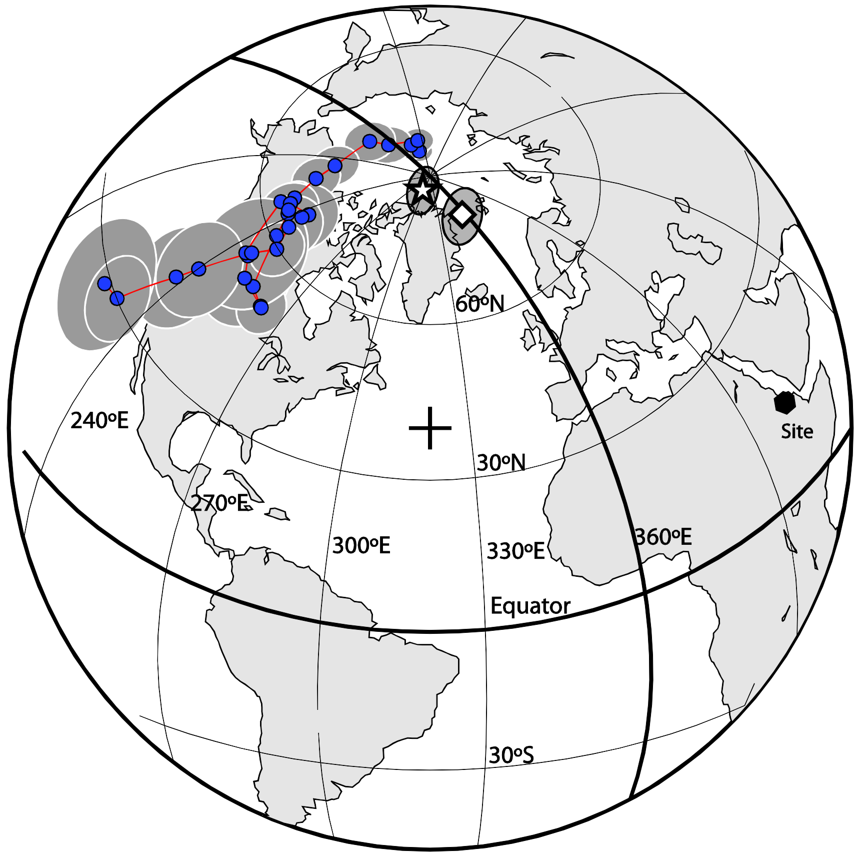


Figure 6. Spherical projections with the major continents in their present day configurations and the Apparent Polar Wander Path (APWP) curve of Africa in West African coordinates (McElhinny *et al.*, 2003; Besse and Courtillot, 1993; 2003). The remagnetized pole position for the Enticho Sandstone at Negash is shown by a star symbol in the *in-situ* coordinate and by a full diamond symbol in the tectonic corrected coordinates; the corresponding 95% confidence circle is given as gray shades. The *in-situ* coordinate has smaller 95% confidence circle and the *in-situ* mean pole position is consistent with the current geomagnetic field position (geographic north). In the tectonic corrected coordinates, the pole gets removed away both from the north geographic pole position and the APWP curve.

the data in the *in-situ* coordinate (smaller 95 percent confidence circle) suggest that magnetization postdates the tilting of the sediments and that the age of magnetization is in the Quaternary Period.

Comparison with Enticho sandstone at Enticho locality

A similar paleomagnetic investigation was carried out recently on Paleozoic glacial sediments of Northern Ethiopia (Tesfaye Kidane *et al.*, 2013). In that work, detailed rock magnetic, optical microscopy and demagnetization behaviors showed that rocks of the Edaga Arbi tillites and Enticho Sandstone at Enticho locality retained original magnetization of high quality (Tesfaye Kidane *et al.*, 2013). The age of deposition of the Edaga Arbi Glacials in Northern Ethiopia and Enticho Sandstone at Enticho had both been determined to be between late Carboniferous and early Permian (Tesfaye Kidane *et al.*, 2013). For the purpose of comparison with the present results, the paleomagnetic data of the Enticho Sandstone from Enticho locality was recalculated. Figure 7 shows the comparison of this recalculated pole position with the Apparent Polar Wander (APW) path curve for Africa in Western African coordinates (Besse and Courtillot, 1991; 2003; Cogné, 2003). This pole is shown in full diamond symbol and the star symbol shows the pole position after the pole is rotated to the co-ordinate of West Africa to allow for extensional rift system from the Benue Trough about a Euler pole position, at 19.2°N, 352.6°E through an angle -6.3° (clockwise) (Lottes and Rowley, 1990; McElhinny *et al.*, 2003). The final transferred pole position is located at Lon = 238.6°E, Lat = 50.3°S (A95 = 5.5°, N=43). This pole with its 95 percent confidence circle intersects the APW path at pole positions corresponding to between 260 Ma and 270 Ma, consistent with the recent age estimation (Tesfaye Kidane *et al.*, 2013) and hence indicating primary magnetization fingerprints from the Enticho Sandstone at Enticho.

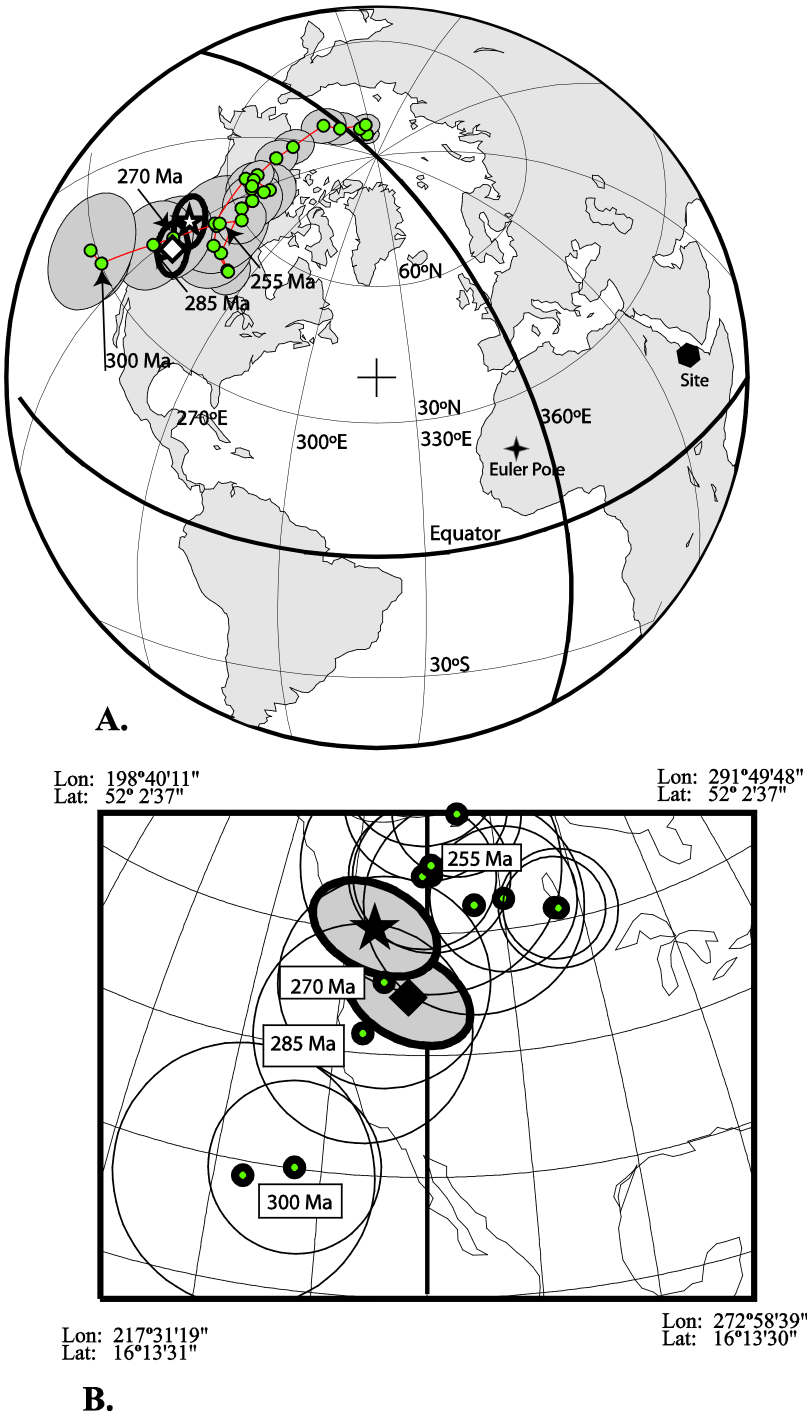


Figure 7. Spherical projection with the major continents in their present day plate tectonic configurations and Apparent Polar Wander Path (APWP) of Africa in West African coordinates (Besse and Courtillot, 1993; 2003; McElhinny *et al.*, 2003). [(A) The Enticho Sandstone (at Enticho) pole position shown as diamond and the rotated pole in West African coordinate about Euler pole position as star symbol for comparison. The rotated pole is consistent with ages of 270–260 Ma.
(B) Blowup portion of the spherical projection to show the details of the pole position clearly. Coordinates of the corners (latitude, longitude) are given. Subdivisions are at intervals of 10 degree.]

CONCLUSIONS

Rock magnetic studies were carried out in order to characterize the magnetic mineralogy carrying the ChRM of the Enticho Sandstone at Negash area, northern Ethiopia, and to determine the range of magnetic grain sizes. These studies have shown that the sampled Enticho Sandstone at Enticho locality preserved original magnetization of high quality which are carried by detrital hematite (Tesfaye Kidane *et al.,* 2013). The Enticho Sandstone at Negash area, Belesa locality, on the other hand, is characterized by coarser grained sand with magnetization carried by magnetically hard and fine-grained titano-hematite and soft materials dominantly coarse titanomagnetite whose magnetization is known to relax quickly with time.

Comparison of the paleopole position from these sediments at the two localities with the current APWP curve for West Africa gives a Quaternary remagnetization age for the Enticho Sandstone at Negash area and a primary magnetization age range of ≈260–270 Ma (Early Permian and Late Carboniferous) for the same sandstone at Enticho locality.

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