Too-low magnetic inclinations in central Asia: an indication of a long-term Tertiary non-dipole field?

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ABSTRACT

Observed Tertiary palaeolatitudes in central Asia are more southerly (by about 1600 km on average) than those predicted from the Eurasian reference palaeopoles. Subsequent northward displacements of the central Asian terranes are unlikely to have been this large. In this study we analyse to what extent non-dipole fields, especially octupole fields, can explain this phenomenon. A global (zonal) octupole field manifests itself in two ways. (1) Because the reference APWP is based mostly on results from the UK and North America, its palaeopoles will be far-sided as seen from the North Atlantic, but near-sided as seen from eastern Asia, giving predicted palaeolatitudes that are too high. (2) An octupole field contribution produces observed palaeolatitudes, as calculated with the dipole formula for central Asia, that are too low. Both effects therefore increase the palaeolatitude anomalies in Asia. We find that an octupole/dipole field ratio (G3) of 0.06 or greater will reduce the palaeolatitude discrepancies significantly and is of the same magnitude as the G3 estimate of a recent analysis of Early Tertiary European and North American data.

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Introduction

It has repeatedly been observed during the last decade that latest Cretaceous and Tertiary palaeomagnetic inclinations are anomalously low in central Asia (e.g. Westphal, 1993; Thomas *et al.*, 1994; Chauvin *et al.*, 1996; Cogné *et al.*, 1999, and references therein), when compared to the reference Apparent Polar Wander Path (APWP) for Eurasia (e.g. Besse and Courtillot, 1991). The observed palaeolatitudes of central Asian terranes are thus more southerly, by some 15° on average, than those predicted by Eurasian palaeopoles. Figure 1 plots the differences between observed palaeolatitudes of the central Asian results (Fig. 2) used in this study and their predicted palaeolatitudes from a reference APWP. It does not make a significant difference whether our own APWP, to be discussed below, is used, or whether a published APWP is used. Chauvin *et al.* (1996) have noted that there is a general tendency for the magnitude of the palaeolatitude anomalies to increase from south-eastern Europe to China. A subset of our own data set, restricted to sites in a present-day latitude band of 31–39°, also shows this trend (Fig. 3), although for the entire data set such a trend is less evident.

Several explanations have been proposed for these puzzling discrepancies, and these have been summarized by Cogné *et al.* (1999). (1) Inadequate demagnetization may have led to palaeomagnetic inclinations that are too shallow because of contaminations by overprints. (2) The observed palaeolatitudes are accurate and reflect large subsequent northward movements of the sampling areas. (3) The reference APWP may be incompletely determined or based on flawed palaeopoles. (4) The reference APWP may be inappropriate for Siberia. Siberia, as the craton to the north of the central Asian terranes, may itself have moved relative to the European sites where the palaeopoles were obtained. (5) The palaeolatitudes of sedimentary rocks may be inaccurate because of inclination shallowing due to depositional processes or compaction. (6) Global or local non-dipole fields may render the palaeomagnetically determined palaeolatitudes inaccurate.

All of these possible causes may have conspired to produce the discrepancies, although some are more likely than others. Most of the

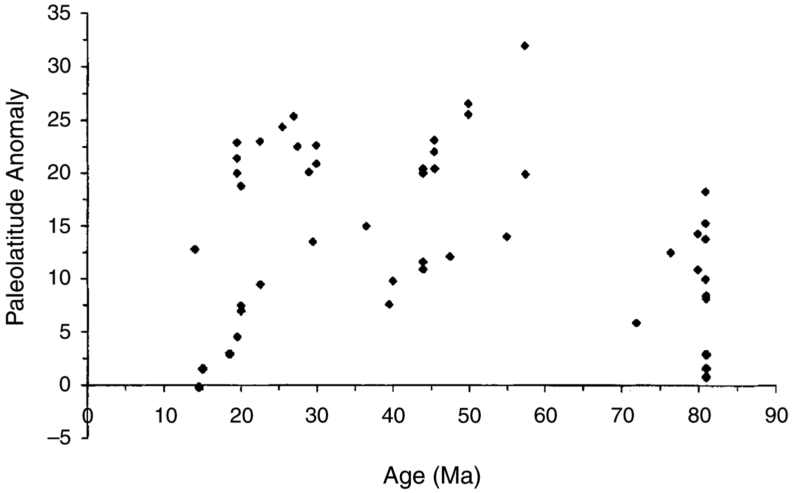

Fig. 1 Palaeolatitude anomalies (calculated as the difference between predicted and observed values) of central Asian sites plotted as a function of time. The predicted palaeolatitudes are calculated for the site locations (in Table 1) from the mean palaeopoles of Table 3.

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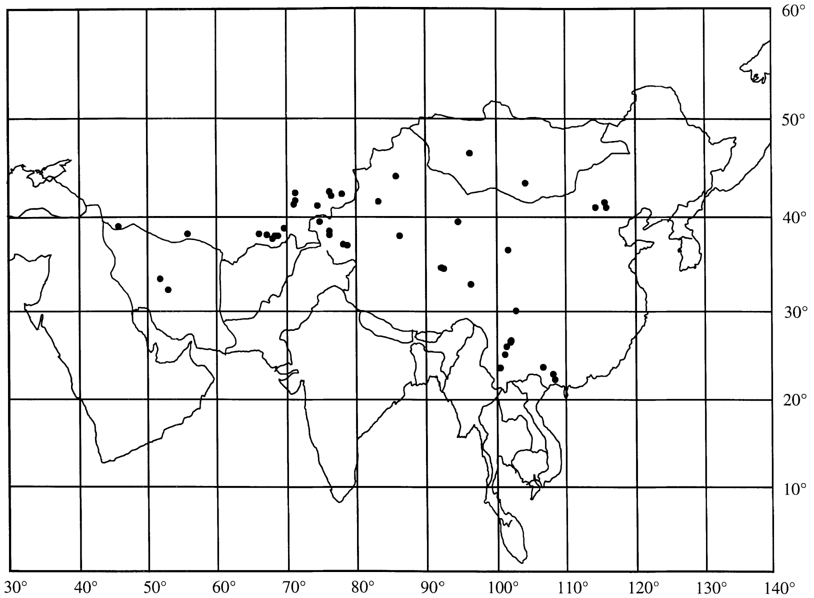

Fig. 2 Location map of the Asian sites, as listed in Table 1.

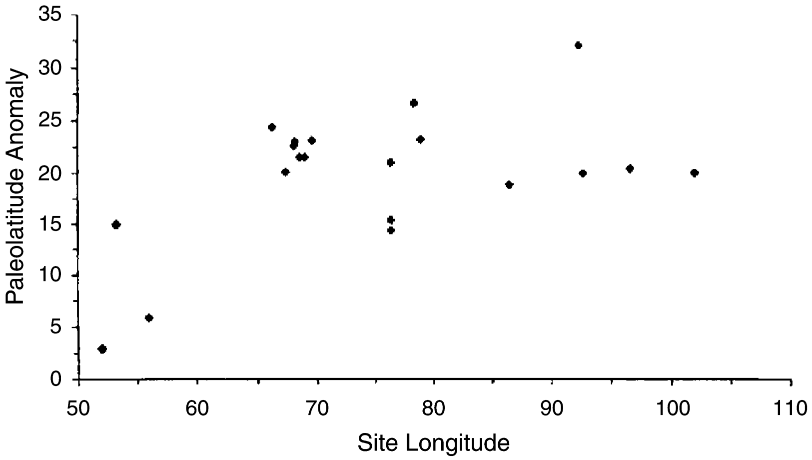

Fig. 3 Palaeolatitude anomalies (calculated as the difference between predicted and observed values, as in Fig. 1) of selected central Asian sites plotted as a function of site longitude. Only sites located between 31 and 39° latitude have been included.

results appear to have been obtained by thorough demagnetization and are supported by convincing field tests, so poor demagnetization techniques likely cannot be blamed for all of the anomalies in the entire dataset. Some northward movement of terranes with respect to Siberia, subsequent to magnetization acquisition, is very likely, but there is a consensus that the magnitude of these displacements has been much less than the 1600 km, on average, that could be inferred from the palaeomagnetic results. Most studies describing the palaeolatitude anomalies used the reference APWP of Besse and Courtillot (1991), and there is no reason to suspect the validity of this APWP for Europe or North America. As we will show below, using a differently constructed reference APWP based on results from North-Atlantic-bordering continents only does not change the analysis. However, the absence of palaeopoles for Siberia means that a 'Eurasian' APWP of necessity is unsatisfactory if relative movements took place between Siberia and Europe, as suggested by Cogné *et al.* (1999). We note, however, that the palaeolatitude discrepancies appear to remain of similar magnitude from 80 Ma through at least 25 Ma (Fig. 1), implying that these relative movements must have taken place in the Miocene or later, for which there is little evidence. As acknowledged by Cogné and co-workers, the locations of the necessary extensional movements, whether in a discrete or a distributed zone, are very speculative, and the whole hypothesis merely replaces a tectonic enigma within central Asia by another presumably to be placed somewhere near the Urals or in eastern Europe.

Too-shallow inclinations because of sedimentary processes have been investigated experimentally by Tan *et al.* (1996) for rocks from Tarim; they found that the silt-sized fraction of the sediments did not show large enough inclination-shallowing effects, whereas the clay-sized fraction did. Most of the central Asian results are based on hematitic silt- or sandstones. The database contains a few igneous rocks (Thomas *et al.*, 1994), which would not show the effects of inclination shallowing, but more results from extrusives are badly needed.

While we cannot exclude the possibility that the palaeolatitude anomalies are caused by inclination error, we find that the last possibility, namely a contribution from non-dipole fields, is certainly also a possible solution. In recent years, attention has been refocused on non-dipole components in the long-term palaeomagnetic field (Kent and Smethurst, 1998; Van der Voo and Torsvik, 2001), but as a possible explanation for the central Asian palaeolatitude enigma, it was proposed already a decade ago by Westphal (1993). According to Chauvin *et al.* (1996), the Tertiary inclination anomaly progressively increases from 0° on the Atlantic margin, to about 10° in the eastern Mediterranean and Middle East, to reach a maximum of 25° in central Asia. They proposed that this reflects a regional non-dipole field during the Tertiary, which at first glance is a very logical explanation. However, as we will show in this study, even a zonal (globally symmetric) non-dipole field can cause systematic anomaly trends as a function of longitude when a comparison with a reference APWP from a remote part of the world is involved.

Van der Voo and Torsvik (2001) tested for the existence of a zonal octupole field from Late Carboniferous through Early Tertiary by comparing the observed palaeomagnetic palaeolatitude distributions for the Laurentian and European landmasses with the patterns predicted from their mean palaeopoles. Their analysis did not provide information about

Table 1 Central Asian Sites

Site	GPDB	Dc	α_{95}	Kd	Dec	Inc	Glat	Glon	Plat	Plon	Age
Mengyejing Fm, Yunnan, China	2927	4	7.9	10.3	42.8	26.1	23.5	100.8	48.5	196.5	14
Mongolian Basalts, Mongolia	2815	3	14	45	18	67	46.5	96.5	77	162	14.5
Hannduba Fm, Inner Mongolia and Hebei	2190	4	4.2	24.4	8.2	61.5	41	114.7	83.4	192.8	15
Hassan-Abad Series, Iran	1802	3	12	28	344.5	49	33.4	52	76.4	311.1	18.5
Tajik Depression Sediments, Tajikistan	2874	4	12	30	336	30	37.7	68.2	60	299	19.5
Tajik Depression Sediments, Tajikistan	2874	4	9	25	310	33	38	69	42	328.5	19.5
Tajik Depression Sediments, Tajikistan	2874	4	13	16	349	35	38.1	67.4	69	277.5	19.5
Dzhety-Ogyuz Fm, N.Tien Shan	2814	4	9	97	357	59	42.2	76.7	86.7	300.6	19.5
Tajik Depression Sediments, Tajikistan	2874	4	15	26	347	33	38	68.6	67	282	19.5
Hannuoba Basalt Fm, Inner Mongolia	2785	4	6.1	47	358.5	59	41	116.2	88.6	29.2	20
Tertiary Basalts, Inner Mongolia	2526	4	6.1	47	358.5	59	41.5	116	88.6	29.2	20
Jianglisai, Altyn Tagh fault	[*1]		6.7		358.4	39.6	38	86.5	74.4	272	20
Sanhaogou Fm, Yunnan, China	2927	4	7.5	15.3	21.1	35.5	23.5	100.7	70	197.8	22.5
Tajik Depression Sediments, Tajikistan	2874	4	11	19	317	33.5	38.8	69.6	47.5	323	22.5
Middle Cenozoic Redbeds, Tajikistan	3085	4	9.7	19.1	3.4	29.6	38.2	66.3	67.4	237.7	25.5
Massaget Fm, Uzbekistan	2814	4	9	33	342	34	41.3	71.3	62.6	290.8	27
Tajik Depression Sediments, Tajikistan	2874	4	11	7	312	32	37.7	68.1	43.5	326	27.5
Dzhety-Ogyuz Fm,N.Tien Shan,Kyrgyzstan	2814	4	11	50	0	44	42.4	78.2	73.4	258.2	29
Mongolian Basalts, Central Mongolia	2815	3	8	19	25	56	43.5	104.5	70	204	29.5
Aertashi, Altyn Tagh fault	[*1]		5		17.6	36.9	38.1	76.4	66.8	210.5	30
Subei, Altyn Tagh fault	[*1]		6.6		344.7	39.7	39.5	94.8	68.6	316.8	30
Kuh-e-kaleh-e-kargushi Series, Iran	1802	3	5.9	112	61	34.2	32.2	53.2	34.2	141.2	36.5
Mengla Group, Yunnan, China	2927	4	7.6	12	84.7	38.9	23.5	100.7	13.2	172.2	39.5
Armenian Sandstones, Armenia	2817	3	12	7.8	8	49	39	46	78	190	40
Talas Basin Sediments, Kirgisistan	2814	4	22	20	343	54	42.5	71.5	74.5	316.1	44
Chaktal Basin Sediments, Uzbekistan	2814	4	9	25	352	42	41.7	71.5	71.3	274.8	44
Eocene Red Bed, Xining, Qaidam	[*2]		13.2	34.8	29.3	40.8	36.5	102	61.6	211.3	44
Fenghuanshan Fm, Guangxi, China	2785	4	4.3	36.3	5	34	22.8	108.4	83.8	236	44
Naryn Redbeds, Kyrgyzstan	2814	4	11	13	5	37	41.2	74.7	69	241.5	45.5
Eocene Red Bed, Xialaxiu, Qiangtang	[*2]		9.5	26.8	322	32.3	32.8	96.6	52.6	352	45.5
Lower Tertiary Limestones and Redbeds, Tarim	[*3]		13.3	34	27.8	30	37	79	58.1	202	45.5
Liuchou and Nadu Fm, Guangxi, China	2738	4	6.5	31.5	325.5	33.2	23.6	107	58.6	18.2	47.5
Leidashu Fm, Sichuan, China	2497	4	12.1	25.7	358.7	13.7	26.4	102.3	70.6	286.1	50
Puska, Altyn Tagh fault	[*1]		8.4		4.3	24.3	37.1	78.4	65.3	248.3	50
Kokturpak Fm, Kyrgyzstan	2814	4	10	48	10	49	42.6	76.4	75	220.9	55
Fenghuoshan Group, Qiangtang	3228	4	6	32.7	25.5	34.6	34.5	92.7	62.6	210.5	57.5
Fenghuoshan Group, Qiangtang	1962	4	7.2	29	9	14	34.6	92.4	61	253	57.5
Limestones and marls, Turkmenistan	1810	3	2.6	526	12	45	38.2	56	74	193	72
Xiaoba, Leidashu Fm, Sichuan, China	1403	4	8.6	26.7	357.6	31.6	26.5	102.3	80.8	296.8	76.5
Douggou and Ziniquan Fm, Junggar	2385	4	6.9	56.9	12.5	51.3	44.2	86	74.3	223.1	80
Yingjisha, Altyn Tagh fault	[*1]		9.9		7.6	37.1	38.1	76.4	71.4	233.6	80
Yingjisha Sediments, Tarim	2661	4	9.9	46.6	7.6	37.1	38.5	76.4	71	234	81
Wuqia Sediments, Tarim	2661	4	7.4	39.5	11	40	39.5	75	70.8	222.6	81
Bashenjiqike Fm, Tarim	1714	4	8.6	114	16.3	39.2	41.6	83.5	66.3	222.9	81
Xiaoba Fm, Sichuan, China	2497	4	6.6	28.8	8.1	38.8	26.5	102.4	81.5	220.9	81
Matoushan Fm, Yunnan, China	2575	4	14.3	12.4	45.6	46.6	25	101.5	49.3	177.1	81
Jiangdihe Fm, Yunnan, China	3219	4	3.5	77.9	26.9	35.6	25.9	101.7	64.5	200.2	81
Upper Series Deposits, Guangxi, China	2738	4	9.3	31.7	349.3	35.3	22.2	108.7	79.4	7.1	81
Upper Cretaceous Redbeds,Sichuan,China	2711	3	3.9		359	51.6	29.9	103.1	88.1	75.7	81
Xiaobu Fm, Sichuan, China	2713	3	5.3		12.6	46.2	26.6	102.4	78.9	186.6	81

Fm = Formation; GPDB = Global Palaeomagnetic Data Base Reference Number (REFNO in Lock and McElhinny (1991); Dc = Demag Code (5 is the best score); α_{95} and Kd are the radius of the cone of 95% confidence and precision parameter, respectively; Dec and Inc are declination and inclination (in degrees); Glat = Site's latitude; Glon = Site's longitude; Plat = Palaeopole's latitude; Plon = Palaeopole's longitude; Age in million years. Additional references to Table 1 (not in GPDB): [*1] Rumelhart *et al.* (1999), [*2] Cogné *et al.* (1999), [*3] Gilder *et al.* (1996).

Table 2 Eurasian reference palaeopoles

Age (Ma)	Dc (Q)	GPDB	Dec	Inc	α_{95}	GLat	GLon	Plat	Plon
2.5	3	1275	339.91	55.32	14.4	35.32	255.1	73.68	172.85
3.5	4	2863	357.23	49.42	3.6	36.21	255.71	83.62	97.8
5	3	846	13.08	63.06	9.2	50	13.3	79.6	130
5.5	3	1275	17.33	51.53	9.7	35.62	255.01	75.23	353.48
8	3	56	1.51	61.3	12.9	48	9	84.3	177.7
15.5	3	2288	5.48	56.5	12.9	46.54	253.33	79.69	48.14
16.5	4	2426	358.6	63.98	5.2	50.5	9.4	85.1	200.9
22.5	4	1402	4.72	55.01	6.7	38.36	261.13	85.29	26.52
23	3	1300	347.78	65.3	8.4	39.8	259.34	78.37	214.06
23.5	4	1299	350.79	53.7	5.2	38.56	261.24	81.43	143.83
24	4	3282	14.11	62	4.4	50.8	8	77.8	130.8
25.5	4	1402	332.93	54.28	8.6	38.36	261.13	68.06	170.18
26	4	3130	348.86	55.65	6.8	38.97	261.05	80.75	157.01
27	4	2492	358.66	40.74	8.8	33.68	264.54	79.55	91.33
27	4	1299	351.67	50.81	5.4	38.56	261.24	80.2	127.79
28	3	2637	17.26	46.94	9.4	31.51	263.49	74.68	1.74
28.5	4	2633	335.1	49.32	5	41.85	262.1	66.85	149.89
30	4	1315	352.91	49.57	4.4	35.41	259.65	82.23	131.55
30	3	2631	354.36	49.01	5	35.41	259.76	82.74	122.13
33.5	3	1566	339.58	43.22	10.3	37.91	262.71	68.51	142.26
33.5	3	311	0.12	63.44	7	50	17	85	196
33.5	4	2400	0.38	51.84	5.5	50.65	254.66	71.81	73.63
34	3	1506	1.06	60.21	3.4	50.3	7	80.8	182
37	4	2943	351.11	51.13	4.3	31.42	265.37	82.42	180.66
40	3	562	6.23	68.59	2.4	56.49	310.32	84.14	89.33
44	3	1632	355.44	60.13	7.7	46.59	262.05	83.54	114.32
47	3	87	6.82	56.64	9	40.4	292.82	83.81	51.54
47	3	1865	1.6	60.59	10.1	40.39	293.03	88.31	338.2
47	4	2560	336.77	63.88	5.6	50.18	256.64	73.82	159.02
49.5	2(5)	755	3.4	63.1	1.5	51.2	355.3	83	154.99
50	2(6)	340	352.27	58.14	4	55	356	73	197
51	4	3150	350.74	54.07	4.9	46.2	262.42	76.45	116.82
51	3	1270	351.66	66.28	2.6	52.48	263.32	83.49	140.98
51	3	1348	346.13	60.98	4	50.84	261.61	77.04	134.17
51	2(4)	1174	3.4	66.77	2	57.1	354.1	82	158
52	3	56	20.18	61.52	16	48	9	74.9	112.19
52	2(5)	1040	12.47	61.49	10	56.5	354.2	74	139
53	4	2759	1.77	63.7	3.4	50.39	265.68	84.81	71.84
53.5	3	83	356.16	63.31	2.7	56.6	353.8	78	187
55	2(5)	85	4.46	62.53	3.5	57.6	353.4	76	160
56	2(4)	654	4.55	54.82	5	55.1	353.9	70	163
57	2(5)	504	335.06	63.89	14	46.03	268.78	72.68	186.28
57	3	419	355.51	68.87	6	62	353	80	189
57	2(3)	650	4.1	66.66	1.9	62	353	77	161.01
57.5	2(3)	86	3.48	58.8	2.5	57.4	353.7	72	165
58	3	1204	1.02	60.02	2.7	56.9	353.8	74	171
59	3	1638	342.05	52.44	17.7	52.34	264.93	66.76	125.83
59	2(6)	1169	358.71	65.79	2.4	57	353.5	81	179.02
59.5	3	1377	359.62	62.38	2.7	56.7	353.8	77	175.01
61	2(6)	1033	348.05	51.43	3	43.84	266.37	74.97	128.92
62	2(5)	1055	2.33	57.82	2.8	56.4	353.9	72	167.99
63	2(4)	1710	351.05	58.82	1.1	39.6	263.65	83.1	176.22
63	3	1914	334.94	71.54	6.6	60.06	263.58	76.34	168.56
63	3	1270	353.71	67.06	3.7	55.54	267.68	83.07	123.58
64	2(5)	1711	352.39	67.58	3.9	55.45	267.55	83.25	133.3
72	3	1240	340.01	55.71	6.2	40.72	264.1	73.76	164.57
74	3	2393	9.41	47.09	8	43.5	5.5	73	156
76	4	2370	356.5	68.65	4.6	55.7	267.04	85.75	117.57
79	1(3)	572	331.43	68.57	13.2	48.58	270.76	71.55	201.8
79	2(5)	121	324.58	67.19	9.6	47.33	275.16	66.67	204.79
80	4	2397	338.93	73.22	6.2	53.79	268.99	77.32	211.24

Table 2 (Continued)

Age (Ma)	Dc (Q)	GPDB	Dec	Inc	α_{95}	GLat	GLon	Plat	Plon
81	4	2382	350.99	67.72	6.6	53.84	267.94	83.64	151.61
86	2(5)	3037	19.94	56.93	3	42.4	46.9	74	148
86	2(5)	3037	17.76	54.02	3	42.6	46.7	74	161
89.5	3	1507	16.44	52.45	5	51.5	8.3	68	148.99
93	3	1495	2.15	57.46	4	52	8	76	181
100	4	1322	346.92	56.49	4.4	40.85	290.76	79.15	184.5

GPDB = Global Palaeomagnetic Data Base Reference Number; Dc = Demag Code (5 is the best score); *Q*: Van der Voo (1993) classification factor (7 is best score), listed only for studies with Dc less than 3; α_{95} is the radius of the cone of 95% confidence; Glat = Site's latitude; Glon = Site's longitude; Plat = Palaeopole's latitude; Plon = Palaeopole's longitude. Site coordinates, palaeopoles and declinations have been rotated into a Eurasian reference frame, using the Euler parameters of Torsvik *et al.* (2001b).

Table 3 Mean Eurasian reference palaeopoles determined by moving window analysis of 20 Ma at increments of 5 Myr

Age (Ma)	α_{95}	GLat	GLon	Plat	Plon
2.5	11.43	55.91	287.6	85.75	134.72
7.5	8.16	58.85	292.43	86.5	120.91
12.5	7.08	56.43	285.88	86.93	109.74
17.5	5.15	51.26	278.76	83.33	145.17
22.5	5.34	44.45	268.39	83.22	135.98
27.5	4.82	45.94	271.23	81.93	139.61
32.5	4.57	46.9	273.05	82.17	137.74
37.5	5.42	48.37	277.75	83.15	128.49
42.5	3.78	58.1	301.2	81.5	138.26
47.5	3.26	60.39	313.39	80.35	152.74
52.5	2.81	60.94	317.44	79.08	154.93
57.5	2.53	62.59	316.76	78.56	156.58
62.5	2.88	62.29	310.09	77.86	161.81
67.5	3.36	61.46	304.13	77.95	156.68
72.5	4.86	53.74	274.32	79.34	175.58
77.5	5.73	64.46	301.73	76.95	175.72
82.5	6.22	66.08	321.94	76.51	172.55
87.5	6.23	66.63	330.88	75.38	177.71
92.5	5.72	54.39	12.24	74.73	161.78
97.5	12.11	54.52	340.41	75.02	166.95

long-term quadrupole fields, but these were deemed less likely than octupole fields because of good agreements between palaeomagnetic and palaeofacies determinations of equatorial positions. They estimated the magnitude of the octupole/dipole field ratio (G3) to be about 0.1 for the 300–40 Ma interval, and suggested that the octupole field may have been responsible for the palaeolatitude anomalies in central Asia, adopting the earlier suggestion by Westphal (1993). In this

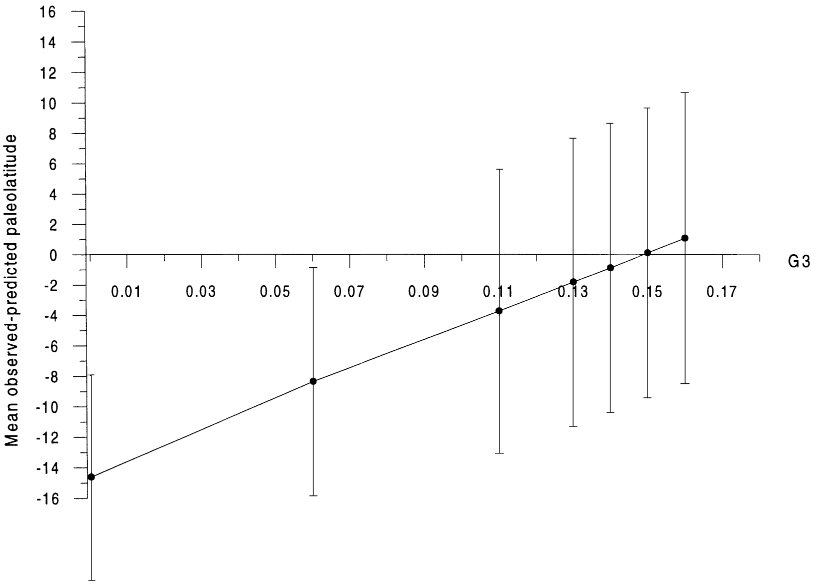

Fig. 4 When the value of G3 (the octupole/dipole field ratio) is increased from zero to 0.15 in calculations of the observed and predicted palaeolatitude values, the mean palaeolatitude anomaly diminishes. Error bars are standard deviations.

paper, we analyse the available data in terms of the magnitude of possible octupole fields that would be needed to reduce significantly the palaeolatitude discrepancies.

Methodology

Two datasets have been compiled from the Global Palaeomagnetic Data Base, updated to the year 2000 (Lock and McElhinny, 1991). One set comprises all central Asian 'primary' palaeomagnetic results with demagnetization code 3 or greater, from localities north of Arabia, the Himalayas and Indochina, and south of the Siberian craton and its margins (Table 1), for the interval 80–10 Ma. Results with both a precision parameter k less than 10 and α_{95} greater than 15° were not included. The localities are contained in the latitude band 20–50° and longitudes 40–120° (Fig. 2). The second set comprises all reliable palaeopoles with either demagnetization code ≥ 3 (Lock and McElhinny, 1991) or $Q \geq 3$ (Van der Voo, 1993), from the stable parts of the North Atlantic bordering continents for the interval 100–2 Ma, in order to construct a reference APWP. Reconstruction parameters to account for the opening of the Labrador Sea and North Atlantic are from Torsvik *et al.* (2001b). Table 2 lists the palaeopoles in a European frame of reference. Results from the North American Cordillera and the Pyrenean–Alpine–Carpathian belts and further south in Europe were not included.

To test for the effects of octupole contributions, we compare results recalculated for various G3 values between 0 and + 0.2, where G3 is the ratio of the zonal octupole and dipole fields. The best estimate of G3 obtained by Van der Voo and Torsvik (2001) in their analysis of North American and European palaeomagnetic results was about + 0.1, whereas Torsvik *et al.* (2001a) found that a G3 of 0.08 best explained the hot spot locations in the palaeomagnetic reconstructions of the Atlantic and Indian oceans. The recalculation of an octupole-corrected palaeolatitude value (θ) is based on the observed inclination (I) in the formula (from equations 6.2.5 and 6.2.6 of Merrill *et al.*, 1998; ignoring a possible quadrupole field):

$$\tan I = [2\cos\theta + \mathrm{G3}(10\ \cos^3\theta - 6\ \cos\theta)][\sin\theta + \mathrm{G3}(7.5\ \cos^2\theta\sin\theta - 1.5\ \sin\theta)]^{-1}.$$

Following the procedures of determining G3 from the data of a single continent (see Van der Voo and Torsvik, 2001), we have attempted to analyse the internal consistency of the Tertiary data from central Asia, by plotting observed vs. internally predicted palaeolatitudes against each other. However, the area comprising all the sites (Fig. 2) does not have a large enough latitudinal extent and the data have too much variation in their observed inclinations to yield a statistically significant plot; nonetheless, the analysis yields a best estimate, albeit not statistically significant, of a G3 value of 0.1.

More successfully, we have resorted to a second approach, which uses first a comparison between observed palaeolatitudes of the central Asian sites (as calculated with the dipole formula) and

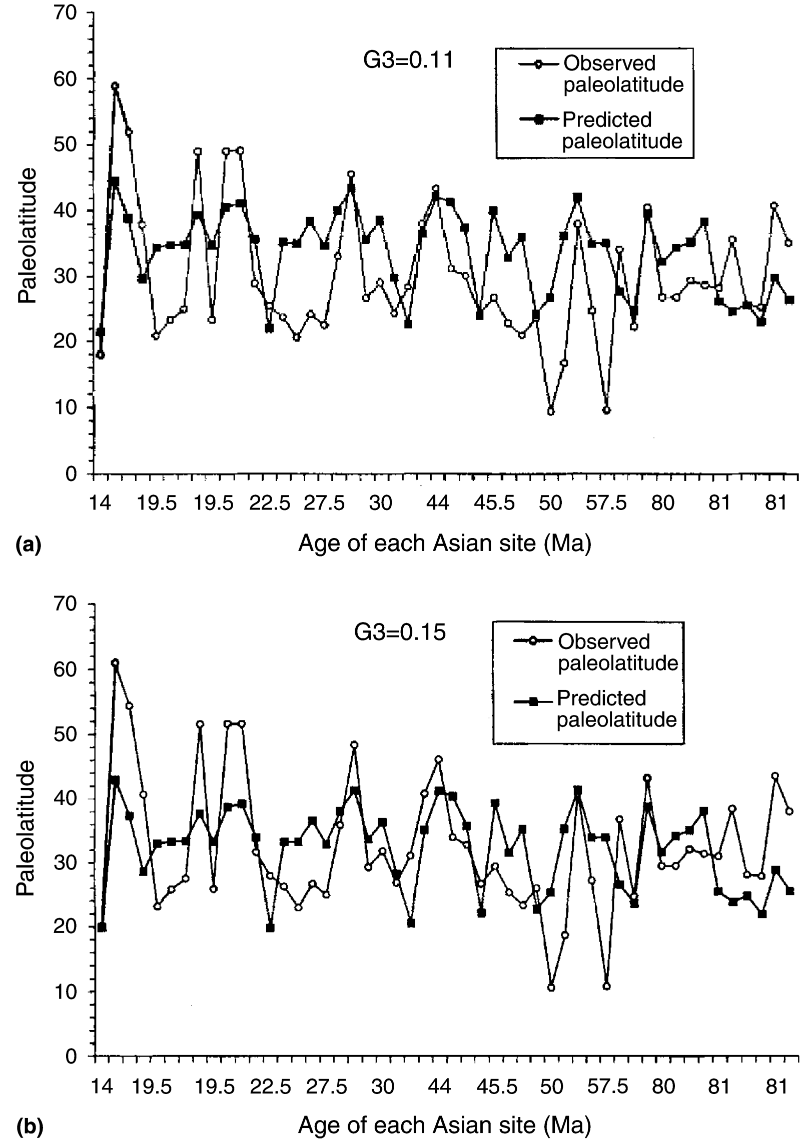

Fig. 5 (a) Observed and predicted palaeolatitudes for the central Asian sites, as calculated with a value of G3 (the octupole/dipole field ratio) of 0.11. Each result is separately plotted along the horizontal scale as a (non-linear) function of age. (b) Same as (a) but for G3 = 0.15.

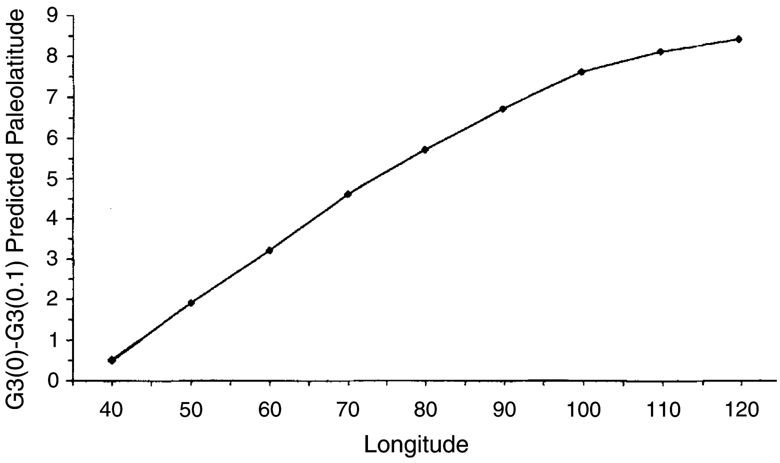

Fig. 6 The differences in predicted palaeolatitudes, as calculated with the geocentric axial dipole formula (G3 = 0) and with a field including a 10% octupole field contribution (G3 = 0.1), as a function of site longitude in Asia. Palaeolatitudes are calculated from the mean reference results obtained in the North Atlantic domain (Table 3), for sites in central Asia. The difference increases to reach a maximum at a longitude of 120°.

palaeolatitudes predicted from the Eurasian reference palaeopoles. Subsequently, both the observed and the predicted palaeolatitudes were adjusted by inclusion of a non-zero G3 in the calculation, using the formula presented earlier. If an octupole field can be held responsible for the palaeolatitude anomalies, we would expect these anomalies to diminish with increasing G3 and to vanish at an optimum G3 value.

Thus, reference Eurasian mean palaeopoles have been calculated for $G3 = 0$ (Table 3) as well as for $0 > G3 > 0.2$, using a 20-Myr moving window at 5-Myr increments. These mean Eurasian palaeopoles are then used to predict the palaeolatitudes for the Asian sampling sites, and these are compared with the palaeolatitudes obtained from the individual studies, which in turn are recalculated for the same G3 ratios as those used for the corresponding reference poles. As expected, the average palaeolatitude discrepancy diminishes with increasing G3 and vanishes for $G3 = 0.15$ (Fig. 4). There is, of course, variation from result to result in the palaeolatitude anomalies, as can be seen in examples of observed and predicted palaeolatitude sets as shown in Fig. 5 for $G3 = 0.11$ and $G3 = 0.15$.

Discussion

We have tested the possibility that a non-dipole field, as documented for the 300–40 Ma interval from North American and European palaeopoles (Van der Voo and Torsvik, 2001), can be held responsible for the palaeolatitude discrepancies that are observed in central Asia. We grant that we cannot exclude contributions to these discrepancies from other processes, notably inclination shallowing and – to some extent – relative convergent movements between blocks in central Asia and Siberia or between Siberia and Europe, but argue that all of the latter are unlikely to be of the magnitude to explain the discrepancies in full. Our study demonstrates that a long-term non-dipole field is a viable contender in the array of possible explanations.

In Fig. 4, we see that for $G3 = 0.11$, the mean difference between observed and predicted palaeolatitudes (plus or minus its standard deviation) is $-3.72 \pm 9.34°$, whereas the mean difference becomes zero at $G3 = 0.15$. However, we cannot conclude that the latter value is a better determination of the octupole field than the $G3 = 0.11$ value, for at least two reasons. The first is that the standard deviations overlap with the zero line for the range of G3 values of about 0.06 or greater, and the second reason is that some inclination shallowing and some relative northward movements, although less than the full 1600 km required by the dipole formula, have likely taken place.

The observation (Chauvin *et al.*, 1996) that the palaeolatitude anomalies increase eastward from the Mediterranean to China is easily explained by the effects of the octupole field on the predicted palaeolatitudes, when using an APWP determined from sites in the North Atlantic domain (Fig. 6). With the mean reference site location centred at a longitude of about 300° (see Table 3), the largest changes in predicted palaeolatitudes will occur at a longitude of 120°, and will be progressively less at lower longitudes.

Conclusions

One of the more likely explanations for the large discrepancies between observed and predicted palaeolatitudes in Asia during the latest Cretaceous and Tertiary can be found in the contribution of a long-term non-dipole field to the total time-averaged geomagnetic field. Our analysis yields an estimate of the octupole/dipole ratio greater than 0.06. This value is about the same as the ratio of 0.05–0.06 in the Oligocene estimated by Schneider and Kent (1990), and is not inconsistent with the Cretaceous – Early Tertiary values of about 0.08 and 0.1, as estimated by Torsvik *et al.* (2001a) and Van der Voo and Torsvik (2001), respectively. Even though only a ratio of 0.15 can reduce the average palaeolatitude anomaly to zero, we allow that some northward movements (~ 100s of km, not 1000s) of the central Asian terranes may have occurred, and that some degree of inclination shallowing certainly cannot be ruled out.

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