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A REAPPRAISAL OF THE GEOMAGNETIC POLARITY TIME SCALE TO 4 MA USING DATA FROM THE TURKANA BASIN, EAST AFRICA

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Abstract. Recalibration of the Pliocene and early Pleistocene geomagnetic time scale using the K-Ar dated fluvial sequence of the Turkana Basin in East Africa agrees with calibrations based on astronomical calculations. Ages estimated here are: Olduvai Subchron, 1.78–1.96 Ma; Réunion Subchrons, 2.11–2.15 Ma and 2.19–2.27 Ma; Matuyama–Gauss boundary, 2.60 Ma; Kaena Subchron 3.02–3.09 Ma; Mammoth Subchron, 3.21-3.29 Ma; Gauss–Gilbert boundary, 3.57 Ma.

Introduction

Since 1985 it has been apparent to us that the time scales based on the paleomagnetic polarity of Pliocene and Pleistocene strata in the Turkana Basin have been slightly discrepant with respect to those based solely on units in the section dated by K/Ar and ^{40}Ar/^{39}Ar dating. In all cases, the ages derived from the directly dated units are older than those estimated for them by assuming constant sediment accumulation rates between magnetic polarity transitions. Two possible reasons for this discrepancy were examined previously. The first is that the potassium-argon ages were measured on materials incorporated into the section substantially after the time of their eruption. Second is that the sediments became magnetized a considerable time after their deposition. Either mechanism would give rise to the observed relations. The discrepancies vary from 0.05 Ma to 0.1 Ma, not sufficiently large to obviate identification of the magnetozones with the geomagnetic polarity time scale, but still larger than could be accounted for by analytical or stratigraphic errors in most cases.

Our intent here is to present a third possibility—that the calibration of the geomagnetic polarity time scale is itself in error. We had discussed this possibility earlier, but dismissed it because of the large amount of consistent data on which the scale was based. Most of the dates on which the time scale was defined, though, are on basalts. By contrast, most of the dates in the Turkana Basin have been measured on anorthoclase. It is well known that dates on whole rock basalts can be discrepantly young, whereas for young volcanic alkali feldspars this is not a generally recognized problem. Several recent papers [Baksi et al., 1992; Spell and McDougall, 1992; Tauxe et al., 1992] prompted us to review the data again. Those papers demonstrate that the Brunhes–Matuyama Chron boundary is approximately 0.78 Ma in age, rather than the long-accepted age of 0.73 Ma. Spell and McDougall [1992] also suggest ages of 0.915 Ma and 1.01 Ma for the boundaries of the Jaramillo Subchron rather than 0.90 to 0.97 Ma. The differences, 0.01–0.05 Ma, are similar to those seen between the paleomagnetically based scale and the K/Ar based scale in the Turkana Basin over a much longer interval. Other workers who based their scales on correlations of Milankovitch cycles with oxygen isotope ratio variations in deep sea cores have also recommended revision of the paleomagnetic polarity time scale. For example, Johnson [1982] suggested an age of 0.790 ± 0.005 Ma for the Brunhes–Matuyama boundary, and Shackleton et al. [1990] proposed an age of 0.780 Ma for the same boundary on a similar basis. Shackleton et al. [1990] also suggested that the limits of the Olduvai Subchron were 1.77 and 1.95 Ma, rather than 1.76 and 1.91 Ma as given by McDougall [1979], and that the Matuyama–Gauss Chron boundary occurred at 2.60 Ma, rather than at the widely accepted time of 2.47 Ma. Hilgen [1991a,b] extended similar calculations to the Gauss-Gilbert Chron. Although there is still a discrepancy regarding the age of the Jaramillo Subchron [Spell and McDougall, 1992], all of the recently recommended changes are in the same direction—the newly estimated ages of the polarity transitions are older than those currently in use.

Method

The paleomagnetic polarity stratigraphy of the Shungura Formation has been described by Brown and Shuey [1976], and Brown et al. [1978]; that of the Koobi Fora Formation, by Brock and Isaac [1974], and Hillhouse et al. [1977, 1986]. Sampling methods and data handling are covered in those papers; Feibel et al. [1989] review the magnetozones in the Shungura Formation, and that need not be repeated here. Potassium-argon and ^{40}Ar/^{39}Ar dating of these formations, in addition to the Nachukui Formation, is scattered through many references, but useful reviews are given in McDougall [1985], Brown et al. [1985], and Feibel et al. [1989]. Table 1 gives data on which the present discussion is based. Additional unpublished paleomagnetic results from the Koobi Fora Formation show that the top of the Olduvai Subchron lies 60 m above the KBS Tuff in Areas 102 and 103.

The Koobi Fora, Shungura, and Nachukui Formations are linked through analysis of tephra [Cerling and Brown, 1982;

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TABLE 1. K-Ar ages, stratigraphic levels of tuffs and paleomagnetic boundaries, and polarity transition ages in the Shungura and Koobi Fora Formations. 'D' = disconformity.

Marker Tuff or Paleomagnetic Transition	K-Ar Age[1] (Ma)	Shungura[2] (m)	Koobi Fora[3] (m)	Calc. Age (Ma)
Silbo	0.74±0.01		537	
		D	D	
Gele	1.25±0.02			
L. Nariokotome	1.33±0.03			
Tuff L / Chari	1.39±0.02	717	522	
Tuff J-4 / Okote	1.65±0.03	667	500	
Top Olduvai		634	423	1.78[4]
Tuff H-4	1.86±0.02	616	373	
Tuff H-2 / KBS	1.88±0.02	603	363	
Bottom Olduvai		559	D	1.96
Top Réunion II		481	D	2.11
Bottom Réunion II		460	D	2.15
Top Réunion I		441	D	2.19
Bottom Réunion I		398	D	2.27
Tuff G	2.32±0.04	370	D	
Tuff F	2.34±0.04	323	D	
Tuff D / Lokalalei	2.52±0.05	244	240	
Matuyama/Gauss		232	225	2.60[4]
Tuff Burgi	2.68±0.03		218	
Tuff C-4 / Ingumwai		191	213	
Tuff B-10	2.95±0.05	146		
Top Kaena			191	3.02
Ninikaa	3.06±0.05		188	
Bottom Kaena			182	3.09
Top Mammoth		103	161	3.21
Bottom Mammoth		85	148	3.29
Toroto Tuff	3.32±0.02		142	
Tuff B / Tulu Bor		66	131	
Gauss/Gilbert		32	99	3.57
Tuff A / Lokochot		32	97	
Topernawi	3.76±0.04		67	
Moiti	≤4.10±0.07		37	

1. McDougall [1985]; Brown et al.[1985]; McDougall et al [1985]; Feibel et al. [1989]
2. Brown & Shuey [1974]; Brown et al [1978]
3. Brown & Feibel [1986]; Hillhouse et al [1986]; unpub. data (JH)
4. Average from Shungura and Koobi Fora Formations

Brown and Feibel, 1986; Brown et al., 1985; Feibel et al., 1989] so that dates obtained in one section can be applied to the others. In past reports our principal goal has been to establish a chronology for these formations, using all information available. Our last attempt considered the discrepancies between the chronology based on paleomagnetic data and that based on isotopic data. Here we apply the isotopic dates to estimate times of polarity transition from the Gilbert–Gauss Chron boundary to the top of the Olduvai Subchron. We assume that the rate of accumulation of strata (including diastems) in a local section is constant, and estimate ages of magnetic polarity transitions by linear interpolation between dated levels, a procedure called stratigraphic scaling by Feibel et al. [1989]. If sedimentation is continuous, or occurred at discrete but regular intervals, deviations from linearity are small. Error estimates for each of the boundaries (Table 2) were derived by combining the uncertainty in stratigraphic placement with the error in the controlling age determinations. The uncertainty in the stratigraphic position of most reversals is less than 5 meters, which introduces an error of 0.02–0.03 Ma to the age estimates. The error on each boundary was estimated separately.

Using stratigraphic scaling, and measured ages combined with the polarity transitions identified in the Shungura and Koobi Fora Formations we obtain age estimates for chron and subchron boundaries (Table 2) which are significantly older than earlier polarity time scales [Mankinen and Dalrymple, 1979; McDougall, 1979]. Congruence between independent estimates from Koobi Fora and Shungura adds confidence to the derived ages. The results agree well with estimates based on orbital tuning [Shackleton et al., 1990; Hilgen, 1991a, b].

Discussion

Together with recent estimates of the Brunhes–Matuyama Chron boundary [Baksi et al., 1992; Spell and McDougall, 1992], and of the Jaramillo Subchron, the estimates provided here suggest that an increase of about 4% is required in the ages of polarity transitions widely in use [e.g., Mankinen and Dalrymple, 1979; McDougall, 1979]. Recalibration of the paleomagnetic time scale simplifies the paleomagnetic story of the Koobi Fora and Shungura Formations, because previously we had to assume that tuffs were deposited several tens of thousands of years after eruption, or that the magnetization of fluvial sediments required several tens of thousands of years, neither of which was particularly palatable.

In Figure 1(a) accepted times of transition [McDougall, 1979] are plotted against the times of transition calculated here, and include those recommended by Spell and McDougall [1992] for the Jaramillo Subchron and the Brunhes–Matuyama Chron boundary. The best fit line through these has a slope of 0.96, meaning that the accepted boundaries are 4% younger than those calculated here. The fit is quite good over the whole range ($r^2 = 0.998$), and the y-intercept is very small.

Table 2. Ages of polarity transition boundaries (Ma) from cited sources and as estimated here.

	Turkana Basin	S[1]	H[2]	M&D[3]	McD[4]
Top Olduvai	1.78±0.04	1.77	1.79	1.66	1.76
Bottom Olduvai	1.96±0.03	1.95	1.95	1.88	1.91
Top Réunion II	2.11±0.04		2.14	2.01	2.07
Bottom Réunion II	2.15±0.04		2.15	2.04	2.07
Top Réunion I	2.19±0.04			2.10	2.23
Bottom Réunion I	2.27±0.04			2.12	2.23
Matuyama–Gauss	2.60±0.06	2.60	2.59 /2.62	2.47	2.47
Top Kaena	3.02±0.06	---	3.04	2.92	2.91
Bottom Kaena	3.09±0.06	---	3.11	2.99	3.00
Top Mammoth	3.21±0.06	---	3.22	3.08	3.07
Bottom Mammoth	3.29±0.06	---	3.33	3.18	3.17
Gauss–Gilbert	3.57±0.05	---	3.58	3.41	3.41

1. Shackleton et al [1990]
2. Hilgen [1991a, 1991b]
3. Mankinen & Dalrymple [1979]
4. McDougall [1979]

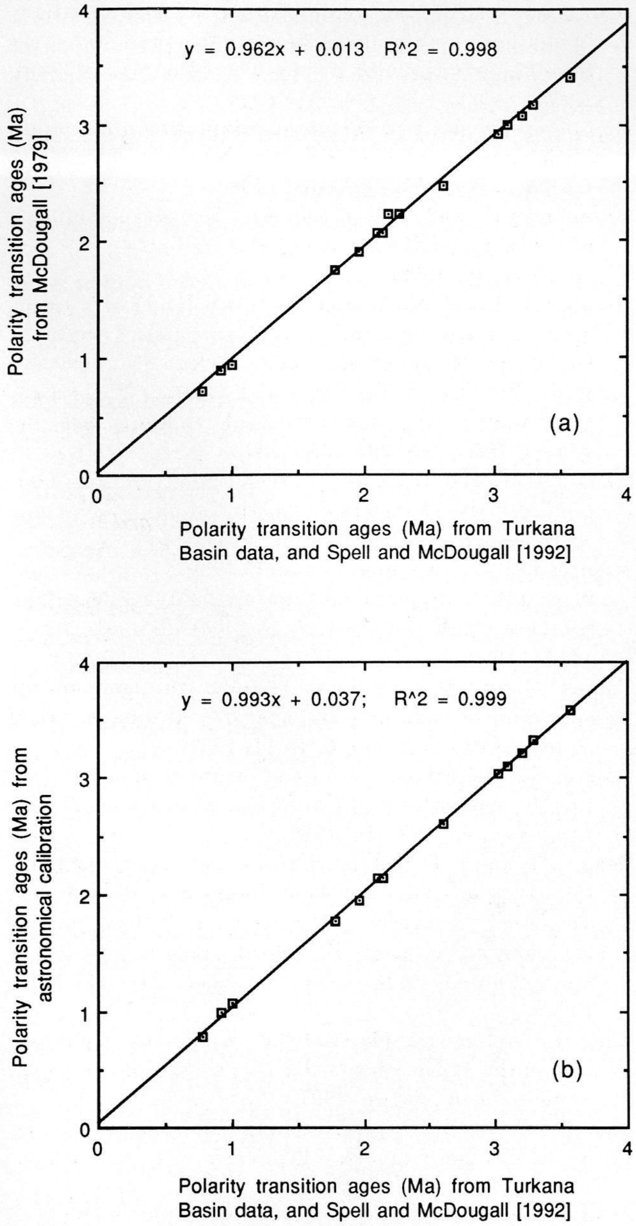

Fig. 1. (a) Magnetic polarity transition ages of McDougall [1979] based largely on K/Ar dating of basalts, compared with magnetic polarity transition ages based on data from K/Ar and ^{40}Ar/^{39}Ar feldspar ages from the Turkana Basin and in Spell and McDougall [1992]. (b) Magnetic polarity transition ages based on orbital tuning [Shackleton, 1990; Hilgen, 1991a,b], compared with magnetic polarity transition ages based on data from K/Ar and ^{40}Ar/^{39}Ar feldspar ages from the Turkana Basin and in Spell and McDougall [1992].

Hilgen [1991a] found differences of about 6% between the polarity timescale of Mankinen and Dalrymple [1979] and his estimates. Figure 1b shows the close correspondence between astronomically calibrated ages and those derived from our data and that of Spell and McDougall [1992]. The intercept of 0.037 Ma would decrease to near zero if the estimate of 0.992 Ma for the top of the Jaramillo Subchron suggested by Tauxe et al. [1992] were used rather than that of Spell and McDougall [1992], assuming that the subchron is approximately 0.10 Ma in duration. The normal polarity and the 0.74 Ma age of the Silbo Tuff give added credence to an age near 0.78 Ma for the Brunhes–Matuyama boundary proposed by workers cited above. With the new estimates for the base of the Jaramillo Subchron, it may be difficult to distinguish the Jaramillo from the Cobb Mountain Subchron [Mankinen et al., 1978].

Our estimate of the base of the Olduvai Subchron (1.96 Ma) is slightly older than that of Hilgen [1991a] (1.95 Ma), but slightly younger than 1.98–2.01 Ma proposed by Walter et al. [1991]. This is important for understanding the history of sedimentation at Koobi Fora, and the paleomagnetic record there. Previously, Hillhouse et al. [1977] assumed remagnetization of a 120 m thick lacustrine sequence of normal polarity below the KBS Tuff because with the KBS at 1.88 Ma, and the base of the Olduvai Subchron at 1.91 Ma, there seemed insufficient time to deposit this much section. The depositional rate would have been 4 m/ka—not impossible, but perhaps unlikely. If the base of the Olduvai Subchron is near 1.96 Ma, this interval was deposited over a period of about 0.08 Ma, at depositional rates near 1.5 m/ka.

The apparent duration of the Réunion I Subchron (0.08 Ma; Table 2) is surprisingly long, but as it extends over Submembers G-4 (part) to G-8 [Brown et al., 1978] it is difficult to see how it can be much shorter, unless the depositional rate for this small part of the section was higher than average. The minimum apparent duration is ~0.05 Ma, assuming that the transition takes place at the top of Submember G-4. Between Tuff H-2 (1.88 Ma) and Tuff G (2.32 Ma) in the Shungura Formation, the interval that contains the Réunion Subchrons, there are no additional age constraints. As age estimates for the Subchron boundaries are dependent upon the assumption of a uniform depositional rate, and on how the age data above and below the interval are utilized, the derived ages are likely to be less accurate than for other parts of the polarity scale.

Hillhouse et al. [1986] showed that the Toroto Tuff is of normal polarity, whereas its redeposited products are reversed. Hence the polarity transition representing the bottom of the Mammoth Subchron must lie very near the age of the Toroto Tuff itself. Our age estimate for the base of the Mammoth Subchron is 0.04 Ma younger than that of Hilgen [1991a], who gave 3.33 Ma for this boundary.

Conclusions

The well-dated fluvial and lacustrine strata in the Turkana Basin can be used to recalibrate the paleomagnetic time scale. The high resolution magnetic stratigraphy from the Turkana Basin yields age estimates for the Olduvai Subchron (1.77 to 1.96 Ma), the Réunion events (2.11 to 2.15 Ma and 2.19 to 2.27 Ma), the Matuyama–Gauss Chron boundary (2.60 Ma), the Kaena (3.02 to 3.09 Ma), the Mammoth (3.21 to 3.29 Ma), and the Gauss–Gilbert Chron boundary (3.57 Ma) which are in good agreement with estimates made from astronomical calibrations. The most likely reason for the systematic underestimate of the boundaries by K/Ar dating is that most (>90%) of the age determinations used for constructing the scale are on basalts. Apparently, on average, a small but significant proportion of radiogenic argon has been lost from the basalts, most likely from the glassy or poorly crystallized or altered mesostasis, despite careful choice of samples.

If our age estimates are borne out, then the ages of fossil hominids in the Turkana Basin [Feibel et al., 1989] must be refined again. The changes will be small, but the changes will not be constant over the whole interval because the estimates were derived by using both assumed ages of paleomagnetic transitions and directly dated tuffs. We find it ironic that the KBS Tuff is useful in calibrating the magnetic polarity time scale, whereas formerly its polarity was used to defend an incorrect age proposed for it [Lewin, 1987].

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