Geophys. J. Int. (2005) **163,** 944–948 doi: 10.1111/j.1365-246X.2005.02802.x

Shallow bias in Neogene palaeomagnetic directions from the Guide Basin, NE Tibet, caused by inclination error

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Accepted 2005 September 12. Received 2005 September 1; in original form 2005 May 4

SUMMARY

Too-shallow inclinations have frequently been observed in Cenozoic sedimentary strata in central Asia, and new palaeomagnetic results obtained by us from the Guide Basin in NE Tibet are no exception. We use a statistical analysis technique developed by Tauxe and Kent (TK03.GAD), which is based on a geomagnetic field model that predicts distributions of palaeomagnetic directions, and show that the too-shallow Neogene mean inclination (44 °) from 627 sites can be corrected to a value of 58 °, which closely matches the inclination predicted for the area. We conclude that syn- to post-depositional flattening is the most likely cause for the widely observed inclination bias in central Asia.

Key words: geocentric axial dipole, inclination shallowing, Neogene, palaeomagnetism.

1 INTRODUCTION

The palaeomagnetic inclination, as a record of palaeolatitude, is crucial to tectonic interpretations of palaeomagnetic data and in palaeogeographic reconstructions. However, many palaeomagnetic data obtained from sediments appear to show a pronounced bias towards too-shallow inclinations, with respect to reference apparent polar wander paths. Such inclination deviations of 10–30 ° have been widely observed in central Asia, and have led to a variety of suggestions about the causes and mechanisms that produced these anomalies. Because the low inclination values for sedimentary rocks as young as Pliocene are inconsistent with a geocentric axial dipole (GAD) model, it has been proposed that the anomalies are caused by global or local non-dipole field effects (Chauvin *et al.* 1996; Si & Van der Voo 2001; Westphal 1993). Other suggestions, in addition to

(1) an octupole field, have included arguments for
(2) erroneous age determination of red beds,
(3) northward displacement of central Asian terranes with respect to the Siberian craton,
(4) displacements between the Siberian core of Asia and Europe,
(5) inaccurately defined Eurasian reference poles or
(6) flattening or compaction of sediments caused by syn- or post-depositional processes (i.e. Chauvin *et al.* 1996; Chen *et al.* 2002a,b; Cogné *et al.* 1999; Dupont-Nivet *et al.* 2002a,b, 2003; Gilder *et al.* 2001, 2003; Tan & Kodama 1996; Tan *et al.* 2003; Thomas *et al.* 1994). A combination of any of these possible causes is, of course, also a possibility. The causes of too-shallow inclinations in the region are still not clear. We can exclude numbers 2 through 5 above as causes for inclination shallowing if we study young formations as the expected direction is well constrained and they cannot have travelled very far. To this end, we present here a set of well-determined Neogene palaeomagnetic directions based on 627 stratigraphic horizons from red bed sections in Tibet. These, like the older red bed units, have mean directions that are significantly shallower than the inclinations expected at the locations. We apply a recently developed method (Tauxe & Kent 2004) for progressively 'unflattening' the directions based on the assumption of sedimentary flattening until the elongation and inclination of the resulting data set matches those expected from a statistical geomagnetic field model (TK03.GAD). This so-called 'elongation/inclination' method predicts a mean inclination for the red bed data presented here.

2 GEOLOGICAL SETTING

The studied area is the Guide Basin, centred at about 36 °N, 101.5 °E in the NE Tibetan Plateau (Fig. 1). This basin is one of the large intramontane molasse basins, such as the Qaidam, Gonghe, Qinghai Lake and Longzhong basins, in which thick sequences of Cenozoic sediments accumulated. In the Guide Basin, these beds unconformably overlie Precambrian and Triassic basement rocks. The Cenozoic strata have been divided into two groups: the Palaeogene Xining Group (likely Oligocene or perhaps Eocene in age) and the Guide Group (∼20.8–1.8 Ma) (Fang *et al.* 2005; Parés *et al.* 2003; Song *et al.* 2001; Yan *et al.* 2005). The basin is drained by the Yellow River and its tributaries; the river has incised more than 900 m into the Cenozoic strata, which are—as a result—well exposed.

Because for sediments older than Late Miocene, the ages are still somewhat preliminary (Fang *et al.* 2005), we focus here only on those formations within the Guide Group that have well-constrained ages (1.8 to ∼11.5 Ma). Samples were collected at six localities (1–6, Fig. 1). Sampling was done with magnetostratigraphy in mind,

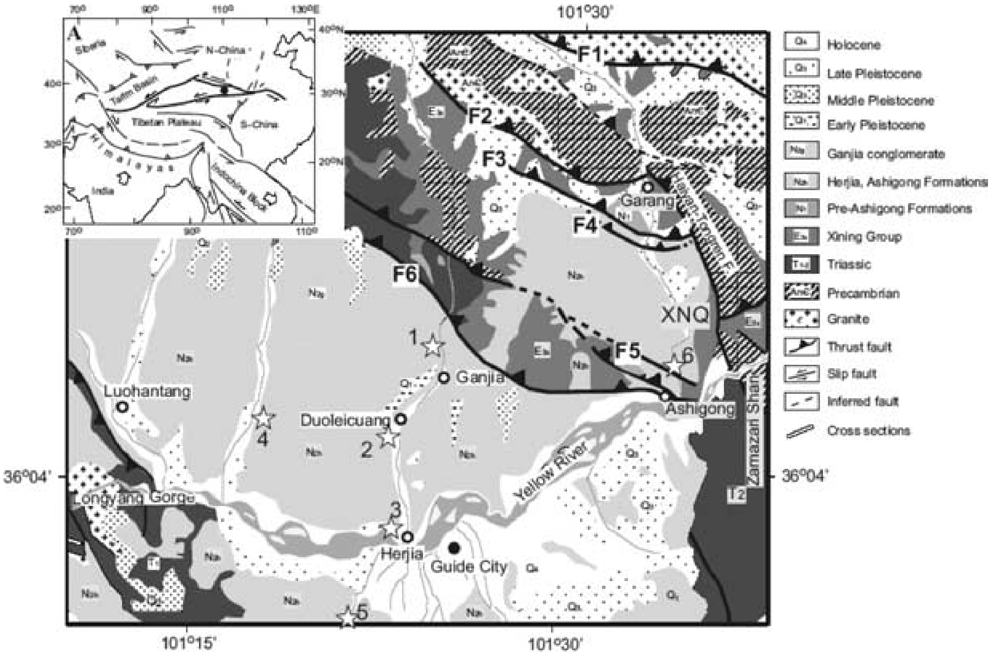

Figure 1. (a) Schematic map of Central Asia, showing the location (dot) of the Guide Basin in the NE Tibetan Plateau. (b) Simplified geological map of the northern part of the Guide Basin. The light-grey colours (Q_1, N_{2g}, N_{2h}) are the dominant Neogene sediments (units 2, 3 and 4–5, respectively; Fang et al. 2005), whereas the darkest colours represent the Triassic and Precambrian basement rocks. Stars with numbers 1–6 show the locations of the studied palaeomagnetic sections.

Table 1. Section-based mean directions and means for four successive time intervals, as well as their predicted inclinations with estimated 95 per cent confidence bounds by 'elongation/inclination' method (Tauxe & Kent 2004). N is the number of sites (stratigraphic levels) included in the mean directions. Dec and Inc are declination and inclination (in °), respectively; α_{95} and k are the statistical parameters associated with the mean directions. All of the Fisherian statistics are 'no', indicating an elliptical distribution of the observed palaeomagnetic directions. Note that, when N is close to or less than 100, the predicted inclinations, Inc (EI), have very large ranges of 95 per cent confidence bounds, making them less reliable. 1–6* is observed mean direction of all six localities (see Fig. 1 for locations). 1–6** is rotation-corrected mean directions of all six localities, obtained by rotating each mean declination of the four time intervals to their common mean of 1.7° in 1–6*.

Section based	Locality	Age range (Ma)	Dec	Inc	a95	N	k	Fisherian	Inc(EI)	95 per cent range
	1	∼2.6–11.5	2.4	47.1	2.9	302	9	no	59.6	53–69
	2	3.1–4.2	2.9	39.4	7.3	38	11	no	47.5	39–62
	3	4–6	360	37.4	6.5	66	8	no	40.9	36–54
	4	∼2.6–6	358.3	40.5	3.7	136	12	no	53.3	44–65
	5	4–5	359.3	39.6	9.6	32	8	no	44.8	37–64
	6	9.5–11.5	8.1	42.9	8.1	53	7	no	49.3	44–66
Time interval based	1, 2, 4	∼2.6–3.6	356.6	45.5	6.5	89	6	no	50.9	45–67
	1–5	3.6–6.5	358.9	42.5	2.6	327	10	no	55.2	49–62
	1	6.5–9.5	8.5	45.6	5.4	103	8	no	54.6	46–69
	1, 6	9.5–11.5	8.3	46.7	5.1	108	8	no	49.4	46–62
	1–6*	**∼2.6–11.5**	**1.7**	**44**	**2.1**	**627**	**8**	**no**	**57.7**	**53–64**
	1–6**	**∼2.6–11.5**	**1.5**	**44**	**2**	**627**	**8**	**no**	**57.1**	**52–62**

so palaeomagnetic sites are defined as particular horizons (∼2–5 m apart) within stratigraphic sections that were measured in detail. At each sampling level (site), at least three oriented cubic specimens (2 × 2 × 2 cm) were obtained. The palaeomagnetic and magnetostratigraphic results from these localities have been previously described (Fang *et al.* 2005; Parés *et al.* 2003; Yan *et al.* 2005); they are summarized here in Table 1, with mean directions given for each of the six localities and for four time intervals included in the Late Miocene (∼11.5 Ma) to Late Pliocene (2.6 Ma).

Only thermal demagnetization has been performed, in about 15 steps from room temperature to 685 °C, or until the intensity was near the noise level of the cryogenic magnetometer. At least four successive steps were used for the calculation of a sample's characteristic direction (ChRM) with principal component analysis (Kirschvink 1980), guided by visual inspection of orthogonal demagnetization diagrams; these ChRM directions pass reversal tests (see details in Fang *et al.* 2005, and Parés *et al.* 2003). The final mean direction for a site with multiple demagnetized specimens was obtained by Fisher averaging of the ChRM directions from the three specimens for that site. Only directions with maximum angular deviation (MAD) angles less than 10° were selected for our purpose.

3 RESULTS

We plot the 627 ChRM directions of the six localities (sections) with MAD angles less than 10° in Fig. 2(a). Section means and

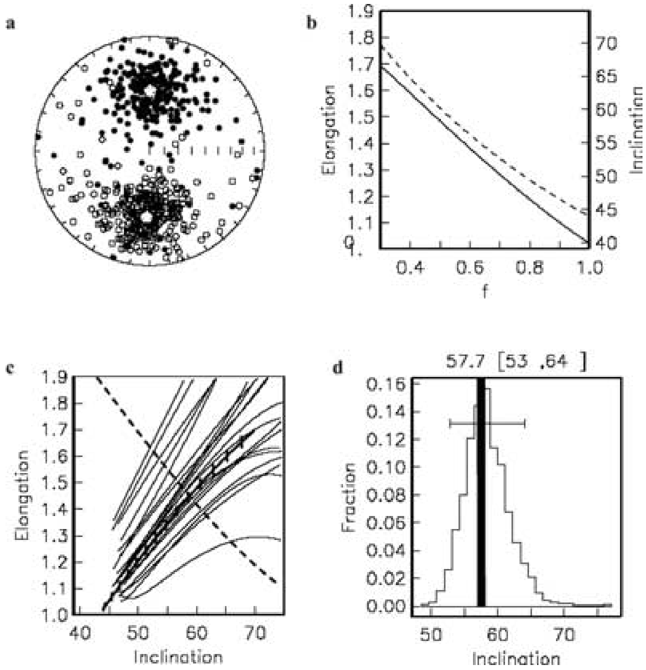

Figure 2. (a) Palaeomagnetic directions of Late Miocene–Late Pliocene sediments from the Guide Basin, NE Tibetan Plateau. The mean directions (white stars) are $D = 0.7^\circ$, $I = 46.5^\circ$ and $D = 182.6^\circ$, $I = -42.7^\circ$ for normal and reversed polarities, respectively (Table 1). The overall mean inclination (after inverting the *R*-directions) is $\sim 44.0^\circ$ (Table 1). (b) Plot of elongation (solid line) and inclination (dashed line) as a function of flattening parameter f (see text for explanation). (c) Plot of elongation versus inclination for the TK03.GAD model (dashed line) and for the Guide data (barbed thick line), for different values of f. Also shown are examples of results from 20 bootstrapped data sets. The crossing points represent the inclination/elongation pairs most consistent with the TK03.GAD model. (d) Histogram of crossing points from 1000 bootstrapped data sets. The most frequent inclination (58°) is in good agreement with those predicted from the Besse & Courtillot (2002) Eurasian APWP (57° at 3.1 Ma and 58° at 11.9 Ma) (shown as the heavy vertical line). The 95 per cent confidence bounds on this estimate are 53–64 (shown as the thin horizontal line).

means of four time intervals are listed in Table 1. The overall mean of these directions is $D = 1.7^\circ$, $I = 44.0^\circ$, $\alpha_{95} = 2.1^\circ$ ($D_{\text{normal}} = 0.7^\circ$, $I_{\text{normal}} = 46.5^\circ$, $D_{\text{reversed}} = 182.6^\circ$, $I_{\text{reversed}} = -42.7^\circ$. The expected inclinations from the Eurasia reference poles (Besse & Courtillot 2002) are 56.6° (pole at 86.7°N, 178.7°E at 3.1 Ma) and 58.1° (85°N, 155.7°E at 11.9 Ma). The observed mean inclination is, therefore, more than 12° shallower than that expected in the Guide Basin.

The shallowing of the inclination observed in the Guide Basin could result from a variety of causes as discussed in the introduction. Sedimentary inclination error is one of the possible causes. We expect that inclination error will follow the well-known formula $\tan I_o = f \tan I_f$ (King 1955), where I_o is the observed inclination, I_f is the applied field inclination and f is the flattening factor. We can, therefore, 'unflatten' the directions in Fig. 2(a) by the inverse of the inclination error formula. After unflattening all the directions by a given value for f (ranging from 1 to 0.3), we calculate a new mean inclination. We plot the variation of the mean inclination as a function of f as the dashed line in Fig. 2(b). Also shown is the 'elongation' of each unflattened data set, where elongation is defined as in Tauxe (1998). Elongation ranges from near circular symmetry in the original data set, to rather elongate in the data set adjusted by an f of 0.3. Therefore, elongation and inclination increase with progressive unflattening.

The question arises, what distribution of directions do we expect from the geomagnetic field. To address this issue, Tauxe & Kent (2004; see also Kent & Tauxe 2005 and Krijgsman & Tauxe 2004) developed a simple statistical model for the geomagnetic field that predicts directional distributions as a function of latitude. Their model was designed to fit the palaeosecular variation data from lava flows from the last 5 million years. The key features of the model (and the lava flow data) are that the distributions of virtual geomagnetic poles (VGPs) are essentially circularly symmetric regardless of sampling location. The immediate consequence of that is that the directional dispersion is not circularly symmetric except for observation sites at high latitudes. Therefore, elongation (as defined by Tauxe 1998) increases as the observation site approaches the equator. Inclination, of course, follows the dipole formula. There is, therefore, a unique elongation/inclination curve that is consistent with the behaviour of the geomagnetic field for the last 5 million years. This predicted curve is shown as the dashed line in Fig. 2(c).

We replot the elongation and inclination pairs calculated for progressive values of f in Fig. 2(b) as the heavy barbed line in Fig. 2(c). This curve intersects the curve predicted from the statistical field model with an inclination of about 58 arrived at using a value for f of about 0.55 and in excellent agreement with the expected value. To assess the uncertainty of this estimate, we repeat the analysis on bootstrapped samples of the data (20 examples are shown as thin lines in Fig. 2c). In Fig. 2(d) we plot a histogram of all inclinations derived from the bootstrapped crossing points as well as the 95 per cent confidence bounds (53°–64°) on either side of the mode at 57.7°. Shown for comparison (heavy vertical line) is the inclination band expected for these sections illustrating the excellent agreement of the 'corrected' inclination with the expected value.

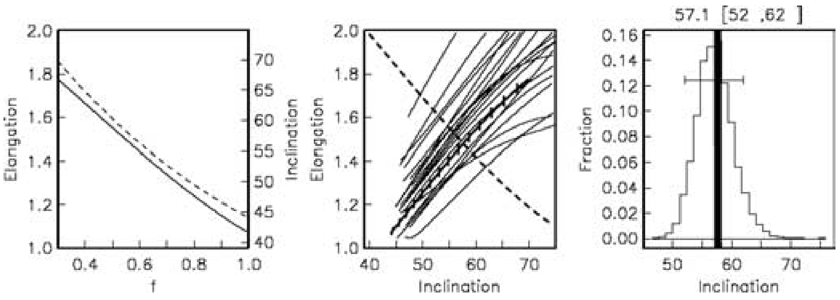

Figure 3. The 'elongation/inclination' method applied to the rotation-corrected Guide Data (see details in Table 1). Other details as in Fig. 2. The small difference in predicted inclinations before and after rotational correction indicates that the minor rotations in the basin do not have a significant influence on the inclination correction.

4 DISCUSSION

A significant inclination bias has been observed in the Guide Basin: the observed inclination departs from that extrapolated from the Neogene Eurasian reference palaeopole by more than 12°. This magnitude of inclination shallowing is quite similar to other values that have been reported for this region (∼10–30°).

Because our analysis involves inclinations that are consistently too shallow over the entire age range from Late Miocene to Late Pliocene (at ∼2.6 Ma) (i.e. no significant difference in inclination among the four subsets, as listed in Table 1), we are confident that we can exclude a corresponding northward drift of the terranes with respect to Siberia, as well as relative motions between Siberia and Europe, as the cause of the anomalies. Such relative motions would simply be too fast, on the order of 10° over a time span of 2.5 million years (40 $\mathrm{cm\,yr^{-1}}$), to be realistic. The well-dated formations of this study also preclude erroneous age dates as an explanation for the inclination anomalies, whereas the Eurasian reference poles for Miocene and Pliocene time are unlikely to be erroneous by as much as 10°.

According to Tauxe & Kent's (2004) model, the elongation of the observed directions does not correspond to that expected if the shallowing were to be caused by an octupole field. The observation that Cenozoic to Upper Jurassic igneous rocks in the region do not show the shallowing (Bazhenov & Mikolaichuk 2002; Gilder *et al.* 2003) also argues for a mechanism for the shallowing that is associated with sedimentary rocks and not with non-dipole fields. It now seems unlikely, therefore, that the persistently shallow inclinations in central Asia are to be attributed to a non-dipole field.

Thus we conclude that sedimentary flattening is the most likely cause for the shallowing of the inclinations in the Guide Basin. Studies of the remanence anisotropy and rock magnetism of Tan *et al.* (2003) also suggest that the anomalously shallow inclinations in central Asia are due to sedimentary effects. This confirms and supports the analysis of Tauxe & Kent (2004), who applied their method to shallow inclination results from Subei in the NE Tibetan Plateau, obtained by Gilder *et al.* (2001). These results could also be successfully corrected.

A companion study has suggested that there may have been minor rotations in the basin since the Late Miocene (Yan *et al.* 2005). In case this caused a pseudo-correction of the inclination due to rotations, all palaeomagnetic data of the four subsets in Table 1 were rotated so that their mean declinations coincide with the common mean at 1.7° (Table 1**). Then they were analysed with the 'elongation/inclination' method as shown in Figs 3(a–c). The predicted inclination of 57.1° with estimated 95 per cent confidence bounds of 52°–62°, shows almost no difference with the previously mentioned predicted inclination of 57.7° and 95 per cent confidence bounds of 53°–64° (Table 1, Fig. 2), indicating that these minor rotations have no significant influence on the inclination corrections.

The Tauxe and Kent's (2004) 'elongation/inclination' method usually requires large palaeomagnetic data sets (typically more than hundred sites), and the bigger the data set, the more precise the predicted inclination. The predicted inclination of 58° in the Guide Basin matches very well with expected values of 57° at 3.1 Ma and 58° at 11.9 Ma, and this success can be attributed to the size of our huge data set ($N = 627$).

ACKNOWLEDGMENTS

This work has been funded by the US National Science Foundation, Division of Earth Sciences, Grant EAR 9903074 to R. Van der Voo and J. M. Parés, and through grants from the University of Michigan's Scott Turner Fund to M. Yan (2001, 2002, 2003), as well as to X.M. Fang by the National Science Foundation of China (NSFC) (#49871010), the Chinese Academy of Science (RJZ[2002]005) and the National Project for Basic Research on Tibet Plateau (G1998040809). We would like to thank Yunfa Miao, Wei Yang and Libin Xiong for extensive help with the field work. Comments by the journal's reviewers Stuart Gilder and Ken Kodama helped improve this paper.

REFERENCES

Bazhenov, M.L. & Mikolaichuk, A., 2002. Palaeomagnetism of Paleogene basalts from the Tien Shan, Kyrgyzstan: rigid Eurasia and dipole geomagnetic field, *Earth planet. Sci. Lett.,* **195,** 155–166.

Besse, J. & Courtillot, V., 2002. Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr, *J. geophys. Res.,* **107**(B11), 2300, doi:10.1029/2000JB000050.

Chen, Y., Gilder, S., Halim, N., Cogné, J.-P. & Courtillot, V., 2002a. New Mesozoic and Cenozoic palaeomagnetic data help constrain the age of motion on the Altyn Tagh fault and rotation of the Qaidam basin, *Tectonics,* **21**(5), 1042, doi:10.1029/2001TC901030.

Chen, Y., Wu, H., Courtillot, V. & Gilder, S., 2002b. Large N–S convergence at the northern edge of the Tibetan Plateau? New Early Cretaceous palaeomagnetic data from the Hexi Corridor, NW China, *Earth planet. Sci. Lett.,* **201,** 293–307.

Cogné, J.P., Halim, N., Chen, Y. & Courtillot, V., 1999. Resolving the problem of shallow magnetizations of Tertiary age in Asia: Insights from palaeomagnetic data from the Qiangtang, Kunlun, and Qaidam blocks (Tibet, China), and a new hypothesis, *J. geophys. Res.,* **104**(B8), 17 715–17 734.

Dupont-Nivet, G., Butler, R.F., Yin, A. & Chen, X., 2002a. Palaeomagnetism indicates no Neogene rotation of the Qaidam basin in north Tibet during Indo-Asian collision, *Geology,* **30**(3), 263–266.

Dupont-Nivet, G., Guo, Z., Butler, R.F. & Jia, C., 2002b. Discordant palaeomagnetic direction in Miocene rocks from the central Tarim Basin: evidence for local deformation and inclination shallowing, *Earth planet. Sci. Lett.,* **199,** 473–482.

Dupont-Nivet, G., Butler, R.F., Yin, A. & Chen, X., 2003. Palaeomagnetism indicates no Neogene rotation of the Northeastern Tibetan Plateau, *J. geophys. Res.,* **108**(B8), 2386, doi:10.1029/2003JB002399.

Chauvin, A., Perroud, H. & Bazhenov, M.L., 1996. Anomalous low palaeomagnetic inclinations from Oligocene-Lower Miocene red beds of the south-west Tien Shan, central Asia, *Geophys. J. Int.,* **126,** 303–313.

Fang, X.M. *et al.*, 2005. Late Cenozoic deformation and uplift of the NE Tibetan plateau: evidence from high resolution magnetostratigraphy of the Guide Basin, Qinghai Province, China, *Geological Society of America Bulletin,* **117,** 1208–1225.

Gilder, S., Chen, Y. & Sen, S., 2001. Oligo-Miocene magnetostratigraphy and environmental magnetism of the Xishuigou section, Subei (Gansu Province, western China): further implication on the shallow inclination of central Asia, *J. geophys. Res.,* **106,** 30 505–30 521.

Gilder, S., Chen, Y., Cogné, J.P., Tan, X., Courtillot, V., Sun, D. & Li, Y., 2003. Palaeomagnetism of Upper Jurassic to Lower Cretaceous volcanic and sedimentary rocks from the western Tarim Basin and implications for inclination shallowing and absolute dating of the M-0(ISEA?) chron, *Earth planet. Sci. Lett.,* **206,** 587– 600.

Kent, D.V. & Tauxe, L., 2005. Corrected Late Triassic latitudes for continents adjacent to the North Atlantic, *Science,* **307,** 240–244.

King, R.F., 1955. The remanent magnetism of artificially deposited sediments, *Mon. Not. Roy. Astr. Soc., Geophys. Suppl.,* **7,** 115–134.

Kirschvink, J.L., 1980. The least-square line and plane and the analysis of palaeomagnetic data, *Geophys. J. R. astr. Soc.,* **62,** 699–718.

Krijgsman, W., Langereis, C.G., Daams, R. & van der Meulen, A.J., 1994. Magnetostratigraphic dating of the middle Miocene climate change in the continental deposits of the Aragonian type area in the Calatayud–Teruel basin (central Spain), *Earth planet. Sci. Lett.,* **128,** 513–526.

Krijgsman, W. & Tauxe, L., 2004. Shallow bias in Mediterranean palaeomagnetic directions caused by inclination error, *Earth planet. Sci. Lett.,* **222,** 685–695.

Parés, J.M., Van der Voo, R., Downs, W.R., Yan, M.D. & Fang, X.M., 2003. Northeastward growth and uplift of the Tibetan Plateau: magnetostratigraphic insights from the Guide Basin, *J. geophys. Res.,* **108,** 1–11.

Si, J. & Van der Voo, R., 2001. Too-low magnetic inclinations in central Asia: an indication of a long-term Tertiary non-dipole field?, *Terra Nova*, **13,** 471–478.

Song, C., Fang, X.M., Gao, J., Sun, D. & Fan, M., 2001. Cenozoic tectonic uplift and sedimentary evolution of the Guide Basin in the northeast margin of the Tibetan Plateau, *Sedimentology,* **19**(4), 498–506 (in Chinese with English abstract).

Tan, X. & Kodama, K.P., 1996, A preliminary study of the effect of compaction on the inclination of the redeposited hematite-bearing sediments disaggregated from Eocene redbeds (Suweiyi Fm) from the Tarim Basin, northwest China, *EOS, Trans. Am. geophys. Un.,* **77**(46), Fall Meeting Supplement, F155.

Tan, X., Kodama, K.P., Lin, H., Fang, D., Sun, D. & Li, Y., 2003. Palaeomagnetism and magnetic anisotropy of Cretaceous red beds from the Tarim basin, northwest China: evidence for a rock magnetic cause of anomalously shallow palaeomagnetic inclinations from central Asia, *J. geophys. Res.,* **108**(B2), 2107, doi:10.1029/2001JB001608.

Tauxe, L., 1998, *Paleomagnetic principles and practice*, Kluwer Academic Publishers, Dordrecht, 299 pp.

Tauxe, L. & Kent, D.V., 2004. A simplified statistical model for the geomagnetic field and the detection of shallow bias in palaeomagnetic inclinations: was the ancient magnetic field dipolar? in *Timescales of the Palaeomagnetic Field*, pp. 101–117. eds Channell, J.E.T., Kent, D.V. Lowrie, W. & Meert, J.G., Geophysical Monograph 145, American Geophysical Union, Washington, DC.

Thomas, J.-C., Chauvin, A., Gapais, D., Bazhenov, M.L., Perroud, H., Cobbold, P.R. & Burtman, V.S., 1994. Palaeomagnetic evidence for Cenozoic block rotations in the Tadjick depression (central Asia), *J. geophys. Res.,* **99**(B8), 15 141–15 160.

Westphal, M., 1993. Did a large departure from the geocentric axial dipole hypothesis occur during the Eocene? Evidence from the magnetic polar wander path of Eurasia, *Earth planet. Sci. Lett.,* **117,** 15–28.

Yan, M.D., Van der Voo, R., Fang, X.M., Parés, J.M. & Rea, D.K., 2005. Palaeomagnetic evidence for a mid-Miocene clockwise rotation of about 25° of the Guide Basin area in NE Tibet, *Earth planet. Sci. Lett.,* in press.