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MAGNETOSTRATIGRAPHY OF THE *HOMO*-BEARING PLEISTOCENE DANDIERO BASIN (DANAKIL DEPRESSION, ERITREA)

ANDREA ALBIANELLI[1] & GIOVANNI NAPOLEONE[1, 2]

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Abstract. Four magnetozones have been found in the 530 m thick profile of the Dandiero Group. The lower unit, the Bukra Sand and Gravel, extends in the R1 reversed magnetozone from 150 m below the tephra level which was used as the reference marker between the sampled sections. The normal magnetozone N1 is almost completely covered by the lacustrine and deltaic sediments of the Alat Formation, while the following reversed magnetozone contains both the Wara Sand and Gravel and the lacustrine Goreya Fm. The N2 polarity zone is completely occupied by the Aro Sand.

This polarity sequence has been calibrated to the geomagnetic time scale using the Early to Middle Pleistocene age of the associated vertebrate fauna and fission-track dating. The four magnetozones were thus regarded as representing the chrons by which the Pleistocene is correlated with magnetochronology. Their three reversal boundaries provided the dates of 1.07, 0.99 and 0.78 Ma, allowing to determine average sedimentation rates close to 1 m/ky. Cyclostratigraphy of the magnetic signal, analysed by the spectral analysis of the time series across the Jaramillo and late Matuyama chrons, confirmed that value. The evidenced cyclicities were directly related to the alternating lithofacies, and both to the astronomical parameters driving the climate changes during the deposition of the Dandiero Group (some five hundred thousand years).

The section with the *Homo* site covers the Jaramillo/Matuyama boundary, and the *Homo* bed located 2 m below this limit is dated 0.992 Ma.

Riassunto. L'indagine paleomagnetica ha interessato una sezione di circa 530 m nel Gruppo del Dandiero. Sono state riconosciute quattro magnetozone. A cominciare da circa 150 m al disotto di uno strato guida cineritico, l'unità più bassa (Bukra Sand and Gravel) è compresa nella magnetozona R1. La magnetozona N1 corrisponde quasi completamente ai sedimenti lacustri e deltaici della Alat Formation, mentre la sovrastante R2 comprende le formazioni Wara Sand and Gravel e Goreya. La magnetozona N2 corrisponde alla formazione dell'Aro Sand. Questa successione magnetostratigrafica è stata calibrata alla Scala Tempo delle Polarità Geomagnetiche attraverso l'età (Pleistocene Inferiore-Medio) della fauna a vertebrati presente nella successione, e delle tracce di fissione. Le quattro magnetozone sono state correlate ai quattro croni individuati nel Pleistocene con le tre relative inversioni di polarità a 1.07, 0.99 e 0.78 Ma. È stata anche ricavata per tutta la successione una velocità di sedimentazione di circa 1 m/ky.

La ciclostratigrafia del segnale magnetico, analizzato attraverso l'analisi spettrale delle serie temporali, e limitatamente ai croni Jaramillo e Matuyama, ha confermato questo valore. Le ciclicità individuate sono state messe in relazione con le alternanze delle litofacies, ed entrambe con i parametri astronomici che hanno influenzato i cambiamenti climatici durante la deposizione del Dandiero Group, durata all'incirca 500,000 anni.

La sezione che include il livello con i resti di *Homo* comprende il limite Jaramillo/Matuyama, ed il livello con *Homo*, che si trova a circa due metri al disotto di questo limite, è datato 0.992 Ma.

Introduction

The Pleistocene Dandiero Group in the Eritrean Danakil depression comprises some 550 m of alluvial, fluvial, deltaic and lacustrine deposits (Abbate et al. 2004) from which human remains have been recovered (Abbate et al. 1998; Macchiarelli et al. 2004).

The aim of this paper is to provide the details of the magnetostratigraphic study of this succession after a preliminary summary appeared in a previous report (Abbate et al. 1998).

The magnetostratigraphy of the Dandiero Group is here documented through combined magnetic, stratigraphic (Abbate et al. 2004), paleontological (Ferretti et al. 2003; Martínez-Navarro et al. 2004) and radiometric (Bigazzi et al. 2004) studies.

The fossil mammals of Early to Middle Pleistocene age found in several sections of the Dandiero basin as well as a tephra with a fission-track age of 1.3 ± 0.3

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[1] Dipartimento di Scienze della Terra, Università di Firenze, Via La Pira 4, I-50121 Firenze, Italy. albix@unifi.it
[2] Museo di Storia Naturale, Sezione di Geologia e Paleontologia, Università di Firenze, Via La Pira 4, I-50121 Firenze, Italy. napo19@unifi.it

Fig. 1 - Location map of the study area.

Ma gave good time constraints for their magnetostratigraphic calibration to the geomagnetic polarity time scale (GPTS) as updated by Cande & Kent (1995), to which the chronostratigraphic scale for the Cenozoic is related (Berggren et al. 1995). The identified post-Olduvaian magnetic chrons, Jaramillo and latest Matuyama, provided the dates of 1.07, 0.99 and 0.78 Ma within which the Dandiero Group sedimentation rates were averaged. They result quite high in comparison with those recorded in the classical nearby sites of the East Africa (e.g. the end-Pliocene Olduvai profile, Grommé & Hay 1963; Tamrat et al. 1995) and similar to those obtained from the fluvio-lacustrine basins of the Italian peninsula (Napoleone et al. 2003, in press).

Geological setting

The Danakil Depression, at the northern margin of the Afar region (Fig. 1), is filled by Miocene to Quaternary sedimentary deposits and volcanic rocks including ash flows (details in Abbate et al. 2004). It is bordered to the west by the Precambrian basement at the foot of the Eritrean plateau and to the east by a ridge of recent volcanites and by the Danakil block.

The continental sequence of the Dandiero Group (Fig. 2A) is located in the northernmost portion of the Danakil depression near Buia. With the exception of the topmost unit (Addai Fanglomerate), we sampled all the formations that compose this group, from the basal fluvial formation (Bukra Sand and Gravel), to upsequence, the deltaic sands with clays of the Alat Fm. containing the human remains, the fluvial unit of the Wara Sand and Gravel, the lacustrine clays of the Goreya Fm. and the fluvial Aro Sand (Fig. 2B).

Magnetic data

Sampling

We sampled four sections across the Dandiero Group for a total amount of 182 oriented hand samples variously spaced in a stratigraphic thickness of ca. 530 m. The *Homo* site section was more closely sampled (see for details Fig. 7).

- Dandiero section: 29 samples along a 185 m profile across the Bukra Sand and Gravel and the Alat Formation;
- Alat section: 52 samples along a ca. 500 m profile across the Bukra Sand and Gravel, the Alat Formation, the Wara Sand and Gravel, the Goreya Formation and the Aro Sand;
- Aladaf section: 90 samples along a 226 m profile across the Alat Formation, the Wara Sand and Gravel,

Fig. 2 - Geologic setting of the surveyed sections, reconstructed in their alluvial-plain-to-lacustrine sedimentary asset of the identified stratigraphic formations (after Abbate et al. 2004). Sampling was closer in the middle portion of the profile and rather apart in both extremes, the 150 m of fluvial deposits of the Bukra Sand and Gravel and the more than 100 m of the arenaceous fluvio-deltaic Aro Sand.

the Goreya Formation;

- *Homo* site section: 11 samples along a 23 m profile across the top of the Alat Formation and the base of the Wara Sand and Gravel.

Section locations are shown in the map reported as Fig. 3 in Abbate et al. 2004.

The fine-grained silt and clay levels, particularly frequent in the lacustrine facies, and the silty interbeds within the more sandy facies were preferentially sampled. Some levels in coarser material were also sampled when the spacing resulted too large. In the laboratory measurements they showed very good magnetic properties as to their intensity and directions. This allowed successful results in the Wara Sand and Gravel which were sampled at closer spacing for conducting the cyclostratigraphic recognition.

Laboratory analyses

The laboratory measurements were performed at the Paleomagnetic Laboratory of the Swiss Federal Institute of Technology (ETH), Zurich. The magnetic signature of the rock samples was identified measuring the fossil vector in its present state of natural remanent magnetization (NRM), and its associated bulk susceptibility, with the aim of reconstructing the paleomagnetic history back to the primary conditions of acquisition of the Earth's magnetic field at the time of deposition of the material.

Cleaning operations to remove all the superimposed magnetic events since that date were carried out applying successive demagnetizations, either by alternative currents (AC) of increasing field intensities and by thermal treatment at increasing temperatures, according to the nature of the magnetic behavior of each lithotype.

Magnetic properties were detected measuring the acquisition of the isothermal remanent magnetization (IRM) in the three orthogonal directions of the specimens and its thermal demagnetization, in addition to the thermomagnetic behavior under a strong applied field with the Curie balance. The latter two experiments were carried out to give more accurate indications of the presence of magnetic minerals which act as good carriers of stable magnetization, representing the characteristic directions of the rock specimens.

Polarities at the NRM stage. The NRM initial step, in most samples, showed high intensity and susceptibility, but not so in the fluvial and lacustrine facies where the former decreased by more than one order of magnitude compared to the previous ones. The average NRMs oscillated from 1 to 50 mA/m with extremes at 0.2 to 80 mA/m, while the susceptibilities were in the order of 10E-4 SI units, which are both one to two orders of magnitude higher than those usually found in most continental sediments, including those of the Apennine basins (Albianelli et al. 1997, 2004).

Directions maintained their dispersion in a very narrow range, either through the profile or during the cleaning treatments, as shown in the next chapters.

It is also interesting to note that the low latitude of the site did not prevent the clear identification of the fossil vector, because even the low dipping inclinations changed their polarity in good accordance to the virtual geomagnetic pole (VGP) latitudes. In particular, the curves for intensity and susceptibility assumed parallel trends, as a result of the stable magnetization acquired during deposition, and were later used to process the spectral analysis for cyclostratigraphy. In correspondence with a more decidedly lacustrine facies their trends actually remained parallel, but a drastic drop in their amounts was measured.

The NRM directions revealed well clustered groupings in normal and reversed polarities, whose disposition was already close to the characteristic directions identified after the following demagnetization treatments.

AC demagnetization. NRMs of the sampled lithologies were cleaned of their possible alterations produced by superimposed parasitic fields, using the AC demagnetization at steps of 5, 10, 15, 20, 30, 40, 55, 70, 85 mT (milli Tesla) of the applied magnetic field. This procedure was effective on most samples, leading to the identification of the characteristic direction of the paleovector already at the 20 mT step. These directions were measured for the three main lithotypes of coarser and finer sand, at Dandiero and Aladaf, and for the fine-grained material respectively in the lacustrine and alluvial plain clay, and in the *Homo* section clay, as shown by the diagrams on the left hand side of Fig. 3. On such polar vector diagrams, the changing directions during demagnetization and at decreasing remanence are projected on the vertical plane for inclination (Z) and on the horizontal one for declination (H). Its decrease in intensity at increasing fields was also visualised in the diagrams on the right of Fig. 3. The data of the second survey perfectly agreed with those of the first profile.

In the Dandiero section, the reversely magnetized sample DN9.1 enhanced the direction of the characteristic magnetization from the initial steps, and then remained steady until the highest steps of the applied field; the removal of the present normal field produced an increase of its remanence and a deviation of directions in the initial steps. In contrast, the tephra showed a rapid decrease in intensity, which at 20 mT dropped to 10 % of the initial one. The directions in the Aladaf sample AL-9 steadily maintained their regular trend.

In the clay of the *Homo* section two opposite conditions were reached, a smooth cleaning was generally shown but an extreme dispersal of directions at successive steps occurred in the H2 level. The latter, though, occurred in decidedly clayey beds rich in organic matter, where the depositional conditions also favoured the reducing activities

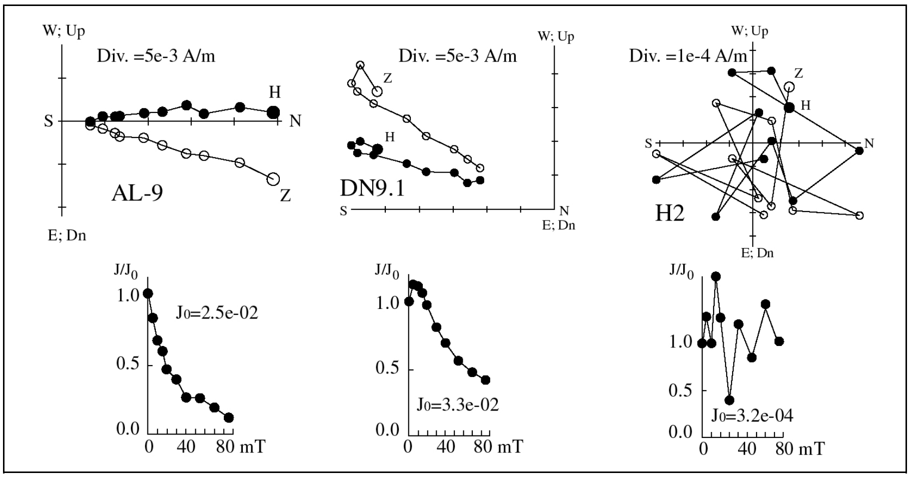

Fig. 3 - Demagnetization under the AC treatment. All samples show a very regular trend, as AL-9 and DN9.1, due to a firm magnetization acquired during deposition of the material, with the exception of some clay samples from the lacustrine facies. These produced, at each demagnetization step, wild directions due to the hard components, which were later removed at high temperatures.

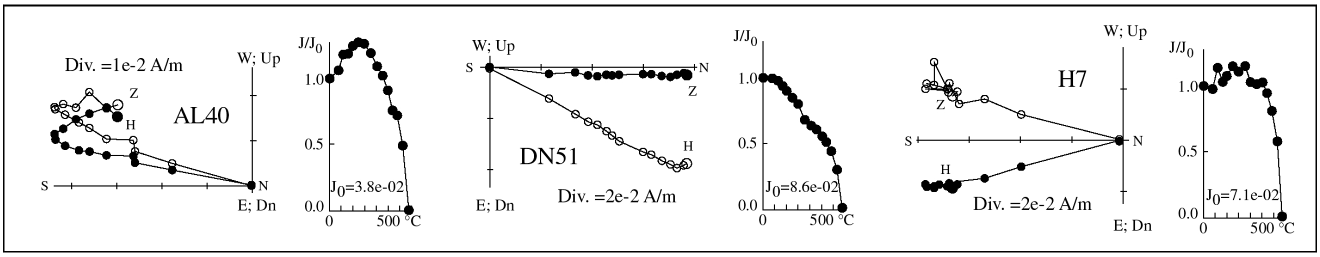

Fig. 4 - Demagnetization of the different rock types by thermal treatment. Most directions of the characteristic vector were clearly enhanced since the lowest steps. The samples shown here and in the AC diagrams are not dip-corrected.

on the original magnetite content. In these conditions the NRM intensity resulted strongly lowered, and the newly formed minerals (ferrimagnetic iron sulphides) produced particularly unstable behaviors shown by the dispersal of directions in their demagnetization diagrams. The same behaviors occur in most of the recent sediments deposited at high rates and with reducing processes, as was also verified in the Plio-Pleistocene Apennine basins of both marine and continental deposits. In the present study, the characteristic directions selected on each sample assumed thereafter a better clustered distribution of points, which led to the polarity sequence thus derived from the VGP latitudes.

Thermal demagnetization. Thermal treatment was applied to all of the samples, using steps of 30 to 50 °C until their intensities were canceled, i.e. when the blocking temperatures were reached for the magnetic minerals present in the rock. The continuous decay in intensity was accompanied by constant directions of the paleovector whose characteristic values were therefore used to calculate the VGP latitudes and fix the polarity zonation (Fig. 4). All lithotypes showed a steady demagnetization trend, with the characteristic directions well defined. On the AL40 reversed sample the normal present-day field was removed before the 250 °C step, while the normally magnetized DN51 moved straigthforward to the origin since the NRM step. The thermal treatment was effective on all lithotypes, including the lacustrine ones, fairly rich in organic matter, as the clayey beds of the *Homo* site (H7) for which the AC demagnetization was uneffective. In these samples the initial steps hardly found a regular trend before 400 °C and then the characteristic directions were reached.

The bulk susceptibility values were measured, at each demagnetization step, in order to detect changes occurring at critical temperatures, when new magnetic minerals are formed by oxidation of the sulphur compounds present in the clay portions of the sediment. The sudden increase in susceptibility disturb the directions up to loose trends when it reached high values, thus preventing further demagnetization. Most of these changes were moderate in the present fine-grained material, and vanished in the coarser and strongly magnetized ones, where the blocking temperatures were reached at higher steps.

Acquisition of the IRM. Saturation of the isothermal remanent magnetization (IRM) was applied to a set of 10 samples from both surveys, in order to enhance the low amount of the clay component affected by reduction, in contrast to the coarser material; the resulting diagrams are shown for three of them (Fig. 5). This experiment was made according to Lowrie's (1990) procedure, applying increasing field ranges in the orthogonal directions of each sample, and stepwise demagnetizing the IRM acquired at the ambient temperature, in order to separate the magnetizations acquired up to 30 mT, 100 mT, and 1 T. Both data sets supported the presence of low coercivity minerals with blocking temperatures in the range of the magnetite, as emphasized by Lowrie (1990), for the lacustrine material (AL sample), and of higher coercivity for the coarser material (B and D samples). The demagnetization diagrams are shown here together with the susceptibility curve,

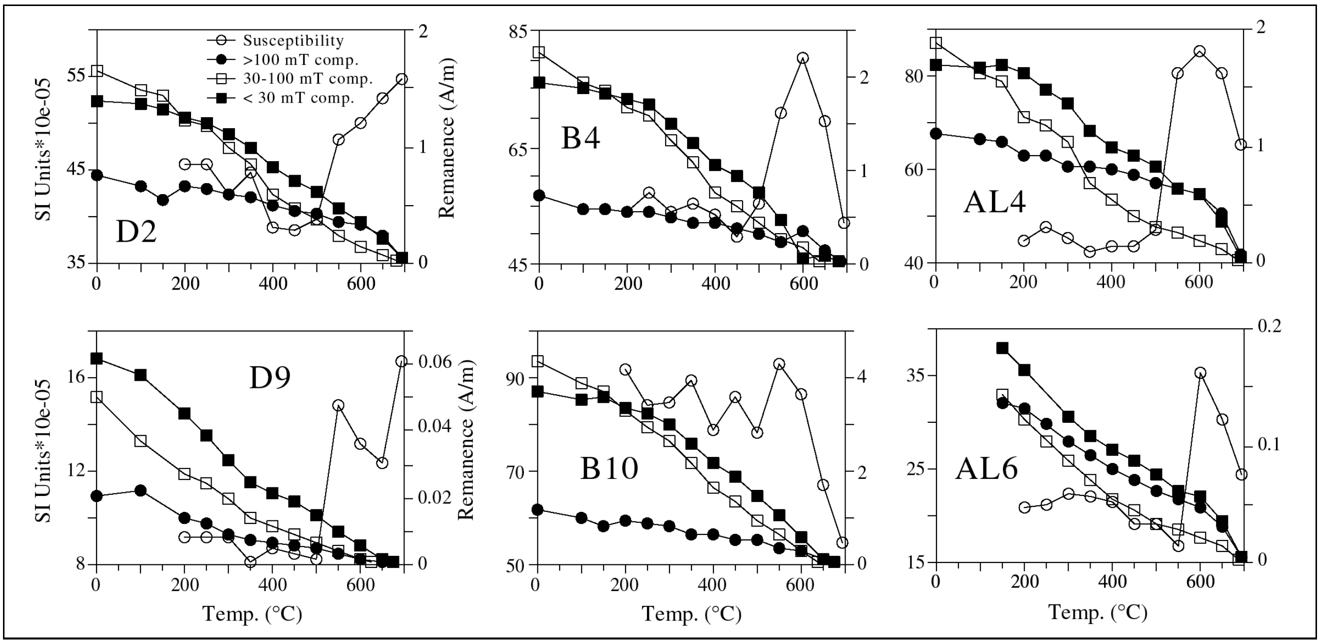

Fig. 5 - Demagnetization diagrams of the IRM acquired after saturation on the three components. High coercivity components are enhanced by the considerable amount of magnetization still acquired in the higher steps of the applied field. Minerals with low coercivities, as the carriers of the primary magnetization, are anyhow dominant.

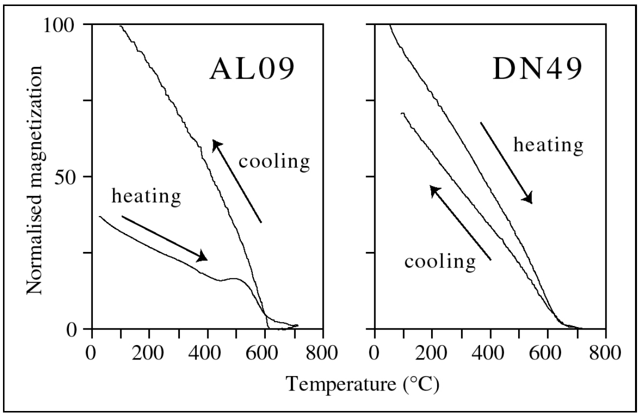

Fig. 6 - The experiments with the Curie balance. The paths under a strong applied field, from the room temperature to the complete demagnetization, and back to low temperature are shown for a weakly magnetized clay (AL09). Its initial magnetization slightly increases with the newly formed magnetic phase, beginning at ca. 450 °C and farther dominating in the acquired field during the cooling path. Sample DN49 represents the behavior of the ignimbrite level.

which assumed higher values in correspondence to the onset of new mineral phases (Fig. 5). But it is worth noting that the values of the susceptibility changes were extremely low, as remarked in the reported scale, confined within few units, while they may normally be orders of magnitude higher. The intensity of the remanence, on the other hand, was very high, testifying a prevailing volcanic origin of the filling material, but decreased by one order in samples like AL6 and two orders in sample D9, as the concentration of the volcanic particles was diluted in the lacustrine facies by adding clayey and carbonatic products.

Curie balance curves. The above mentioned low content of sulphide magnetic minerals, that is oxidized into new magnetite during the heating process, was also emphasized by the Curie balance curves produced during the therrmal cycle recorded under a strong applied field (Fig. 6). Also the lacustrine deposits, as seen in sample A09, were able to enhance a minor change for their higher abundance in clay and organic material, which did not affect the curves of the more sandy material or the tephra below the donuts (sample DN49). This latter evidence adds to the various ones thus far produced, emphasizing a strong volcanic signature in the sedimentary materials.

Magnetochronology

The magnetic properties of the sampled sediments substantiate the reliability of the primary magnetization, which makes viable the magnetostratigraphic reconstruction shown below.

The Alat section is the most complete among the four sampled sections and can be regarded as the reference section, because it shows the four polarity zones covering all the formations surveyed in the Dandiero fluvio-deltaic and lacustrine sequence (Fig. 7). Its Pleis-

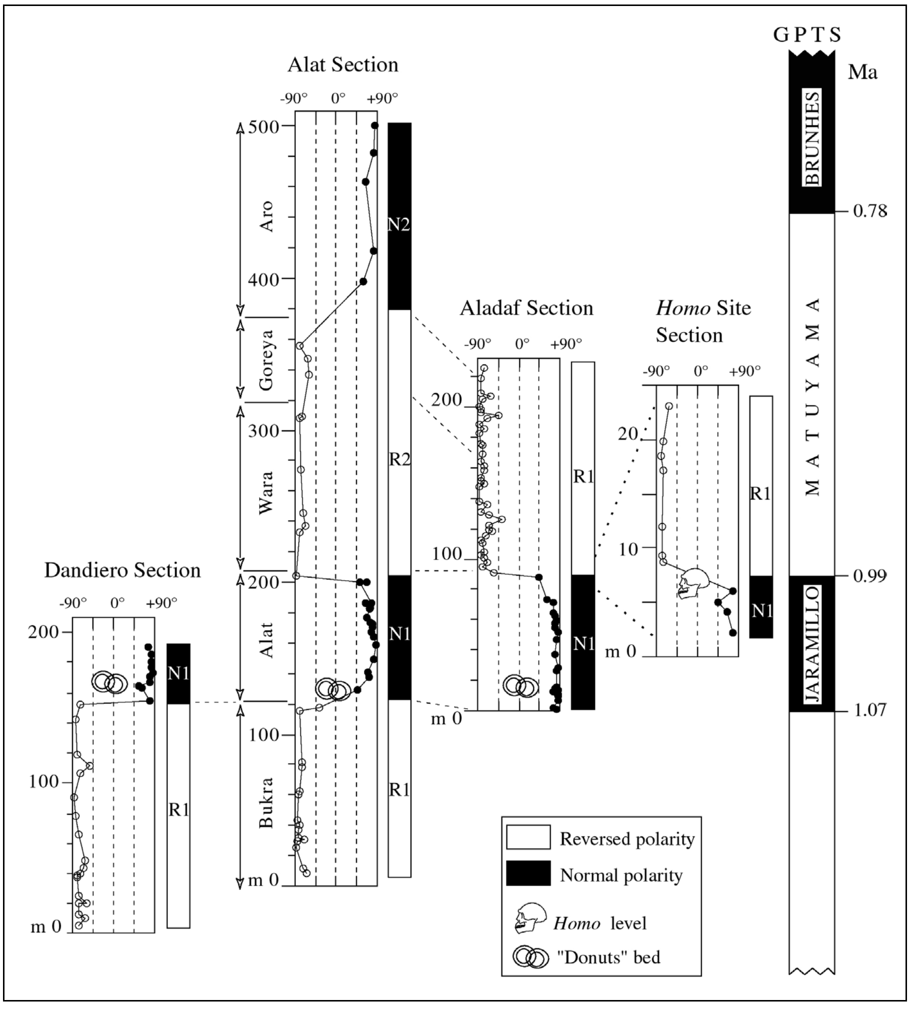

Fig. 7 - Generalised magnetochronology of the Dandiero Group. The VGP latitude distribution is shown for the three main profiles and the *Homo* short section. Their magnetostratigraphic correlation derived from the magnetozone thicknesses calibrated to the GPTS. Its Jaramillo chron is tied with the lower magnetozone of the Aladaf section, which represents the highest accumulation rate but is the most reliably confined interval (see the discussion in the text). Therefore, the Brunhes boundary is more distant from top of Jaramillo, as its correlated interval in the Alat section was there deposited with a smaller rate. The upper Aladaf section and the Dandiero section were unbounded and the rate of 1 m/ky measured from cyclostratigraphy may be used for them.

tocene age, provided by biochronology and supported by the fission track dating, indicates that the four magnetozones represent the GPTS magnetochrons younger than the Olduvai Chron (Cande & Kent 1995). On top of it, in fact, the Pleistocene boundary is correlated in the GPTS with the short reversal close to its end (see the Vrica stratotype established in southern Italy, Van Couvering 1997).

Characteristic declination and inclination values have been used to obtain VGP latitudes and polarity zonation (Fig. 7). The recognized magnetozones are, from bottom to top, R1, N1, R2, N2. The Bukra Sand and Gravel fall in the reversed magnetozone R1 and the Alat Fm., with the exception of its uppermost beds, in the normal magnetozone N1. Wara and Goreya units are both comprised in the R2 zone. The sampled interval of the Aro Sand is included in N2, but a correlation with the Aladaf section (see below) shows that its very base could be reverserly magnetized.

The N1 magnetozone has been calibrated to the Jaramillo Chron (C1r.1n) and R2 magnetozone to the latest Matuyama (C1r.1r). These two intervals therefore span 1.07 to 0.99 Ma and 0.99 to 0.78 Ma, respectively. These dates allow to estimate that almost half of the 500 m thick Alat section was deposited in 290 ky. Assuming a similar average sedimentation rate for the remaining half, the whole Alat section could cover 580 ky, with a steady rate of 0.86 m/ky. Also the partial intervals reproduce almost the same rate, 0.90 m/ky given by the 72 meters comprised in the 80 ky Jaramillo and 0.81 ± 0.10 m/ky by the 170 ± 20 m/210 ky for the latest Matuyama.

The Aladaf section provides sedimentation rates slightly different from those obtained for the Alat section. The Alat Fm. is there 97 thick and the basal 17 meters underlie the donut key bed. The first 90 meters of the same formation are assumed to correlate with the whole Jaramillo and with this assumption the sedimentation rate is 1.1 m/ky. This is approximately ca. 25% higher than that found in the Alat section. It has to be noted that the base of N1 is unbounded and its calibration with the Jaramillo will be discussed later.

Further comparisons can be done between the Alat section and the Dandiero and the Aladaf sections, which are shorter than Alat section and include a smaller number of magnetozones.

The Dandiero section has been surveyed for 185 m in the Bukra Sand and Gravel. It is unbounded on both ends and, therefore, does not provide elements for an estimate of the sedimentation rates. It, however, records with great detail the transition from R1 to N1, that is from Matuyama to Jaramillo. This transition occurs 14 m beneath the donuts key bed, which has been used to correlate the Aladaf and Dandiero sections with the Alat section (Fig. 7).

In the Aladaf section two magnetozones have been recognized. The N1 corresponds almost completely to the Alat Fm. with the exception with the topmost 7 m which belong to the overlying R1 magnetozone. The latter includes the Wara Sand and Gravel, the Goreya Fm. and the basal layers of the Aro Sand.

The sedimentation rate can be calculated for the lower portion of this section through the correlation of N1 with Jaramillo and a value of 1.1 m/ky is obtained.

If we apply this rate to the R1 magnetozone, its 136 m of sediments would have been deposited in ca. 120 ky. This means that the base of the Aro is dated ca. 90 ky prior to the onset of the Brunhes, while in the Alat Section the Goreya/Aro transition falls very close to the Brunhes boundary (210 ky after the Jaramillo).

The lower limit of the N1 magnetozones in the Aladaf section raises a similar problem due to the lack of a downward transition to a reversed polarity. The donut key bed can help to remove such an uncertainty. In the Aladaf section, it is 73 m downsequence from the Jaramillo upper limit and 17 m from its base. In the Dandiero section the lower limit of the Jaramillo has been found 14 m below the donuts key bed and in the Alat section this key bed coincides with the base of the N1. If we regard the donut key bed as an isochron, the different thickness between the donut level and the base of the Jaramillo should be accounted for by differences in the sedimentation rates in the three sections. An interesting feature to be noted is that the beds below the donut key bed in the Aladaf section seems to witness a rapid downward transition to the Bukra Sand and Gravel. Thus, it seems reasonable to assume that the base of the Jaramillo should be very close or coincident with the base of the section and that all the extent of the Jaramillo would be represented by the N1 Aladaf magnetozone. This supports the previous estimate based on a complete correspondence between the N1 and the whole Jaramillo of 1.1 m/ky.

It should be noted that the average sedimentation rates obtained from magnetostratigraphy of the various sections result quite consistent, and this is remarkable for continental successions.

If we assume the mean value of 0.98 m/ky between the 0.86 m/ky (Alat section) and 1.1 m/ky (Aladaf), the major sedimentary and magnetostratigraphic events of the Dandiero Group can be dated as follows:

- The base of the sequence, 150 m below the onset of the Jaramillo (1.07 Ma), in the Bukra Sand and Gravel along the Dandiero section, is 1.22 Ma old;
- The transition of the Bukra/ Alat Fm. is at 1.07 Ma;
- The tephra, associated with the donuts bed, is placed at 1.055 Ma in the Dandiero section;
- In the *Homo* site section the hominid-bearing level, 2 m below the Jaramillo/Matuyama boundary, can be tightly dated at 0.992 Ma;

- The transition of the Alat Fm. to the Wara Sand and Gravel, placed less than 10 m above the end of Jaramillo, is dated 0.98 Ma;
- The Wara and Goreya units are magnetostratigraphically bounded only in the Alat section. The top of the Goreya Fm. is very close to the Brunhes boundary and is dated 0.80 Ma. The identification of the Brunhes boundary in the Aro Sand (Alat section) is particularly significant because it establishes a correlation with the marine Middle Pleistocene biostratigraphic boundary. Its detection is remarkable since it is not frequently found in continental series and its precise placement in the Quaternary sequences is still open to debate (Spassov et al. 2001).
- The Aro Sand covers more than 100 ky and reaches 0.67 Ma in the Alat section.

The cyclostratigraphic record

A cyclostratigraphic approach applied to the Aladaf section provides additional evidence on the sedimentation rates and a correlation of the magnetic signature with the astronomical parameter changes. In this 226 m thick section the close sample spacing (90 sampled horizons) allows spectral analysis on its time series. The resulting 2.5 m spacing corresponds to approximately 2.5 ky.

The intensity of NRM and the susceptibility raw data were processed for the entire section, which includes the Alat, Wara and Goreya units and the base of the Aro Sand as reported in the schematic lithologic profile on the left hand side of Figure 8. The beginning of the time series was chosen to coincide with a firm date, represented by the base of the Jaramillo (Fig. 7) recognized through the correlation with the Dandiero section. A further date to correlate the Laskar curves with the magnetic profiles is provided by the top of Jaramillo (0.99 Ma).

The short eccentricity index and the summer daily insolation are plotted from 820 to 1070 Ka, as calculated by Laskar (1990). The first curve is represented with an excursion from 0.01 to 0.06 (marked with – and + in the bottom abscissa) and the second from 400 to 500 W/m2 (marked in the top abscissa). Both curves reveal a general decrease in amplitude from older to more recent times and period lengths in the ranges of 100 ky (eccentricity) and 20 ky (precession), which were directly correlatable with both magnetic signals.

Larger precessional and eccentricity index excursions fit very closely with the higher magnetic intensities and their larger excursions, and viceversa with the magnetic minima. To such oscillations are notably tied the lithology changes of the Aladaf sequence reported on the left side.

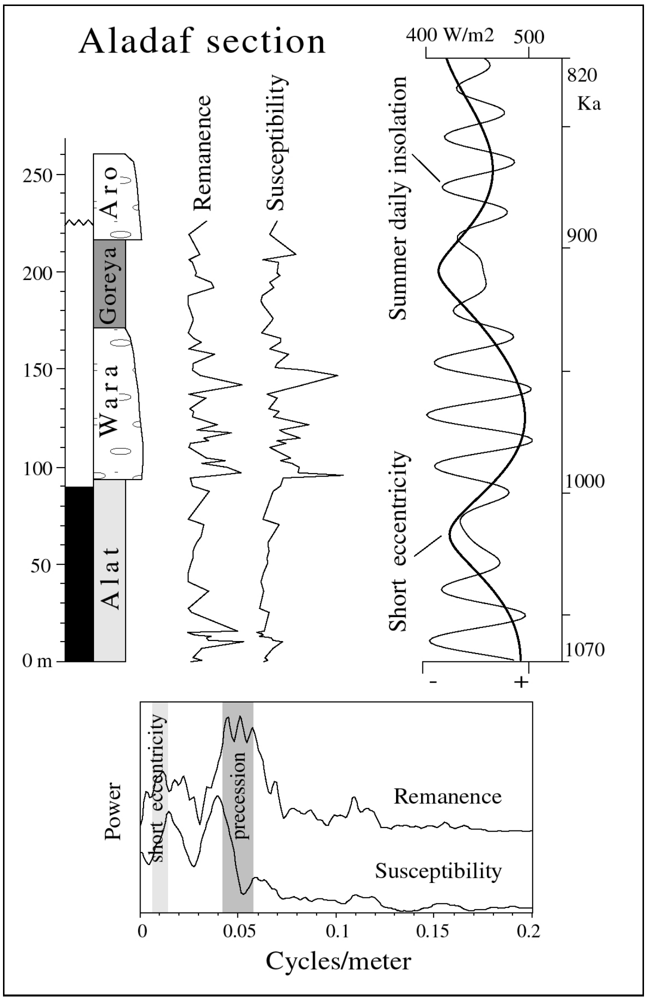

Fig. 8 - Cyclostratigraphic use of the magnetic signal after the power spectra processing on the NRM and bulk susceptibility records from the Aladaf section. The overall 226 m thickness of the sequence includes the schematic lithology of the fluvial to lacustrine deposits from the Bukra Fm to Goreya and beginning of Aro Fm. The magnetic curves are plotted by the side, fitting the curve of the summer daily insolation and of eccentricity index (after Laskar 1990), for the dates 800 to 1070 Ka. The Milankovitch periods (low eccentricity and precession) are visually corresponding to the magnetic oscillations, whose spectra are shown in the lower diagram. The maximum amplitude oscillations in the precession are reproduced by larger amplitudes of the magnetic signal, with a close correspondence to the lithology changes.

With a remarkable agreement of their raw data, both magnetic records maintain a parallel trend through the complete high within two lows, only slightly disturbed by a minor shift of the remanence height at the base of the section. The lows correspond to the deltaic and lacustrine fine-grained formations and the high to the more sandy deposits.

The power spectra processing on both records, reported in the diagram on the bottom of the figure, defines cycle periods well fitting the Milankovitch conditions for precession and eccentricity. Two peaks, marked by shadowed intervals, are prominent, one of higher frequency centered on the one twentieth of cycle/meter and the other of lower frequency at nearly one hundredth. Standing the correspondence between lithological and magnetic signature changes, the precession components, with their durations in the range of 20 ky, and the eccentricity (100 ky) can be regarded as modulating factors of the deposition.

The average sampling rate of approximately 2.5 ky (226 ky/90 samples) was sufficient to detect the precession periods, while the length of the time series, slightly greater than 200 ky, is not enough to detect the short-eccentricity components. The power spectrum, however, exhibits the 100 ky period with a fair amplitude (Fig. 8).

It may be stressed that in the Aladaf section the 80 ky duration of the Jaramillo are covered by a measured thickness of 90 m. If we apply the sedimentation rate obtained from this interval (90 m/80 ky) to the 136 m thick unbounded magnetozone above the Jaramillo, the onset of the Aro Fm. would fall at 0.87 Ma, a date slightly earlier than that found in the Alat section (0.80 Ma, very close to the Brunhes boundary). Thence, the 1 m/ky value provided by the cyclostratigraphic analysis is used to estimate the time duration of the unbounded portions of both Aladaf and Dandiero sections.

Discussion

Magnetic stratigraphy and Milankovian cycles duration confirm the high accumulation rates in the Jaramillo and latest Matuyama magnetozones of the Dandiero Group. They can be matched with similar rates of predominantly deltaic settings in the near hominid-bearing sites of Ethiopia, where 0.7-0.8 m/ky are reported (Awash valley, Renne et al. 1999). In earlier times, at the Olduvai site in Tanzania, the rates are sensibly lower. In this case we are dealing with a subaerial and lacustrine deposition of tephra between the two main lava flows calibrating the Olduvai magnetochron (Grommé & Hay 1963; Tamrat et al. 1995).

Due to the unbounded limits of the magnetostratigraphic series, dates in the time span from 1.22 Ma to 0.67 Ma were determined with an accuracy of ± 20 ky. This uncertainty does not affect to any extent the high resolution dating of the *Homo* site. The *Homo*-bearing beds are one-million-years old and their age may actually be specified with the only support of their position coinciding with the polarity change, regardless of either the average sedimentation rate of the Jaramillo chron or the tuning of power spectra to the astronomical parameters. The stratigraphic position of the *Homo* remains is just 2 m below the upper limit of Jaramillo (0.99 Ma) and with an accuracy of 1 ky its date can be fixed at 0.992 Ma.

A further implication relates to the cyclicities recorded in these continental sediments, as enhanced by the spectral analysis. Milankovitch cyclicities were clearly evidenced as a strong imprint of the magnetic signal in the sediments. This approach, applied to the Aladaf section (Fig. 8), has already shown how clear is the correspondence of the lithologic layering with the astronomical parameters. It has been remarked that the Wara Sand and Gravel, released much stronger signals than the silts of the Alat and Goreya Fms. These oxidized deposits accumulated during climate conditions of higher insolation rate, forced by the precessional oscillations throughout the eccentricity period, whereas the reduced sediments accumulated during periods of lower insolation. Consequently, the lacustrine-palustrine facies was deposited in the Aladaf series during times when the lowest peaks of the eccentricity index and the minimum amplitudes of the precession coincide.

The thicknesses of these units with reduction facies are 50 m for the Goreya Fm. and 90 m for the Alat Fm. With the sedimentation rate so far discussed of 1 m/ky, it results that the reducing conditions for each unit lasted 50 ky and 90 ky, respectively. These differences can be accounted for by local factors. One would expect a duration of ca. 100 ky for both units, in accordance with the global climate oscillations recorded in the oceanic deposits as changes in the stable isotopes ratio (Shackleton et al. 1984). The same pattern with wet and dry episodes has been obtained through the magnetic signal in the oceanic deposits (Maher & Hounslow 1999) and the thick continental loess deposits of Eurasia (Heller et al. 1991; Forster & Heller 1997). Thence, whereas the 90 ky of the Alat Fm. cover a complete short eccentricity cycle in accordance with the global record, the Goreya 50 ky imply a different response of the local paleoenvironment to climate forcing.

The time series of the Dandiero Group was long enough to enhance the presence of the eccentricity cycle, but the sampled interval was too short to show the onset of its variations superimposed on the obliquity and precession, which occur in the oceanic sediments.

However, this close correlation between the astronomical curves and the magnetic record is noticeable because it shows how the sedimentary facies and their environmental conditioning are linked to the climate record in a period of generalized deterioration (also reported in Abbate et al. 2004).

The changing regime of the wind circulation, during this exactly dated time span of 855 to 1070 Ka, together with the base level fluctuations, may account for the variable amounts of dust transported from the catchment areas, including volcanic settings. Such events have also been detected as variable amounts of sediments from continental origin deposited in the Indian Ocean basins with Milankovitch cycles rhythmicities (de Menocal & Bloemendal 1995; Maher & Hounslow 1999).

Conclusions

The paleomagnetic survey carried out in the Dandiero Group, where the Buia human remains were found, led to the recognition of four polarity zones. Owing to biochronology of associated Early to Middle Pleistocene age mammal fauna and fission track dating, two of them are calibrated to the Jaramillo (C1r.1n) at 1.07-0.99 Ma and to the latest Matuyama (C1r.1r) at 0.99-0.78 Ma.

The magnetic zonation led to a very high resolution dating of the succession, and provided a similar precise definition for the sedimentary and biochronologic events recognised throughout. The dating of the *Homo* level was obtained with a 1 ky resolution, and the resolution of the other events reached accuracies of 2 to 20 ky.

An average sedimentation rate of 0.96 m/ky was calculated over the total thickness (530 m) of the sequence versus the covered time span of 550 ky. Similar rates are provided by individual magnetozones from various sections and are confirmed by the cyclostratigraphic analysis. Because of its vicinity (2 m below) to the boundary at 0.99 Ma (end of Jaramillo), the *Homo* level was dated 0.992 Ma. Moreover, the short distance of 15 ± 2 m above the lower limit of the Jaramillo allowed to date the donut key bed. This peculiar depositional event, used for correlation between the magnetostratigraphic sections, has been dated at 1.055 ± 0.002 Ma.

A similar age can be given to the widespread tephra episode recognized in the Alat Fm. which is associated with the donut bed.

Other events have been less accurately dated due to insufficient sampling and unfavourable stratigraphic position with respect to the magnetozones. Based on both magnetostratigraphy and cyclostratigraphy, sedimentation rates however were noticed to have remained remarkably steady, even in the sandy levels of the delta deposits. For this purpose, magnetostratigraphy provided the three tie points to the GPTS used for calibration, and cyclostratigraphy yielded the best evidence for quantifying the duration of the different formations in the unbounded magnetozones.

In addition, cyclostratigraphy marks the climate oscillations in the Dandiero Group and these changes are recorded as variable abundances of the magnetic particles. The same climate changes with cyclic oscillations are enhanced by the isotope analyses in the oceanic deposits. They revealed, in the time interval of the Buia sequence, the last major change in the cooling trend. This trend began in the latest Early Pliocene, from long-lasting warm conditions, and was followed by the onset of longer cycle periods (40 and 100 ky) with dominating amplitudes of the temperature excursions acting on the geologic system. The acme of this process is reached with the recent glaciations. As both proxies, the isotopic ratio and the magnetic record, reproduce well the Milankovian cyclicities, a direct link to the climate changes was recorded in the Aladaf section from 855 to 1070 Ka. The magnetic curves of susceptibility and NRM intensity showed a decrease in correspondence with periods of low insolation, at the rhythm of the short eccentricity index forcing the sedimentation with two complete oscillations of 100 ky. They consist of two alternating cycles of sandy and limy facies, from the base of the Alat Fm. through the lowermost Aro Fm. The precessional signal of larger amplitude was correlated with the stronger magnetic signal relative to the more oxidized products of the Wara Fm., and bounded by the two minima of the low eccentricity limits. The less oxidized products deposited in correspondence with these minima and their magnetic signature reached the lowest intensity as well. Therefore, the deltaic-lacustrine sediments deposited when the global climate was in a glacial phase. These conditions recurred twice, constraining the two progradational and retrogradational stages (alternating in the Maebele Synthem above the Bukra Fm., see Abbate et al. 2004) into episodes driven by the short eccentricity. The envelope of such episodes is represented by the long eccentricity curve (400 ky), which is the dominating astronomical parameter forcing the sedimentation.

The alternating facies from the Alat Fm. to the Boulder Bed truncating the Dandiero Group lasted one complete cycle of the long eccentricity. The same duration was given by the magnetic polarity record in the Alat section.

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