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Magnetostratigraphy of the Koobi Fora Formation, Lake Turkana, Kenya

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The Koobi Fora Formation, a Pliocene and Pleistocene sequence of sedimentary deposits northeast of Lake Turkana, has yielded numerous fossils and stone artifacts of early hominids. Stratigraphic correlation of the hominid-bearing deposits throughout the Turkana region was established primarily by the chemistry and isotopic ages of volcanic tuffs and complemented by magnetostratigraphic studies. We have reinterpreted previously published magnetostratigraphy from the upper part of the Koobi Fora Formation because the original stratigraphy and dating of tuffs have been revised. In our reinterpretation we include previously unpublished data from the uppermost part of the formation. The upper magnetozones correlate with parts of the Brunhes Normal-Polarity Chron and Matuyama Reversed-Polarity Chron (about 0.6–0.85 Ma) and are separated from the magnetozones of the upper part of the Matuyama (2.0–1.25 Ma) by a disconformity. The Olduvai Normal-Polarity Subchron is represented within the Matuyama, but the lower part of the Matuyama (2.4–2.0 Ma) is missing due to an erosional disconformity. We have also determined magnetozones in the lower part of the Koobi Fora Formation, which had not been sampled for paleomagnetism during the earlier studies. Our time calibration of the magnetozones is made possible by isotopic dating of several tuffs and by chemical correlation of Koobi Fora tuffs with dated tuffs in the Shungura Formation of southern Ethiopia. The tephra correlations are corroborated by the excellent concordance between the magnetostratigraphies of the Koobi Fora and Shungura formations. The lower part of the Koobi Fora spans the interval from about 4 Ma to 2.4 Ma, within the Gilbert Reversed-Polarity and Gauss Normal-Polarity chrons. Rock magnetic studies indicate that detrital magnetite carries most of the stable remanence, although hematite contributes to the remanence as indicated by thermal demagnetization. The hematite, which presumably formed by postdepositional oxidation of original iron oxide grains, carries chemical remanent magnetization (CRM) that diminishes the sharpness of polarity zone boundaries. The CRM accumulated continuously within the uppermost 10 m of sediment below the land surface, so that the CRM reinforces the depositional remanent magnetization within thick magnetozones but obscures magnetozones having durations of roughly less than 70,000 years in sections where the sedimentation rate was approximately 15 cm/1000 years.

Introduction

Detailed reports on the magnetostratigraphy of the Turkana basin, east Africa, were last made by *Brown et al.* [1978] for the Shungura Formation in southern Ethiopia and by *Hillhouse et al.* [1977] for the Koobi Fora Formation in northern Kenya (Figure 1). These Pliocene and Pleistocene deposits, which crop out near the northern shore of Lake Turkana, have yielded important discoveries concerning the physical evolution and tool-making abilities of early hominids [*Coppens et al.*, 1976]. New developments concerning the stratigraphy, dating, and correlation of the fossiliferous deposits, plus new paleomagnetic studies of the Koobi Fora Formation, warrant a reevaluation of the regional magnetostratigraphy.

A key development has been the correlation of seven volcanic ashes between the Koobi Fora and Shungura formations [*Cerling and Brown*, 1982; *Brown et al.*, 1985]. Establishment of these ties has required stratigraphic revision of the Koobi Fora Formation [*Brown and Cerling*, 1982; *Brown and Feibel*, 1986], as originally described by *Vondra and Bowen* [1978] and *Findlater* [1976]. Volcanic ash beds in the lower part of the formation were assigned new names and new correlations of isolated outcrops were made on the basis of chemical fingerprinting of tephra. Also, a revised isotopic chronology using K-Ar and $^{40}Ar/^{39}Ar$ methods has been established for the Koobi Fora Formation [*McDougall*, 1985]. Most of the new information comes from the lower part of the Koobi Fora Formation, below the KBS Tuff. The stratigraphy and chronology of the deposits above the KBS Tuff, where most of the hominid fossils were discovered, have changed little since 1980, when an age of less than 2 Ma for the KBS Tuff became generally accepted [*McDougall et al.*, 1980].

The magnetostratigraphy originally developed by *Brock and Isaac* [1974] and later expanded by *Hillhouse et al.* [1977] did not adequately cover the older part of the Koobi Fora Formation, although this was not apparent until the stratigraphy was revised by *Brown and Cerling* [1982]. The first objective of the present paleomagnetic study was to fill this gap in the magnetostratigraphy. The second objective was to link the new magnetostratigraphy at Koobi Fora with the polarity zonation of the lower part of the Shungura Formation, located along the Omo River about 100 km north of the Koobi Fora camp. Using polarity transitions to establish additional time calibration points in the Turkana basin strengthens the chronology that has been established from isotopic dating and tuff correlations. The magnetic time lines provide independent age control for several widespread Turkana tuffs, two of which were discovered in Deep Sea Drilling Project (DSDP) cores in the Gulf of Aden [*Sarna-*

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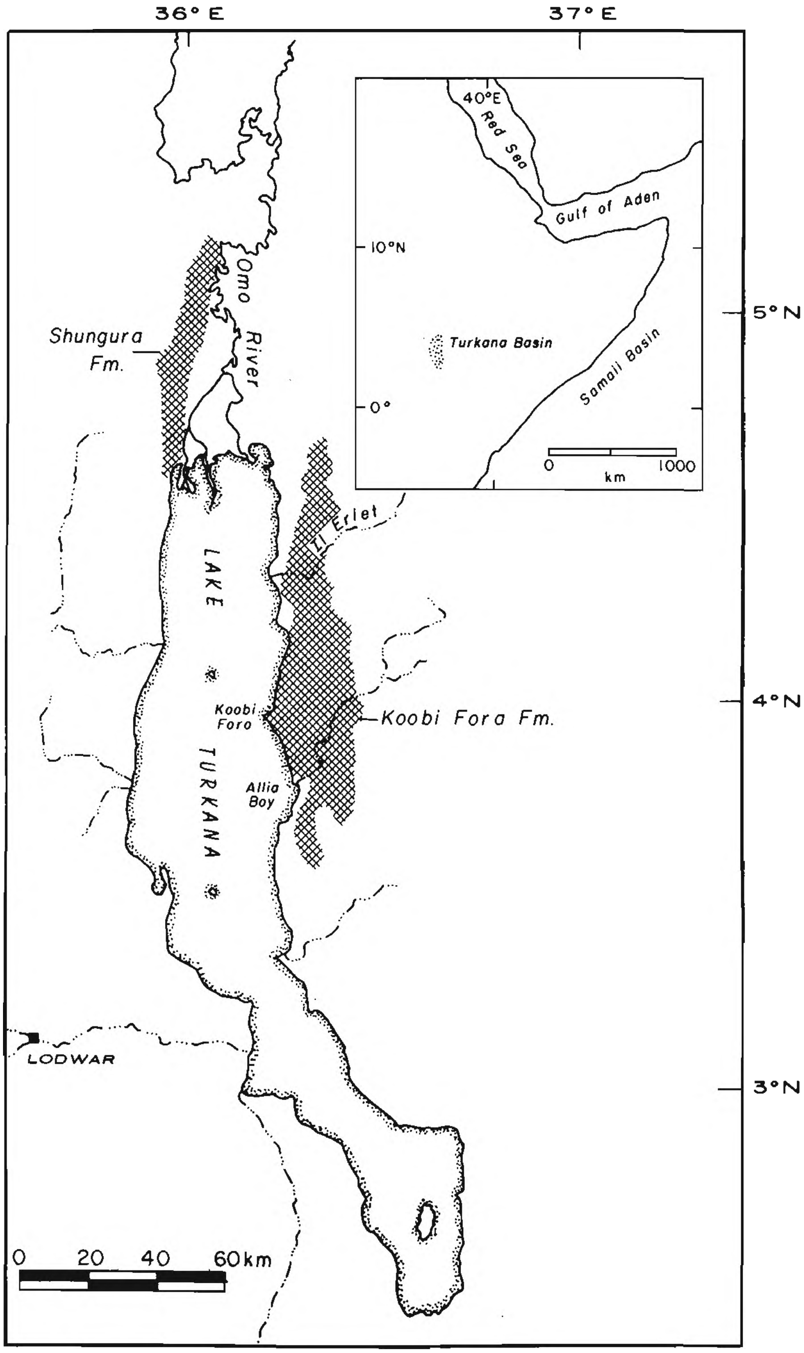

Fig. 1. Index map of the Turkana basin, showing outcrop areas of the Koobi Fora Formation and Shungura Formation.

Wojcicki et al., 1985]; one of these tuffs has also been identified at the Hadar hominid site in Ethiopia [*Brown*, 1982; *Aronson et al.*, 1983]. Therefore the temporal correlation of deposits in the Turkana basin can be extended over a large region, 1000 km northward into Ethiopia and 1600 km east into the Gulf of Aden. Our third objective was to investigate the rock magnetic properties and to model the magnetization process in the Koobi Fora Formation. Preliminary results of our study were reported by *Hillhouse* [1984].

STRATIGRAPHY AND PALEOMAGNETIC SAMPLING

Brown and Cerling [1982] and *Brown and Feibel* [1986] revised the stratigraphy of the Koobi Fora Formation after chemical analysis of the marker tuffs revealed discrepancies in some early correlations. These reports review the many contributions made by geologists and paleontologists who developed the basic stratigraphic framework of the Koobi Fora region. Background to previous isotopic studies and new average ages for pumice-bearing tuffs in the Koobi Fora Formation are given by *McDougall* [1985] and *McDougall et al.* [1985]. We used these new ages exclusively in this report.

The Koobi Fora sediments (Figure 2) were deposited on upper Miocene to lower Pliocene basalts, of which the youngest was dated at 4.3 Ma. The lower 240 m of the Koobi Fora Formation are extensively exposed in the badlands east of Allia Bay and south of the Laga Bura Hasuma. This part

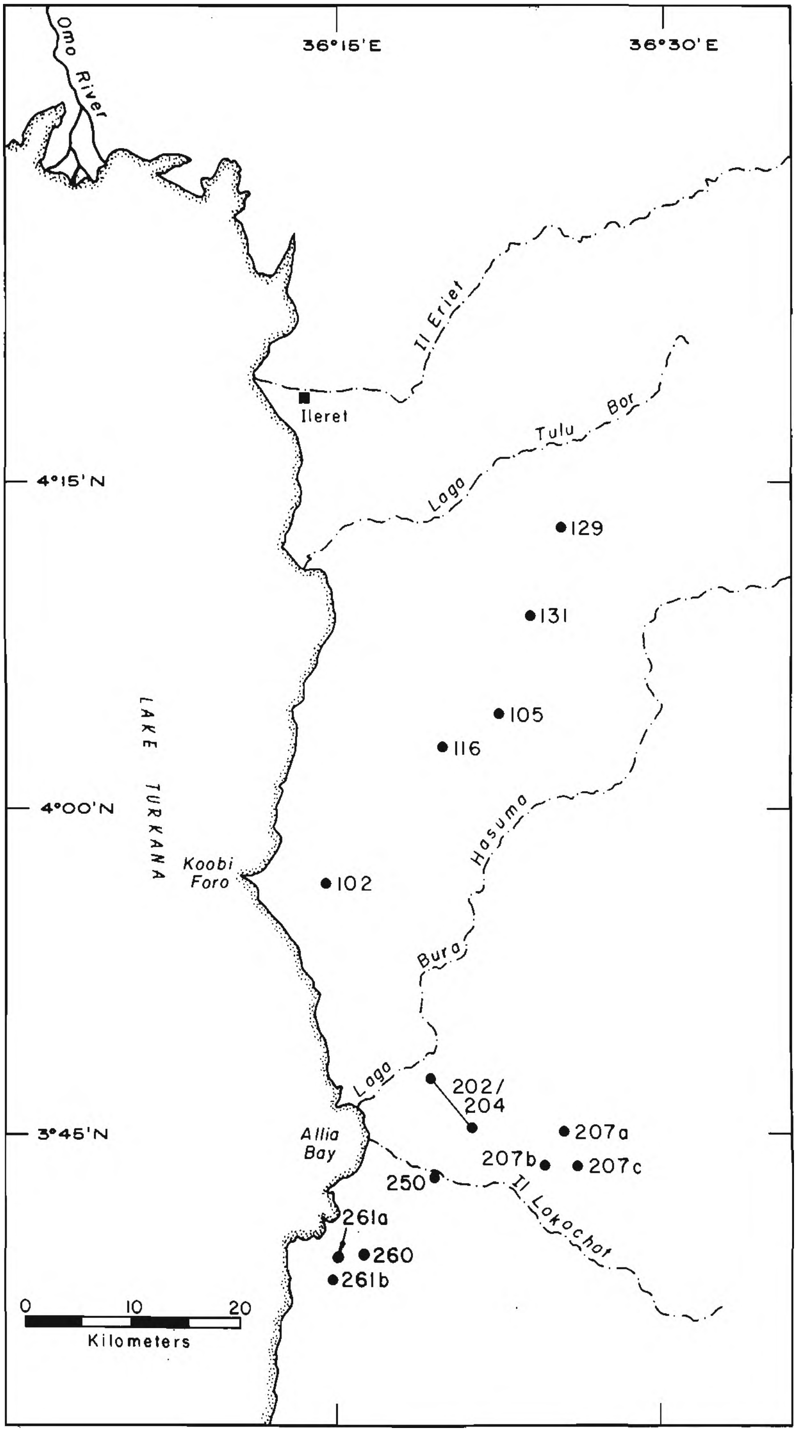

Fig. 2. The Koobi Fora region, showing sites in the Koobi Fora Formation that were sampled for paleomagnetism. Site numbers are keyed to Figure 6.

of the stratigraphic section was informally called the Kubi Algi Formation in earlier reports. In the recent redefinition of *Brown and Feibel* [1986] this part of the section consists of Lonyumun, Moiti, Lokochot, Tulu Bor, and the lower part of the Burgi Members of the Koobi Fora Formation, from oldest to youngest. The stratigraphic section contains numerous tuffs useful for correlating isolated outcrops separated by younger cover or faults. The oldest marker is the Moiti Tuff with a maximum age of 4.1 Ma. Other major tuffs in ascending order are the Lokochot, Tulu Bor, Toroto (3.32 ± 0.02 Ma), Allia, Ninikaa (3.06 ± 0.03 Ma), Hasuma, Ingumwai, and Burgi tuffs.

About 10 m above the Burgi Tuff, the section is concealed by younger surficial deposits. The upper 300 m of the Koobi Fora Formation, which crops out extensively between the Koobi Fora camp and Ileret, is separated from the Kubi Algi section by a disconformity. Comparison of suid fossil successions within the Koobi Fora and Shungura formations indicates a substantial hiatus in deposition at Koobi Fora [*White and Harris*, 1977]. The hiatus spans about 400,000 years, according to the current chronology of the Shungura Formation [*Brown et al.*, 1978, 1985].

Tuffaceous marker beds in the upper part of the Koobi Fora Formation are, in ascending order, the Lorenyang, KBS (1.88 ± 0.02 Ma), Malbe (186 ± 0.02 Ma), Okote complex and related tuffs (~1.65 Ma), and Chari (1.39 ± 0.02 Ma) tuffs. All but one paleomagnetic section studied by *Hillhouse et al.* [1977], the Tulu Bor Tuff type locality, are in the upper part of the formation. Marker beds within the paleomagnetic columns that were correlated with the Tulu Bor Tuff are now known to be considerably younger.

In 1982 we collected samples for paleomagnetic study from the area east of Allia Bay in the deposits formerly called the Kubi Algi Formation. The total paleomagnetic column is pieced together from nine sections correlated by volcanic ash beds. Most parts of the stratigraphic column were sampled at two localities usually separated by 10 km or more. The new magnetostratigraphy covers the interval from the Moiti Tuff up to a level 20 m above the Burgi Tuff, a cumulative thickness of about 210 m.

Only well-consolidated siltstone, claystone, and tuff were sampled, as previous experience at Koobi Fora had shown that sandstone and friable sediments were unsuitable for paleomagnetic study. Sites were selected in stream channel walls and steep slopes to avoid deeply weathered surfaces. At each level, small blocks were oriented with a level and compass and were then cut from the outcrop. In the laboratory, specimens were shaped into crude cylinders with hand tools, weighed, and then cemented into 10-cm^3 cylinders using a mylar mold filled with filter grade diatomaceous earth and sodium silicate solution. This technique allows thermal demagnetization of the specimens, which was not possible during the original paleomagnetic studies at Koobi Fora because the specimens had been glued into plastic boxes. Two specimens were prepared from the blocks obtained at each level in the stratigraphic column.

PALEOMAGNETIC METHODS

The magnetic components preserved at each level were determined by progressive demagnetization using alternating field (af) and thermal methods. One specimen from each level was treated at 16 af settings up to 100 mT in a fixed-specimen degausser. A second specimen from each level was thermally demagnetized at 16 temperature steps up to 580°C, and, if necessary, five additional steps were taken up to 680° or until the magnetization was reduced to the level of experimental noise. The heatings were performed in air and in a magnetic field of less than 5 nT. Results of the demagnetization experiments were plotted on orthogonal vector diagrams and component end points were selected by visual inspection. We used Kirschvink's [1980] method of principal component analysis to calculate secondary and characteristic magnetizations.

Some specimens used in the af experiments were given isothermal remanent magnetizations (IRM) in direct fields up to 0.7 T (7000 G) to investigate the magnetic mineral content. Curie temperatures of selected mineral separates were determined with an automatic thermobalance employing 0.2–0.4 T direct fields. Heatings were performed at ambient pressure in an argon atmosphere to inhibit oxidation of the mineral separate.

PALEOMAGNETIC RESULTS

Natural remanent magnetizations of the Koobi Fora sedimentary rocks ranged from 1×10^{-7} to 5×10^{-4} A m^2/kg and gave a geometric mean value of 5×10^{-5} A m^2/kg (1 A m^2/kg = 1 emu/g). Analysis of the demagnetization diagrams revealed that many of the specimens carried antipolar components of magnetization, and thorough demagnetization of each specimen was required. Conventional treatment in which single-step magnetic cleanings are applied after a small number of pilot specimens are analyzed would be unsatisfactory because the coercivity of remanence and unblocking temperature distributions were highly variable among the specimens. As we shall demonstrate, the magnetization of the Koobi Fora Formation is not a simple depositional remanent magnetization (DRM), but is the sum of DRM, chemical remanent magnetization (CRM), and viscous remanent magnetization (VRM).

We have selected demagnetization results from three tuffs and a siltstone to illustrate the dominant magnetic properties of the Koobi Fora Formation. Coercivities of remanence (Figure 3*a*) ranged from the extremely hard distribution of the Lokochot Tuff to the initially soft distributions of the Allia Tuff and the siltstone, while the Tulu Bor Tuff exemplifies the more typical distribution. The orthogonal vector diagram from af demagnetization of the Tulu Bor Tuff (Figure 4*a*) shows the removal of a weak, normally polarized VRM up to 10 mT then the reduction of a directionally stable component up to 100 mT. The 100-mT limit of the treatment was not strong enough to reduce the remaining magnetization to less than 10% of the NRM. The weak component is probably VRM acquired during the Brunhes Normal-Polarity Chron. The vector diagram obtained from the Allia Tuff (Figure 4*b*) shows the removal of a normal VRM up to 20 mT then reduction of a stable reversed component between 20 mT and 100 mT. Secondary magnetization of the siltstone was removed by the 10 mT step with about 3% of the original intensity remaining after the 100-mT step (Figure 4*c*). Secondary magnetization of one specimen from the Lokochot Tuff was not removed until the treatment exceeded 35 mT (Figure 4*d*).

Thermal demagnetization of companion specimens from the same three tuffs and siltstone gave unblocking temperature distributions (Figure 3*b*) showing sharp declines in intensity near 580°C, the Curie temperature of magnetite. Many specimens required heating beyond 580°C, some to as high as 680°C, before the remaining magnetization was diminished to the level of experimental noise. As shown by a comparison of the vector diagrams from the af and thermal treatments of the Tulu Bor Tuff, Allia Tuff, and the siltstone (Figures 4*a*–4*c* and 5*a*–5*c*), the thermal treatments revealed similar stable components of magnetization with the VRM being removed by heating to 174°, 339°, and 98°, respectively. When the demagnetization treatments gave such straightforward results, end points for the principal component analysis were easily selected and a best fit line was calculated. We used the resultant direction to calculate a virtual geomagnetic pole (VGP) and have plotted VGP latitudes on the stratigraphic column (Figures 6*a* and 6*b*).

Specimens from the Lokochot Tuff type locality carry antipolar components of magnetization that could not be separated by the demagnetization treatments. The directional plot (Figure 7) shows af and thermal cleaning paths for

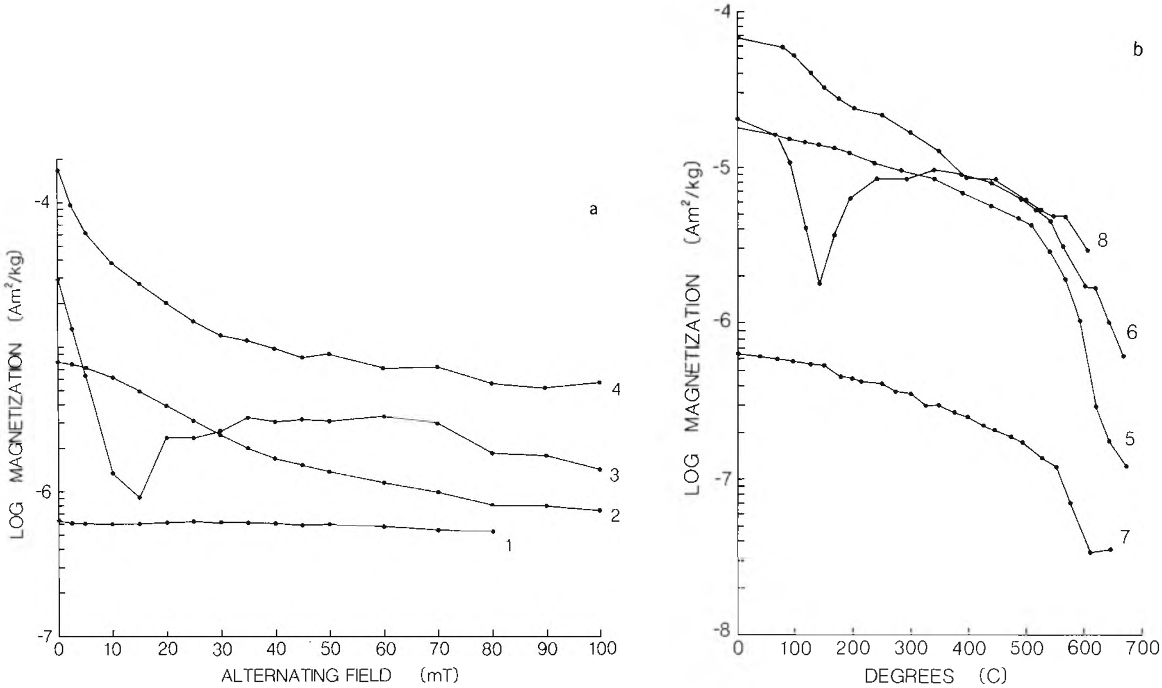

Fig. 3. (*a*) Decrease of natural remanent magnetization during af demagnetization of specimens from the Lokochot Tuff (1), Tulu Bor Tuff (2), Allia Tuff (3), and siltstone (4). (*b*) Thermal demagnetization of natural remanent magnetization of the Tulu Bor Tuff (5), Allia Tuff (6), Lokochot Tuff (7), and siltstone (8).

specimens from the Lokochot Tuff at area 250 (type locality) and area 261 (see Figures 2 and 6*b*). The specimens from the type locality have normally polarized NRMs, and although the directions change toward the reversed hemisphere during demagnetization, they fail to stabilize. We interpret the magnetization to be a superposition of normal and reversed components which have similar resistances to the demagnetization treatments. Zones of mixed magnetizations are most common near polarity transitions (Figures 6*a* and 6*b*), indicating that the magnetization was acquired over a long period of time after deposition. Principal component analysis of these specimens will yield the last component removed by the demagnetization treatment but will not yield the final end point. Therefore we have added arrows to Figures 6*a* and 6*b* to show the sense of directional change at the end of the demagnetization experiment.

The acquisition of IRM as a function of the applied direct field helps to identify mixtures of magnetite and hematite grains in sedimentary rocks. IRM curves were determined for the Tulu Bor, Lokochot, Allia, and Toroto tuffs (Figures 8*a* and 8*b*). The curves all show sharp increases in IRM intensity at applied fields below 0.15 T, a common characteristic of minerals in the ulvospinel-magnetite solution series. The small but steady increase in IRM beyond 0.3 T indicates that hematite is also present in the Koobi Fora tuffs. These results are consistent with the unblocking temperature distributions which showed sharp declines in magnetic intensity near the Curie temperature of magnetite followed by a final decline in intensity near the Neel temperature of hematite. The high coercivity of remanence exhibited by many af demagnetization curves beyond the 50-mT step is also consistent with a hematite fraction in the sediment.

Thermomagnetic analysis (Figure 9) of magnetic separates from several tuffs confirmed the presence of titanomagnetite having Curie temperatures between 560° and 580°C. However, this technique cannot detect hematite when magnetite is also present due to the much greater saturation magnetization of magnetite. On heating, the thermomagnetic curves also show an inflection between 300° and 400° which does not appear in the cooling curves. The inversion of a titanomaghemite fraction to magnetite plus members of the ilmenite-hematite family could explain the inflection, although the inversion of a small fraction of maghemite to hematite could produce a similar result.

The magnetic mineralogy of the Tulu Bor, Lokochot, Toroto, and Allia tuffs was further examined by reflected-light microscopy of polished grain mounts that were prepared from nine magnetic separates. In addition, we examined three magnetic separates of tuffaceous siltstones from just below the Koobi Fora Tuff in area 103. The observations were made under a magnification of 1050×. All specimens including the siltstones contain volcanic titanomagnetite exhibiting high-temperature "exsolution" features and low-temperature oxidation rinds. For example, the Toroto Tuff contains roughly equant grains of titanomagnetite-ilmenite with lamellar structure. These grains are extensively pitted and surrounded by microcrystalline hematite and red pigment. In some grains the original exsolution features are entirely replaced by hematite. In the Tulu Bor Tuff, most of the magnetic minerals are finely disseminated within glass shards about 60 μm in diameter. The individual magnetic grains are usually less than a few microns in diameter and are surrounded by red, translucent pigment. Rarer constituents of the Tulu Bor Tuff are rounded pellets of hematite with botryoidal internal structures. In the Lokochot Tuff, glass shards enclose titanomagnetite crystals about 5 μm in diameter. The crystals typically have a thin rind of hematite and are surrounded by cloudy areas of red pigment. Although most of the magnetic material in the tuffs is finely dissemi-

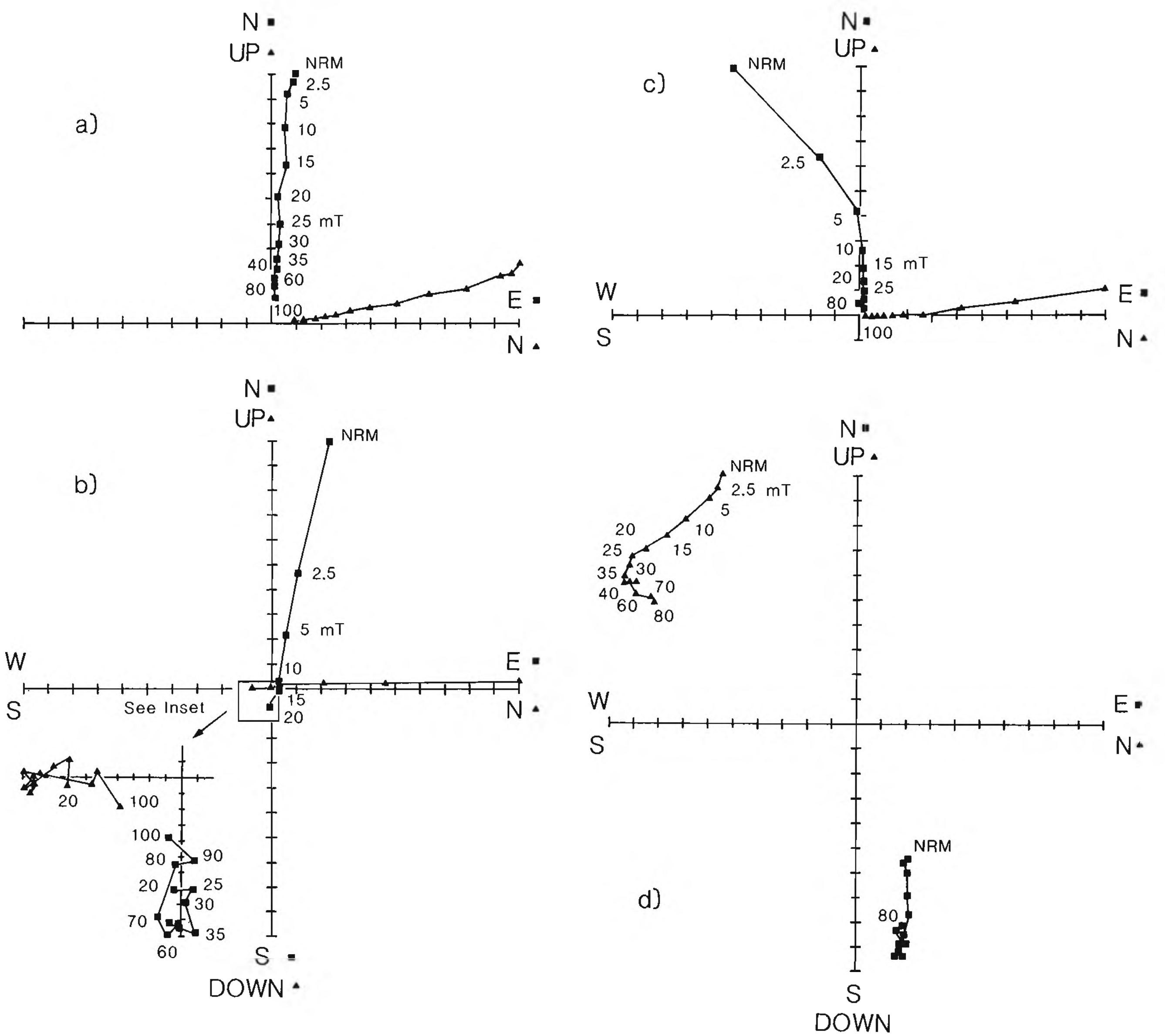

Fig. 4. Orthogonal vector diagrams obtained from AF demagnetization of representative specimens. Squares denote projection of magnetization vector in the horizontal plane; triangles are in the north-south vertical plane. (*a*) Tulu Bor Tuff, axis scale = 7.64 × 10^{-6} A m^2/kg. (*b*) Allia Tuff, axis scale = 2.83 × 10^{-5} A m^2/kg; inset shows blow-up of high field steps, scale = 3.27 × 10^{-6} A m^2/kg. (*c*) Siltstone 65 cm below Ingumwai Tuff, axis scale = 1.47 × 10^{-4} A m^2/kg. (*d*) Lokochot Tuff, axis scale = 5.41 × 10^{-7} A m^2/kg.

nated within the silt-sized glass shards, separate titanomagnetite grains with diameters up to 25 μm are also present. While most of these larger grains have relict exsolution lamellae that have been replaced by hematite, some grains preserve clear titanomagnetite cores with cracks and pits lined by titanomaghemite.

In the tuffs, hematite in pigment and microcrystalline form probably formed after deposition because the alteration of primary titanomagnetite grains is seen within glass shards. The angular shard morphologies and the clean basal contacts of the tuffs indicate that the sediments were carried rapidly to their sites of deposition before significant amounts of microcrystalline hematite could form. The replacement of titanomagnetite-ilmenite intergrowths by hematite probably occurred after deposition as well, although some grains might have been reworked from older oxidized deposits. Some of the hematite clearly originated prior to deposition, such as the rounded, botryoidal pellets of the Tulu Bor Tuff. Also, some of the primary magnetic grains have features of high-level deuteric oxidation where titanomagnetite is replaced by hematite-ilmenite intergrowths during eruption of the magma.

MODEL FOR THE MAGNETIZATION PROCESS

As shown in Figures 6*a* and 6*b*, the magnetization of the lower part of the Koobi Fora Formation yields a consistent pattern of magnetozones. Thermal and af treatments usually revealed the same polarity at each level except near the polarity transitions just above the Lokochot and Ninikaa tuffs and within the Toroto-Allia tuff interval. Analysis of the demagnetization vector diagrams indicates that the scatter of VGP latitudes at the polarity boundaries is due to the

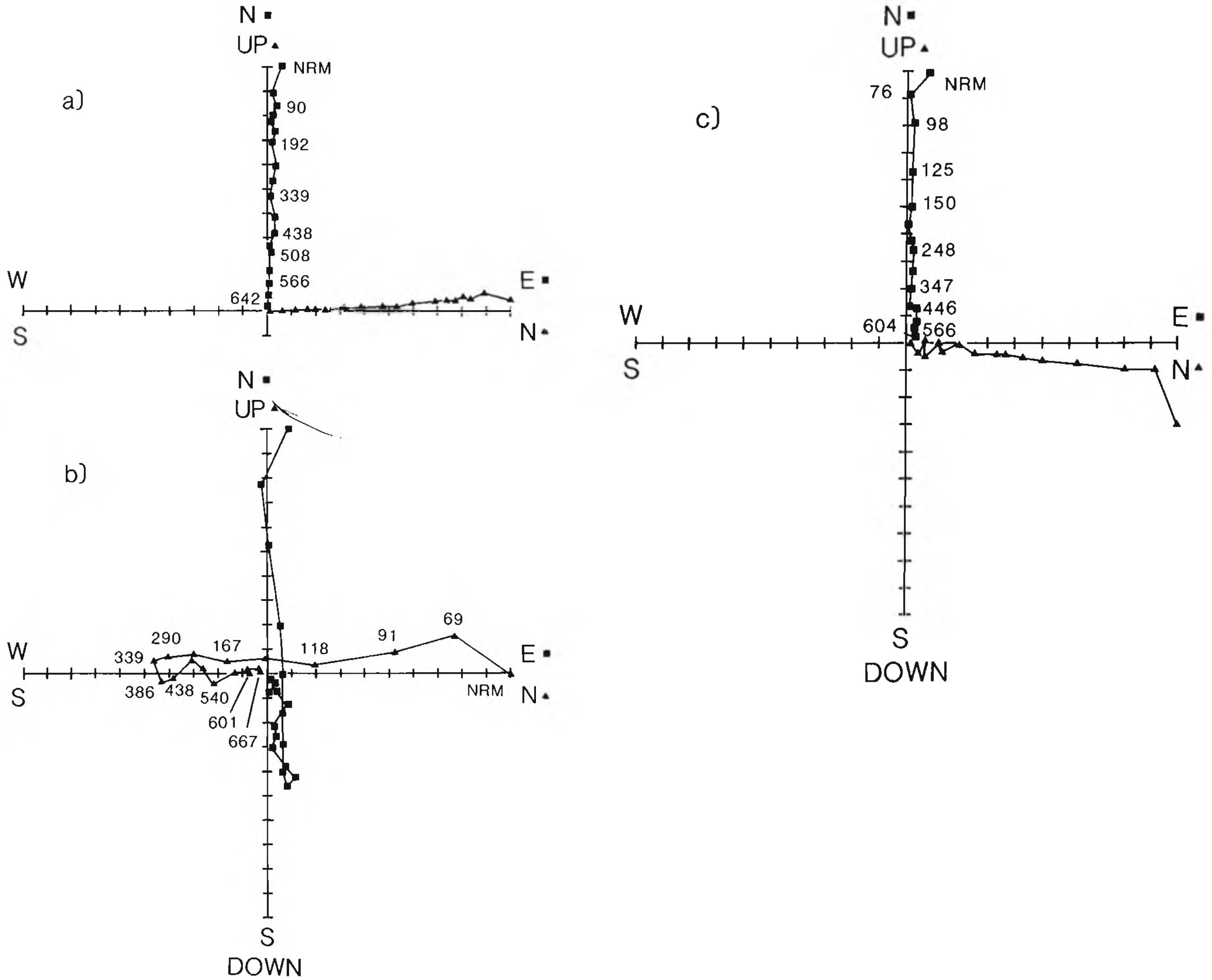

Fig. 5. Orthogonal vector diagrams obtained from thermal demagnetization of companion specimens to those in Figures 4*a*, 4*b*, and 4*c*. Symbols as in Figure 4. (*a*) Tulu Bor Tuff, axis scale = 1.09×10^{-5} A m^2/kg. (*b*) Allia Tuff, axis scale = 2.03×10^{-5} A m^2/kg. (*c*) Siltstone, axis scale = 6.50×10^{-5} A m^2/kg.

superposition of normal and reversed magnetic components rather than transitional behavior of the geomagnetic field. We have also observed the complex magnetic properties and mineralogy of the deposits, which indicate that the remanence is shared by titanomagnetite and hematite. Given this information, we propose a model for the magnetization process within the Koobi Fora Formation.

The rift volcanoes of Ethiopia and Kenya provided an ideal medium for recording geomagnetic events in the Turkana basin. Numerous eruptions of volcanic ash added two major magnetic constituents to the sediment loads of the rivers and floodplains: titanomagnetite grains with exsolution features and glass shards with finely disseminated titanomagnetite crystals. Both magnetic species have properties conducive to acquiring a stable depositional remanent magnetization (DRM). They combine small effective domain sizes for long-term stability of the magnetization with strong thermoremanent magnetic moment to help aline each grain's magnetic direction with the ambient field during deposition. The exsolution lamellae create additional energy barriers to pin domain walls, which give the magnetization a potentially longer relaxation time. Similarly, glass shards carry a stable TRM in a multitude of disseminated, single-domain or pseudo-single-domain titanomagnetite crystals. The potentially large magnetic moment of these grains provides ample torque to interact with the geomagnetic field and the large grain size of the shards (10–60 μm) resists misalining forces such as Brownian motion. One disadvantage of the larger grain sizes is misalinement due to water currents, especially for flat or elongate shards.

We believe that with the exception of coarse sandy beds, the Koobi Fora sediments acquired a stable DRM soon after deposition. Deposition often took place on floodplains subject to frequent drying, so the magnetization was probably fixed at the surface. In lacustrine environments, water-filled pores near the sediment-water interface would cause the lock-in zone to be lower, but probably within 50 cm of the interface.

Wetting and drying of the floodplains also exposed the sediments to a highly oxidizing environment which promoted the formation of chemical remanent magnetization (CRM) in hematite. As the fresh titanomagnetite surfaces became nucleation centers for hematite crystals, CRM would develop, eventually preserving the ambient field di-

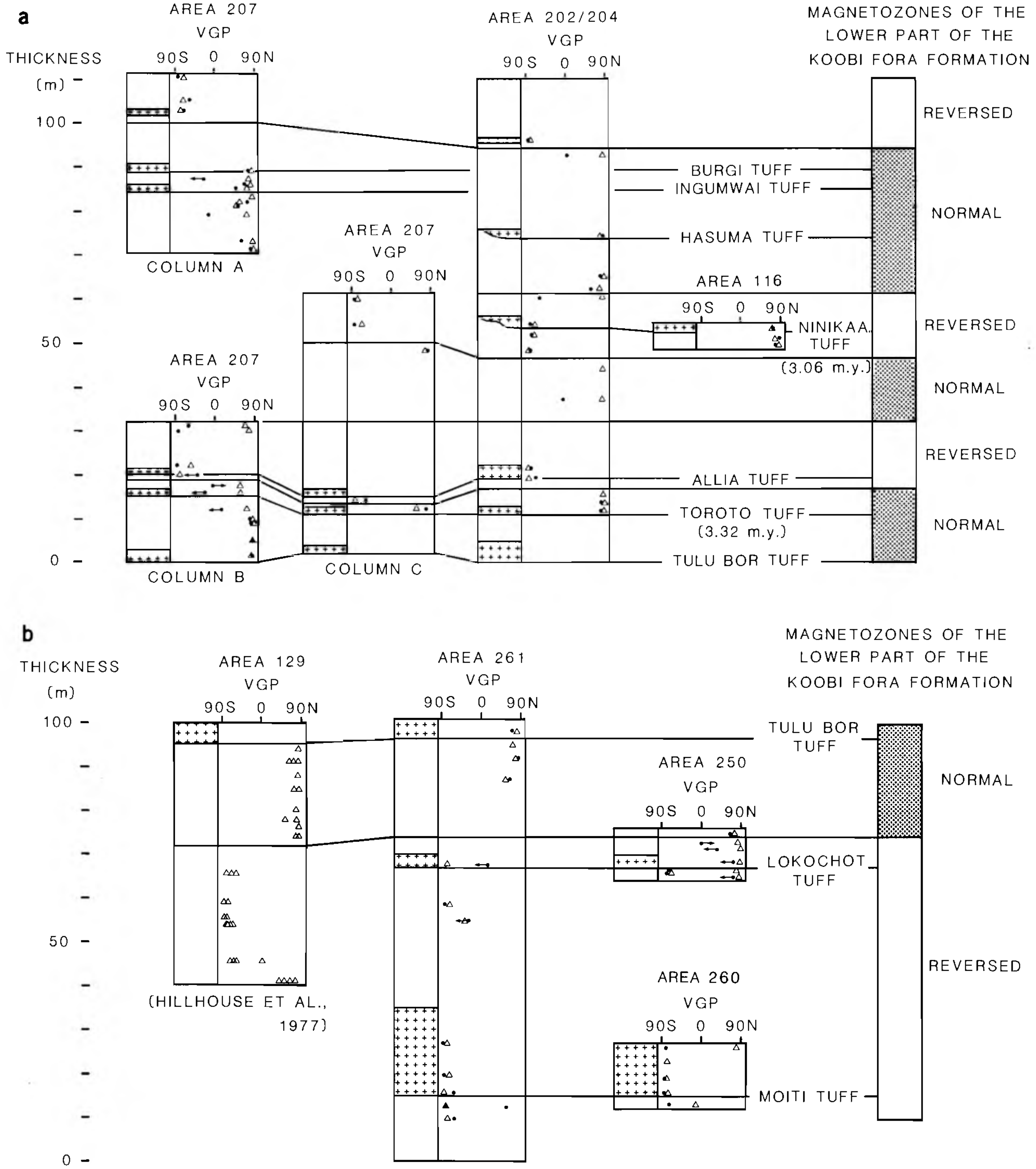

Fig. 6. Magnetozones of the lower part of the Koobi Fora Formation, as interpreted from the paleomagnetic columns. VGP latitudes are given for magnetic directions obtained by principal-component analysis of af (triangle) and thermal (dot) demagnetization data. Arrows indicate last sense of VGP-latitude change if direction had not stabilized. (*a*) Column between Tulu Bor and Burgi Tuffs. (*b*) Column below the Tulu Bor Tuff.

rection when the hematite crystals grew to the appropriate size. We believe that the formation of CRM was most intense soon after deposition and that the process essentially ceased after burial exceeded 10 meters. Burial would inhibit oxidation and cut off the formation of CRM. Also, as the hematite rinds developed, the surface area available for the formation of new hematite would diminish.

Our time estimate for the duration of CRM acquisition is based on the thickness of the mixed polarity zones and the average sedimentation rate for the basin. For example, near the Lokochot Tuff the zone of mixed polarities spans about 10 m. The average sedimentation rate, given K-Ar ages for the Ninikaa, Toroto, and Moiti tuffs, is about 0.15 m/1000 yr. Hence the mixed zone represents about 70,000 years of deposition on average, although the actual durations would vary depending on the depositional environment. Analysis of the mixed-polarity zones near polarity transitions shows that CRM cannot always be separated from DRM by either af or

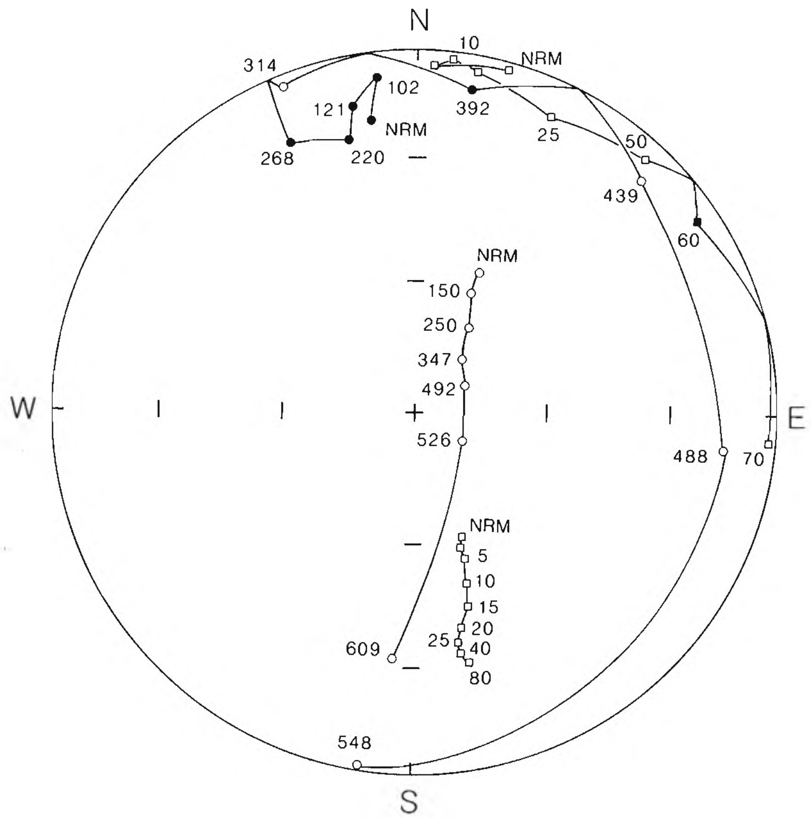

Fig. 7. Change in magnetic direction of 4 specimens from the Lokochot Tuff during af (squares) and thermal (circles) demagnetization. Open symbols are in the upper hemisphere; solid symbols are in the lower hemisphere of the equal area projection. The af values given in milliteslas, temperatures given in degrees Celsius.

thermal treatment. Therefore, if the CRM process had not ceased within a relatively short time after deposition, we would not be able to recover the consistent polarity pattern of Figures 6*a* and 6*b*. According to our model, each stratigraphic horizon carries quickly acquired DRM plus CRM that represents geomagnetic field behavior during the 70,000-year interval immediately after deposition. During a long polarity interval, when the next polarity reversal does not occur for at least 70,000 years, CRM acquired at a given horizon will reinforce the DRM signal. After the field reverses polarity, CRM will reinforce the DRM above the actual transition horizon, while CRM will create mixed polarities in the 10-m-thick zone beneath the transition horizon. Therefore, in interpreting the magnetostratigraphy

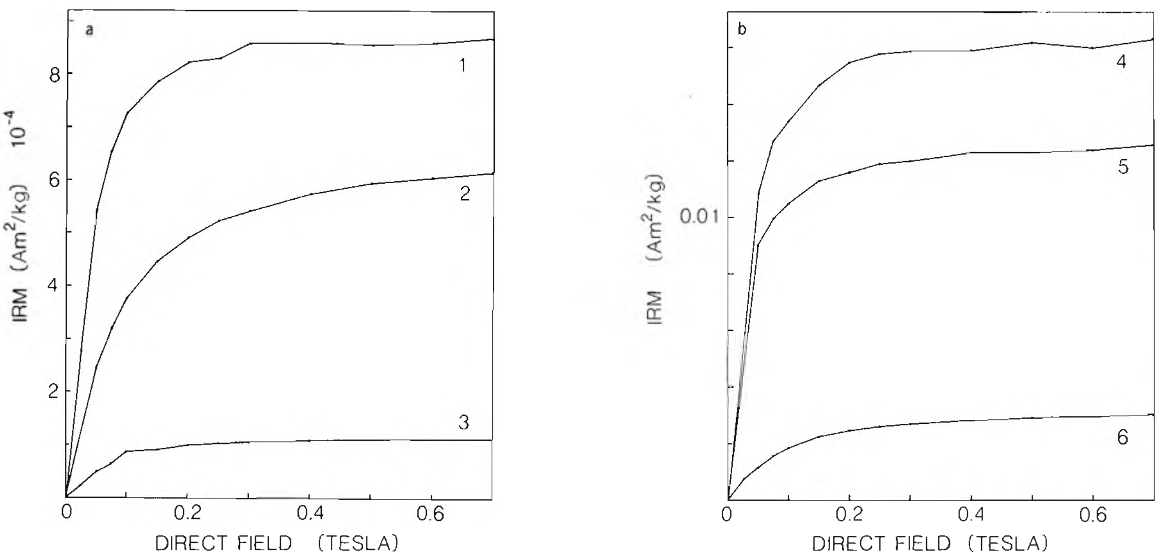

Fig. 8. Acquistion of IRM as a function of the applied direct field. (*a*) Tulu Bor Tuff (1), Lokochot Tuff (2, 3). (*b*) Allia Tuff (4, 6). Toroto Tuff (5).

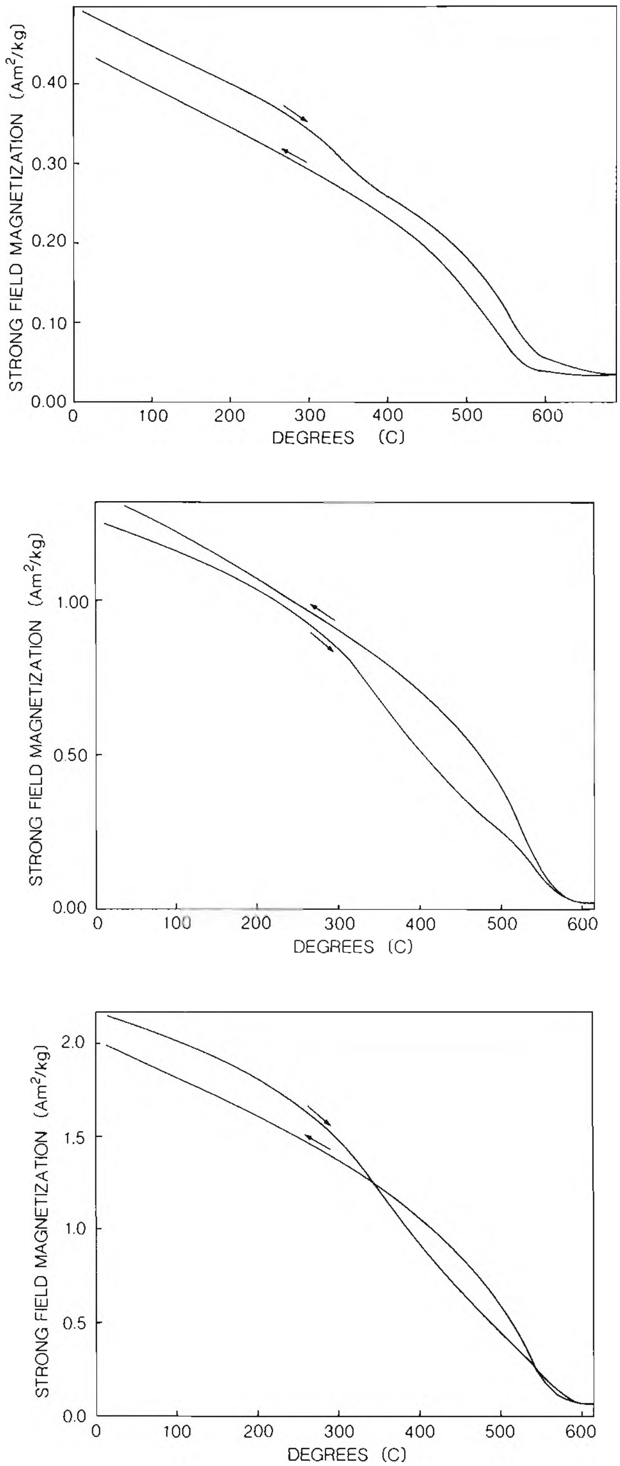

Fig. 9. Strong field magnetization as a function of temperature for magnetic separates from (*a*) Tulu Bor Tuff, (*b*) Toroto Tuff, and (*c*) Allia Tuff.

it is best to draw the magnetozone boundaries at the top of the mixed polarity zones. This places the magnetozone boundary at the polarity switch as recorded in the DRM. The boundaries of short geomagnetic polarity intervals may be obscured by CRM that is acquired over a 70,000-year interval. Polarity transitions that are preceded and followed by long periods of stable polarity, such as the Gauss-Gilbert transition or the Matuyama-Gauss transition can be located more accurately.

The demagnetization experiments also revealed magnetic components of normal polarity that were removed by the first few treatment steps. These components are probably due to VRM acquired during the Brunhes Normal-Polarity Chron. VRM is acquired by magnetic domains having relatively short relaxation times, such as ultrafine superparamagnetic hematite grains or large, multidomain magnetite crystals.

INTERPRETATION OF THE MAGNETOSTRATIGRAPHY

We can now establish an excellent correlation between the magnetostratigraphies of the lower parts of the Koobi Fora and Shungura formations, given chemical correlations of four tuffs that occur in both formations [*Brown et al.*, 1985]. In Figure 10 we compare magnetozones for the Shungura as determined by *Brown et al.* [1978] with the generalized paleomagnetic column from our study of the Koobi Fora Formation (Figures 6*a* and 6*b*). Correlation between the Lokochot Tuff and Tuff A of the Shungura is corroborated by a reverse-to-normal polarity transition that occurs just above the tuff at both localities. The Tulu Bor and Tuff B are in thick normal polarity zones at both localities. Shungura tuffs C and C4 correlate with the Hasuma and Ingumwai, respectively, and all occur within a normal polarity magnetozone.

Isotopic ages determined from the tuffs of the Koobi Fora and Shungura Formations [*McDougall*, 1985; *Brown et al.*, 1985] allow a secure correlation of the magnetozones with the geomagnetic polarity time scale of *Mankinen and Dalrymple* [1979]. We interpret the Moiti-Lokochot interval as being all reversed, although a 25-m-thick zone was left unsampled because suitable sediments were not found. The age of the Moiti Tuff (<4.10 Ma) relative to the Cochiti Normal-Polarity Subchron (3.90–3.80 Ma) is uncertain because the magnetozone might have been missed by a gap in the sampling or due to an unconformity. The Gauss-Gilbert boundary (3.40 Ma) is correlated with the polarity transition just above the Lokochot-Tuff A level. The beginning of the Mammoth Reversed-Polarity Subchron (3.15 Ma) correlates with the normal-to-reverse boundary between the Allia and Toroto Tuff (3.32 Ma). The Mammoth and Kaena Reversed-Polarity Subchrons can be identified in the Koobi Fora Formation, but it appears that only the Mammoth Subchron was sampled in the Shungura Formation [*Brown et al.*, 1985]. At Koobi Fora the Ninikaa Tuff has reversed polarity in area 116 but has normal polarity in the area 202/204 column (Figure 6*a*). The discrepancy is probably due to CRM overprinting just below a reverse-to-normal transition boundary that we interpret as the end of the Kaena or to reworking of the tuff upward in the section. Our interpretation places the Ninikaa Tuff between the 3.01 and 2.92 Ma polarity transitions, somewhat younger than the isotopic age (3.06 ± 0.03 Ma) of pumice from the Ninikaa Tuff. The normal-to-reverse transition that is above the Burgi Tuff at Koobi Fora and that is just below Tuff D (2.52 Ma) at Shungura correlates with the Matuyama-Gauss transition (2.48 Ma).

In general, isotopic ages from tuffs within the Koobi Fora and Shungura formations tend to be 50,000–100,000 years older than ages we would interpolate for the tuffs from the magnetostratigraphy. The difference may be caused in part by reworking and redeposition of pumice used for dating to higher stratigraphic positions. This is clearly the case for the

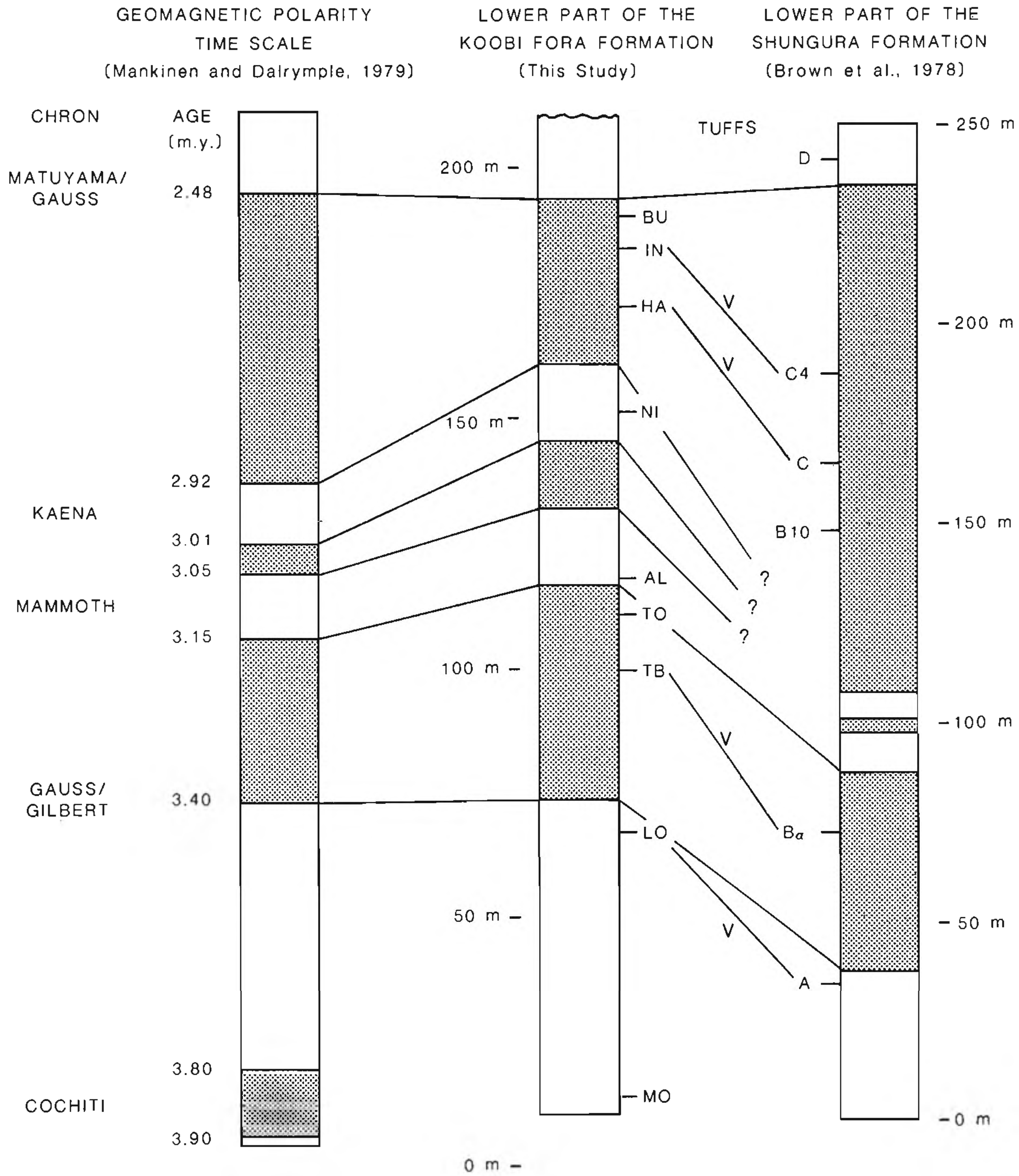

Fig. 10. Correlation of magnetozones of the lower Koobi Fora and Shungura formations with the geomagnetic polarity time scale. Stippled areas denote normal polarity. Lines with Vs denote correlative tuffs. Koobi Fora tuffs: MO, Moiti; LO, Lokochot; TB, Tulu Bor; TO, Toroto; Al, Allia; NI, Ninikaa; HA, Hasuma; IN, Ingumwai; BU, Burgi.

Toroto tuff in area 207 where two tuffs of the same composition are separated by several meters of section. The lower (purer) tuff has normal polarity, whereas the upper, less pure tuff (which has pumice dated at 3.32 Ma) has reversed polarity. In addition, the accumulation of CRM tends to move the magnetozone boundaries to positions in the stratigraphic column that are lower than the actual polarity boundaries as defined by the DRM. Working together, these sources of dating errors might explain the apparent offset between the isotopic and paleomagnetic chronologies.

The discovery of several Turkana tuffs in DSDP cores from the Gulf of Aden [*Sarna-Wojcicki et al.*, 1985] further secures the correlation of the transition at the Lokochot-Tuff A level with the Gauss-Gilbert transition. On the basis of electron probe analysis of glass shards, tephra layers in DSDP holes 231 and 232A were correlated with the Lokochot Tuff. In addition, the Tulu Bor, Moiti, and an unnamed tuff were identified in the core from hole 231 in the same stratigraphic sequence that occurs at Koobi Fora. Independent age control for hole 231 is provided by nannofossil datums which, in other oceanic cores, are correlated to the geomagnetic polarity time scale. The Lokochot-equivalent tephra of hole 231 is coincident with the last appearance datum of *Reticulofenestra pseudoumbilica*. In cores V28-179 and V28-185 from the central Pacific Ocean this datum is 0.5–1.5 m below the Gauss-Gilbert boundary [*Backman and Shackleton*, 1983].

Magnetostratigraphy of the upper part of the Koobi Fora Formation was originally studied by *Brock and Isaac* [1974] and later extended by *Hillhouse et al.* [1977]. In the latter article, two interpretations were proposed for the correlation of the Koobi Fora magnetostratigraphy with the polarity

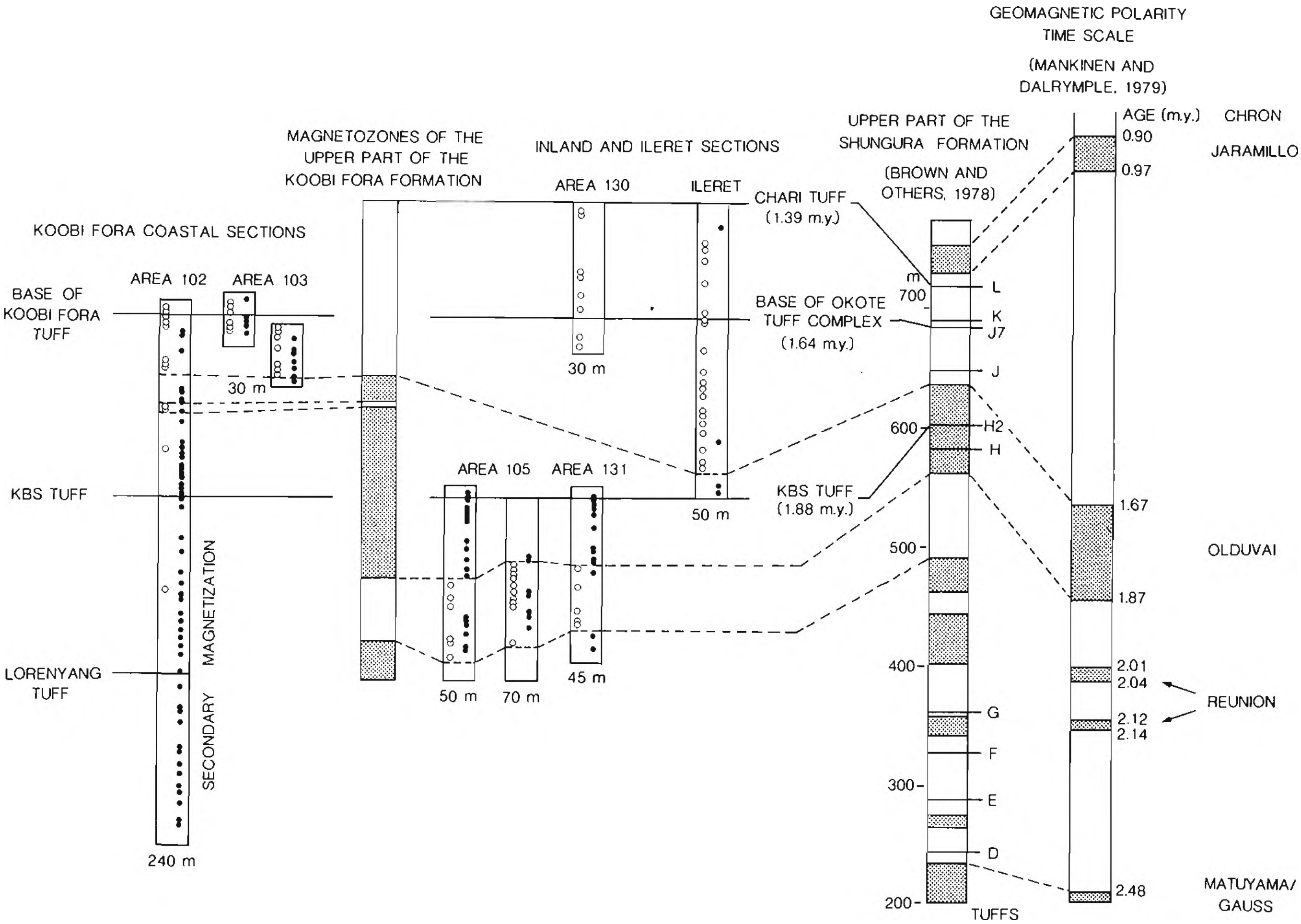

Fig. 11. Revised interpretation of magnetostratigraphy from the upper part of the Koobi Fora Formation (modified from *Hillhouse et al.* [1977, Figure 4]) and the upper part of the Shungura Formation. Solid dots indicate normally polarized sample levels; open circles are levels of reversed polarity. Isotopic ages (in parentheses) are from *McDougall* [1985] for the Chari and KBS tuffs and from *McDougall et al.* [1985] for the Okote Tuff Complex.

time scale because isotopic dating of the KBS Tuff was in dispute. Also, as indicated by a note added in proof at the end of the article, the correlation of tuffs in areas 105 and 102 with the Tulu Bor Tuff was not as secure as was originally thought when the paleomagnetic studies began. Subsequently, intensive efforts to date the KBS Tuff using conventional K-Ar and Ar^{40}/Ar^{39} methods resulted in a secure age determination of 1.88 ± 0.02 Ma [*McDougall*, 1985]. Chemical studies [*Brown and Cerling*, 1982] demonstrated that a tuff originally correlated with the Tulu Bor Tuff in area 102 is in fact a much younger unit, now designated the Lorenyang Tuff. Also, the correlation of the Tulu Bor Tuff in area 105 is now known to be incorrect. Therefore we must reinterpret the magnetostratigraphy of the upper part of the Koobi Fora Formation.

In the revised magnetostratigraphy of the upper part of the Koobi Fora Formation (Figure 11), the Tulu Bor Tuff type section from area 129 has been removed because it belongs in the lower part of the formation within the Moiti-Tulu Bor interval. (We have added the area 129 column to the new data shown in Figure 6*b*). An unconformity probably separates the paleomagnetic columns of the upper Koobi Fora (Figure 11) from the top of the paleomagnetic columns in the lower part of the formation (Figures 6*a*, 6*b*, and 10). The magnetozones in the younger Koobi Fora beds generally are consistent with tuff correlations [*Cerling and Brown*, 1982] and the magnetostratigraphy [*Brown et al.*, 1978] of the Shungura Formation. The Chari (1.39 ± 0.02 Ma) Tuff correlates with Tuff L (1.34 ± 0.10 Ma) of the Shungura Formation. The Black Pumice Tuff of the Okote Complex correlates with Tuff J7 of the Shungura Formation; both must be somewhat younger than 1.65 Ma, and all are within a reversed polarity magnetozone. The KBS Tuff and its correlative, Tuff H2 of the Shungura, are in a normal magnetozone. In linking the magnetostratigraphy of the Koobi Fora Formation with the polarity time scale we have followed the interpretation of *Brown et al.* [1978] by placing the KBS Tuff in the Olduvai Normal-Polarity Subchron (1.87–1.67 Ma) and the upper reversed zone, which includes the Okote and Chari tuffs, in the middle part of the Matuyama (1.67–0.97 Ma).

The reversed polarity zone of areas 105 and 131 is correlated with the interval between the upper Reunion Normal-Polarity Subchron (2.01 Ma) and the base of the Olduvai Subchron (1.87 Ma). Except for a single reversed horizon, this magnetozone appears to be missing in area 102 and may be obscured by secondary magnetization as was originally proposed. The Lorenyang Tuff is clearly of normal polarity and probably is within the Olduvai Subchron. The lower limit of this normal magnetozone in area 102 is not further

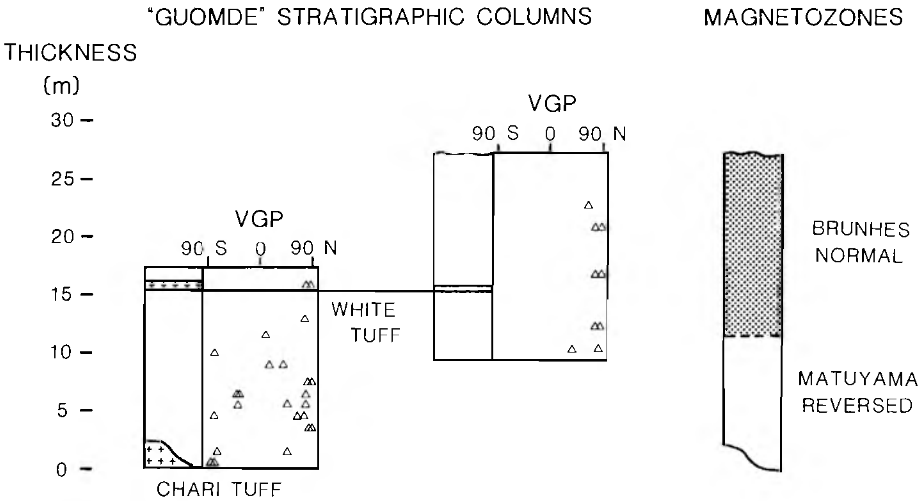

Fig. 12. Interpretation of magnetozones from the former "Guomde Formation," now considered part of the Chari Member of the Koobi Fora Formation. Triangles indicate latitude of VGP obtained from specimens treated in alternating fields of 10–30 mT.

constrained, but a new collection of paleomagnetic samples has been obtained in an effort to investigate this problem.

Comparison of the magnetostratigraphies of the Koobi Fora and Shungura formations (Figures 10 and 11) indicates that Shungura members E and F, plus parts of D and G, are not represented in the sampling at Koobi Fora. We suspect that an unconformity can account for at least part of the gap because suid fossils equivalent to those from Shungura members D through F have not been found in the Koobi Fora Formation. The gap roughly spans the interval 2.4–2.0 Ma as indicated by the magnetostratigraphy.

In 1973, paleomagnetic samples were collected by J. Hillhouse, J. Ndombi, and W. Iles from two sections within what was termed at that time the Guomde Formation near Ileret. The "Guomde" deposits were later shown by *Brown and Cerling* [1982] to comprise a variety of lithostratigraphic units of widely varying age and composition. Subsequently, the deposits at Ileret were included as part of the Koobi Fora Formation by *Brown and Feibel* [1986]. For completeness, we include paleomagnetic results on the samples taken in 1973 because they can be correlated precisely with the type section of the Chari Member of the Koobi Fora Formation (Figure 12).

After af treatment of 10–30 mT, specimens from the Chari Member at Ileret gave highly variable VGP latitudes within the sampled stratigraphic horizons, indicating the superposition of normal and reversed-polarity components. However, consistent results were obtained from the siltstones at the base of the member, and from a white tuff 13 m higher in the section. This white tuff has been analyzed by one of us (F.H.B.) and is compositionally indistinguishable from the Silbo Tuff (0.74 ± 0.01 Ma), which has normal polarity. The basal siltstones have reversed polarity, as does the Chari Tuff; the white tuff has normal polarity, implying a polarity change within the intervening part of the section. We interpret the polarity change as the Brunhes-Matuyama transition (0.74 Ma). In this particular section the Chari Tuff is part of an erosional surface that was covered by the younger siltstones of the Chari Member. The disconformity between the Chari Tuff and the overlying sediments represents a gap in sedimentation that spans approximately 500,000 years. However, in other areas near Ileret, part of this time is represented by sediments because a tuff which lies between the Chari and Silbo tuffs has been dated at 1.25 Ma [*Brown et al.*, 1985].

Conclusions

The early paleomagnetic studies of the Koobi Fora Formation employed af cleanings in the range 10–20 mT, which generally yielded a consistent pattern of magnetozones. However, some paleomagnetic columns gave poorly grouped magnetic directions, apparently due to unremoved components of Brunhes age VRM. Using this prior experience, we were able to obtain better results from the lower part of the Koobi Fora Formation by a more selective sampling scheme and more thorough demagnetization treatments. Companion specimens from every horizon were progressively demagnetized in a detailed sequence using af and thermal methods. The cleaned magnetic directions were obtained by principal component analysis of the demagnetization results. A consistent pattern of magnetozones was obtained from coeval stratigraphic sections, although antipolar components of magnetization were commonly revealed near polarity zone boundaries. Neither demagnetization method was consistently effective in separating the antipolar components. Unblocking temperature distributions found in these specimens indicate that the magnetic remanence is shared by titanomagnetite and hematite.

The presence of titanomagnetite and hematite was confirmed by rock magnetic studies. Thermomagnetic analysis of magnetic separates yielded Curie temperatures of 560°–580°, indicating titanomagnetite with a low titanium content. Inflections in the thermomagnetic curves near 350° are possibly due to a fraction of titanomaghemite, a product of low-temperature oxidation. IRM curves give the characteristic shapes of magnetite-hematite mixtures. Finally, microscopic examination of polished grain mounts revealed volcanic titanomagnetite grains with high-temperature exsolution features and haloes of authigenic hematite. In the tuffs the remanence is probably carried by finely disseminated grains of titanomagnetite and hematite pigment contained within the glass shards.

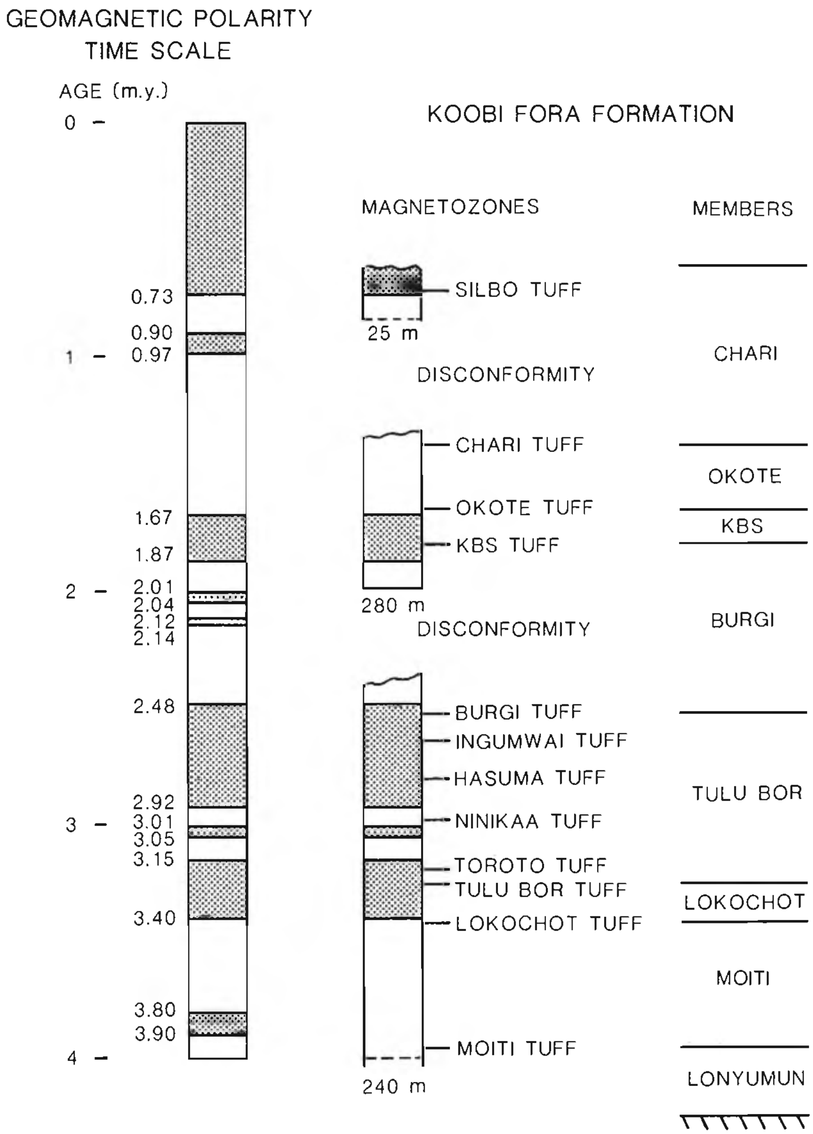

Fig. 13. Summary of the magnetostratigraphy of the Koobi Fora Formation and its temporal correlation with the polarity time scale of *Mankinen and Dalrymple* [1979].

We propose a model for the magnetization process whereby an original DRM carried in titanomagnetite is augmented by CRM in authigenic hematite. The acquistion of CRM was most significant within the uppermost 10 m of sediment below the land surface. Presumably, low-temperature oxidation and the CRM process are retarded by deeper burial of the strata and by rapid decrease of fresh titanomagnetite surface areas as hematite rinds form. During long intervals of stable polarity the CRM reinforces the DRM signal. After the geomagnetic field reverses, CRM adds antipolar components to the DRM in a 10-m-thick zone below the horizon that marks the actual polarity switch of the field. Hence drawing the magnetozone boundaries at the top of zones having superposed antipolar components locates the polarity switch in the DRM more accurately.

The stratigraphic interval from the Moiti Tuff up to the Burgi Tuff was deposited between 4.1 and 2.4 Ma, as indicated by K-Ar dating and correlation of the magnetozones with the geomagnetic polarity time scale (Figure 13). The older part of the Matuyama Reversed-Polarity Chron, from 2.4 to 2.0 Ma, is not found at Koobi Fora, partly due to an unconformity and gaps in the sampling. We found an excellent match between the magnetostratigraphies of the lower parts of the Koobi Fora and Shungura formations. The magnetic correlation is consistent with stratigraphic correlations that employ the chemistry of several volcanic ashes.

We have reinterpreted the magnetostratigraphy from the upper part of the Koobi Fora Formation because isotopic dating of the KBS Tuff is now secure and earlier mapping of the Tulu Bor Tuff in areas 102, 105, and 131 has been shown to be incorrect. The upper magnetozones of the Koobi Fora match well with paleomagnetic columns from the Shungura Formation, when the magnetic data are integrated with the chemical correlation of the two tuffs. The stratigraphic interval from roughly 50 m below the KBS Tuff up to the Chari Tuff was deposited during the period from 2.0 to 1.4 Ma. The KBS Tuff, dated by K-Ar and Ar^{40}/Ar^{39} methods at 1.88 ± 0.02 Ma, is within the Olduvai Normal Subchron. Near Ileret, the Brunhes-Matuyama polarity boundary occurs in sediments that were deposited on the eroded surface of the Chari Tuff. In this area the time gap associated with the disconformity is about 0.5 m.y.; however, in other areas the stratigraphic section is more complete.

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