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Palaeomagnetic results from late Cretaceous and early Tertiary limestones from Tingri area, southern Tibet, China

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ABSTRACT

Palaeomagnetic studies have been carried out on the late Campanian (Zhepure Shanbei Formation: ZSbF), early Palaeocene (Zhepure Shanpo Formation: ZSpF) and early to mid-Eocene (Zhepure Shan Formation, member V: ZSFmV) limestones from the Tethyan Himalaya west of Tingri (28°48'N, 86°54'E) in southern Tibet (China). A primary component in the ZSbF is proven by normal and reverse polarity zones in a stratigraphic succession of uniform layers (1 site, 24 specimens). The inclination (-50.2°) approximately fits to the expected palaeolatitude of the area for late Campanian. However, this result has to be considered with caution because of non-antipodal remanence directions. The ZSpF shows a recent field direction only and is affected by gyroremanence acquisition. In contrast to results published earlier by Besse et al. (1984), no primary component could be identified in the ZSFmV. The characteristic remanence (ChRM) isolated in this unit (5 sites, 32 specimens) is most likely of secondary origin. The significance of the fold test is below the 95% level due to rather uniform bedding attitudes, but tilt corrected inclinations are unrealistically high for the area. The polarity of the ChRM is reverse and thus represents a palaeoremanence acquired sometimes between the Brunhes/Matuyama boundary and Eocene times. Declinations of Besse et al. (1984)'s primary direction and of our secondary component in the ZSFmV coincide and suggest that no rotation of the Tingri area occurred between Eocene and the time where the remanence was acquired.

INTRODUCTION

Apparent polar wander paths (APWP) document the convergence of the Indian and Eurasian plates (e.g. Besse and Courtillot, 1991). India's rapid drift rate of 15-20 cm/yr during late Cretaceous to Eocene time dropped to less than 5 cm/yr at 55-50 Ma (Patriat and Achache 1984, Klootwijk et al., 1985; Klootwijk et al., 1991). It is currently a matter of discussion whether this striking drop represents the initial collision or the complete closure between the Indian and Eurasian crust. Indication of collision around the Cretaceous/Tertiary (C/T) boundary were reported by Jaeger et al. (1989), Klootwijk et al. (1991) and Patzelt et al. (1996). Such an early collision requires a northward extended so-called 'Greater India'. Palaeomagnetic results for the Gamba and Duela areas in southern Tibet (Patzelt et al., 1996) indeed suggest that the northern margin of the Indian Plate exceeded its current outline by about 1500 km at the longitude of about 89°E around the C/T boundary. In contrast, Besse et al. (1984) derived from palaeomagnetic studies near Tingri (about 87°E) a measure of only a few hundred kilometres for the Greater India's northern extent during late Palaeocene.

Indications to oroclinal bending and rotational underthrusting models were obtained from declination data (Klootwijk et al., 1985; Appel et al., 1991; Patzelt et al., 1996). Steeper than expected inclinations in the Annapurna and Everest areas are due to northward tilting probably related to ramping along the Main Central Thrust (Appel et al., 1991; Rochette et al., 1994).

The Tethyan Himalaya represents the northernmost zone of the Indian Plate and as such is of key importance to establish its deformation history and to reconstruct the northern margin of India prior to collision. This paper reports a further palaeomagnetic investigation of limestones from the Tethyan Himalaya west of Tingri.

GEOLOGICAL SETTING

Principal tectonic units of the Himalayan arc are shown in Fig. 1. The Tethyan Sedimentary Series extend between the Indus-Yarlung suture zone to the north and the Higher Himalaya to the south. Our sampling area near Tingri (latitude 28°48'N, longitude 86°54'E; No. 4 in Fig. 1) is located about north of Mt. Everest. The dominant structural element is an east-west striking syncline, which forms an orographically prominent massif of about 40 km length, the Zhepure Mountain. A type section of the late Cretaceous to Eocene sequence (Fig. 3), the stratigraphically highest units in this area, was described by Willems and Zhang (1996).

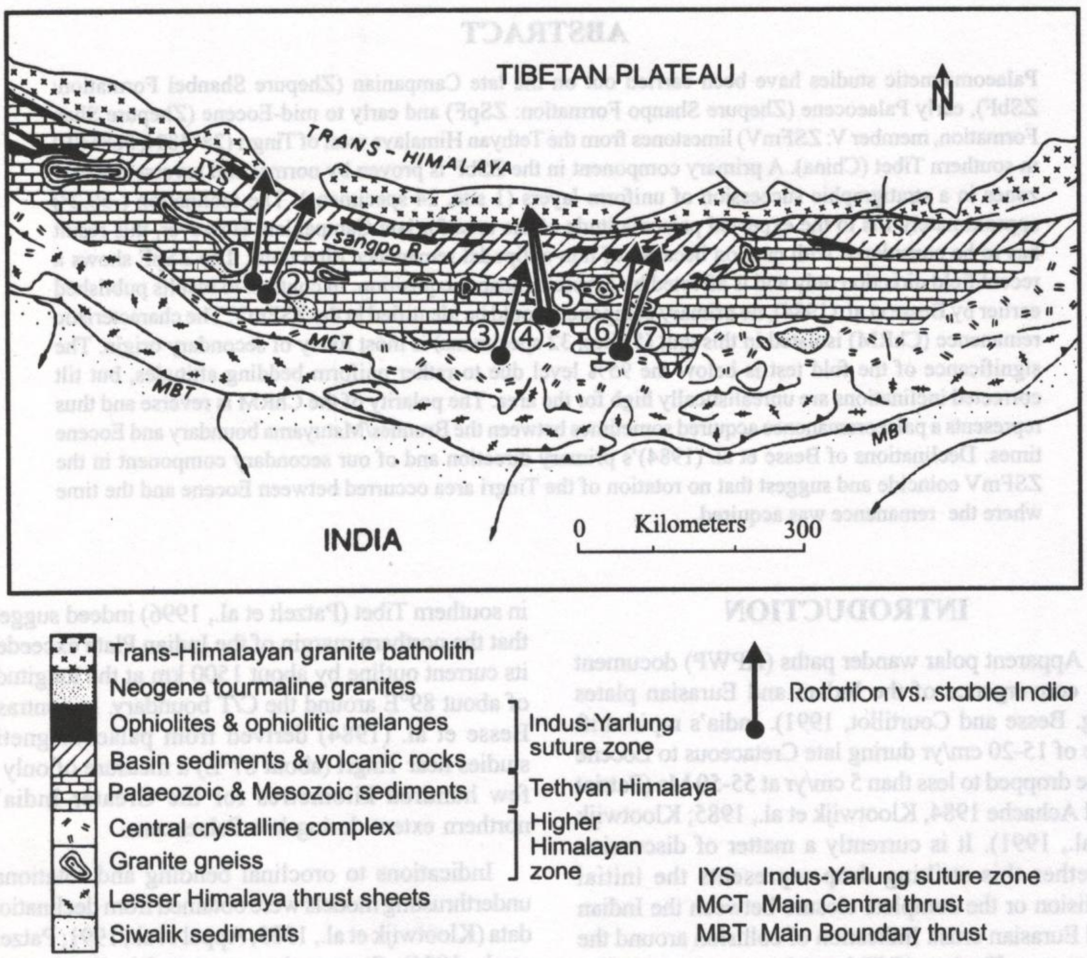

Fig. 1: Geological map modified after Searle et al. (1986). Arrows denote rotations relative to stable India determined from palaeomagnetic results. Legend: 1. Tethyan Himalaya (TH)/Thakkhola (Klootwijk and Bingham, 1980); 2. TH/Annapurna-NyiShang (Appel et al., 1991); 3. Everest-leucogranite (Rochette et al., 1994); 4. TH/Tingri (this paper); 5: TH/Tingri (Besse et al., 1984); 5. TH/Gamba-Duela, Zongpu (Patzelt et al., 1996); 6. TH/Gamba-Duela, Zongshan (Patzelt et al., 1996).

Table 1: Site information and statistical data. T3/4: Zhepure Shanbei Fm (ZSbF), H: Zhepure Shan Fm Mbr.V. (ZSFmV). N: number of specimens measured; spec. n/r: number of n(ormal) and r(everse) specimens used for statistics; bedding: dip arrow given by azimuth, dip.

Sample Site	Lithology	Age	N	Spec. n/r	Bedding	In situ Dec.	In situ Inc.	Tilt corrected Dec.	Tilt corrected Inc.	a95	k
T3/4	Limestone	Late Campanian	36	10/14	188,47	192.6	-82.8	7.1	-50.2	10.7	8.6
H64	Limestone	Early (to mid.?) Eocene	10	0/10	180,31	147.6	-45.2	111.1	-67.3	9.7	23.3
H65	Limestone	Early (to mid.?) Eocene	9	0/6	171,38	167.8	-41.2	160.6	-78.4	17.7	15.3
H67	Limestone	Early (to mid.?) Eocene	10	0/3	172,30	156.3	-52.2	117.4	-78.5	16.8	54.9
H68	Limestone	Early (to mid.?) Eocene	9	0/7	178,26	170.5	-33.4	165.1	-59.2	7.6	64.6
H69	Limestone	Early (to mid.?) Eocene	8	0/5	162,25	174.4	-60.0	217.2	-82.4	6.8	127
H71	Limestone	Early (to mid.?) Eocene	8		2,63	No significant result (scattering remanence directions)					
H72	Limestone	Early (to mid.?) Eocene	10		345,56	No significant result (low intensities after few demagnetization steps)					
H73/74	Limestone	Early (to mid.?) Eocene	13		223,26	No significant result (low intensities after few demagnetization steps)					

		In situ	Tilt corrected
Zhepure Shan Fm., Mbr. V (H64, H65, H67, H68 & H69)	N = 5 sites	163.2 -46.8 a95=12.9, k=41.3	147.3 -75.6 a95=13.1, k=34.8
	N = 31 specimens (all sites)	161.9 -45.4 a95=5.9, k=20.0	143.0 -73.4 a95=6.3, k=17.7

SAMPLING

Site locations are shown in Fig. 2 (bedding attitudes are given in Table 1). Core samples of 2.5 cm diameter were taken with a portable gasoline drill. Orientation was generally done by a magnetic compass. In the summer of 1992, a total of 13 sites (130 samples) were drilled in the early Palaeocene part of the Zhepure Shanpo Formation (ZSpF; 3 sites in thinly bedded nodular limestones, 2 sites in intercalated sandstone layers) and in the early to mid-Eocene part of the Zhepure Shan Formation, member V (ZSFmV; 8 sites in massive limestones). A further 36 samples have been obtained from thinly bedded limestones of the Zhepure Shanbei Formation at one site (ZSbF; 40 m thick succession). This site belongs to the type section of Willems and Zhang (1996), and the sampling was done already in the summer of 1986 for magnetostratigraphic purposes.

Site locations of Besse et al. (1984) and of our group are quite close together on the slopes of the Zhepure Mountain ridge (Fig. 2). However, the exact stratigraphic position of Besse et al. (1984)'s sites is confusing. They date their samples into late Palaeocene but according to their site description (top of the ridge), they must be expected to originate from the massive Eocene limestones.

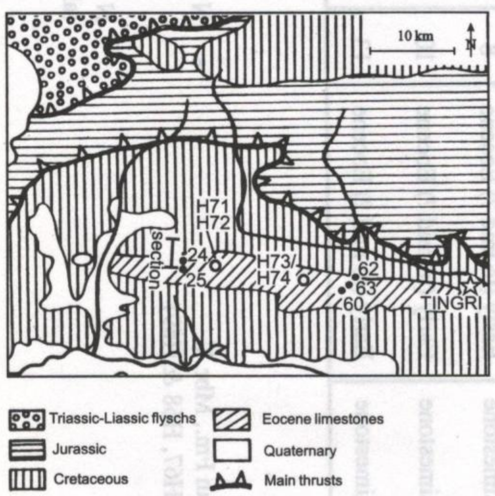

Fig. 2: Sampled area west of Tingri with site locations of this study (around 'section' and H71,72,73/74). Besse et al.'s (1984) sites are shown by numbers (24,25,60,62,63).

SAMPLE TREATMENT

The core samples were cut into specimens with a standard length of 2.2-2.3 cm. Identification of ferromagnetic minerals was based upon isothermal remanence acquisition (IRM) up to 1.6 Tesla and subsequent stepwise thermal demagnetisation of the saturation IRM (SIRM). In addition, the demagnetisation behaviour of the natural remanent magnetisation (NRM) was considered. Detailed stepwise cleaning was performed on duplicate specimens from selected samples. In each case, one of the specimens was subjected to alternating field treatment (AF) and the other specimen was thermally demagnetised (TH). The AF-treated specimens were subsequently used for IRM tests. Susceptibility measurements after each heating step were carried out to detect possible mineral alterations. Depending on the results of the pilot studies and magnetic mineral analyses, the bulk of the specimens was then demagnetised through application of the most suitable procedure, either by TH-treatment (using MTDM1 and Schonstedt furnaces), AF-treatment (using 2G and Highmoor AF demagnetisers), or a combination of both. Remanence directions were measured with cryogenic magnetometers (LETI Remanometre à Squid RS 01 from LETI with a noise level of about 0.02 mA/m, 2G Enterprises 755R with a noise level <0.01 mA/m and attached automatic degaussing system). Orthogonal vector plots and equal area projections were used to examine the demagnetisation behaviour of the specimens. Magnetic directions were determined mainly from straight segments of the demagnetisation path (modified PCA version after Kirschvink, 1980), and in part from stable end-point directions. Mean directions were calculated by using Fisherian statistics (Fisher, 1953).

RESULTS

Zhepure Shanbei Formation (ZSbF; Late Campanian)

IRM acquisition and thermal demagnetisation curves (Fig. 4a) prove magnetite as the dominant ferromagnetic mineral. In the stratigraphically upper

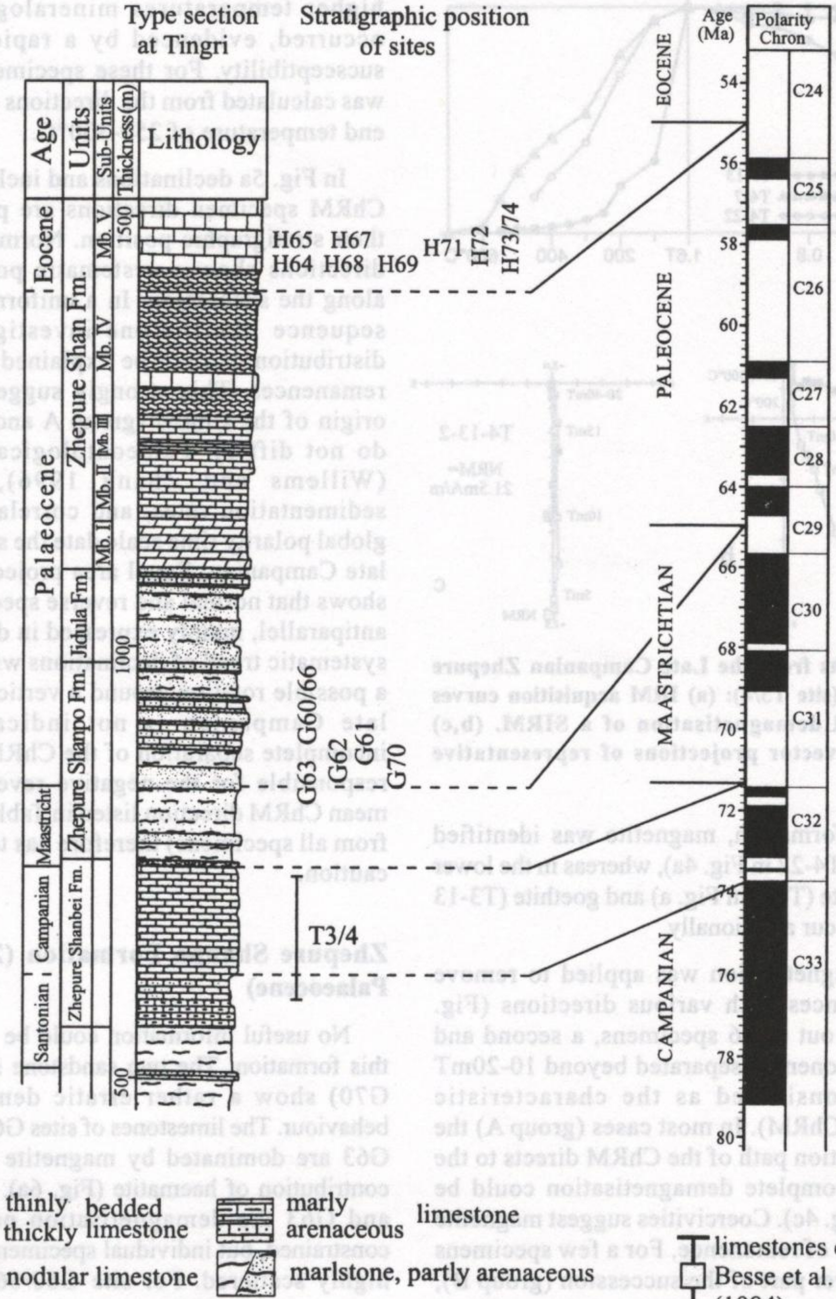

Fig. 3: Lithological sequence of the type section at Tingri (modified from Willems and Zhang, 1996) including the stratigraphic positions of sampling sites (horizontal numbers: sites from which results could be obtained; vertical numbers: sites with no results). The correlation to the polarity time scale (after Ogg, 1995) is based on biostratigraphy (Willems and Zhang, 1996), and polarity of magnetic remanences.

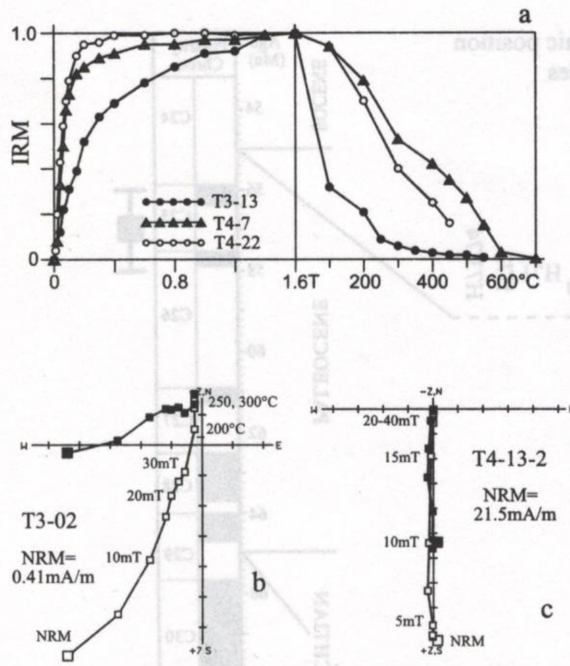

Fig. 4: Results from the Late Campanian Zhepure Shanbei Fm (site T3/4): (a) IRM acquisition curves and thermal demagnetisation of a SIRM. (b,c) Orthogonal vector projections of representative samples.

part of the formation, magnetite was identified exclusively (T4-22 in Fig. 4a), whereas in the lower part, haematite (T4-7 in Fig. a) and goethite (T3-13 in Fig. 4a) occur additionally.

AF demagnetisation was applied to remove soft remanences with various directions (Fig. 4b,c). In 24 out of 36 specimens, a second and harder component is separated beyond 10-20mT which is considered as the characteristic remanence (ChRM). In most cases (group A) the demagnetization path of the ChRM directs to the origin and complete demagnetisation could be achieved (Fig. 4c). Coercivities suggest magnetite as the carrier of remanence. For a few specimens from the lower part of the succession (group B), the AF demagnetisation path did not direct towards the origin (Fig. 4b), and subsequently TH demagnetisation was applied. A sudden drop of intensity at the first step of 200°C indicates the presence of goethite. The 200-300°C trajectory shows progressing demagnetisation pointing to a residual magnetite or haematite component. At higher temperatures mineralogical changes occurred, evidenced by a rapid increase of sucsceptibility. For these specimens the ChRM was calculated from the directions obtained at the end temperature of 250-300°C.

In Fig. 5a declinations and inclinations of the ChRM specimen directions are plotted against their stratigraphic position. Normal and reverse directions show a systematic polarity pattern along the succession. In a uniform sedimentary sequence like the one investigated, such a distribution can not be explained by secondary remanences. This strongly suggests a primary origin of the ChRM (group A and B specimens do not differ). Palaeontological indications (Willems and Zhang 1996), reasonable sedimentation rates, and correlation with the global polarity time scale date the succession into late Campanian. Equal area projection (Fig. 5b) shows that normal and reverse specimens are not antiparallel, mainly expressed in declinations. A systematic trend of declinations with time due to a possible rotation around a vertical axis during late Campanian is not indicated. Hence, incomplete separation of the ChRM seems to be responsible for the negative reversal test. The mean ChRM direction listed in Table 1 (calculated from all specimens) therefore has to be used with caution.

Zhepure Shanpo Formation (ZSpF; Early Palaeocene)

No useful information could be obtained from this formation. The two sandstone sites (G62 and G70) show a rather erratic demagnetisation behaviour. The limestones of sites G60/66, G61 and G63 are dominated by magnetite with a minor contribution of haematite (Fig. 6a). For sites G61 and G63 the demagnetisation paths are well constrained, but individual specimen directions are highly scattered. For site G60/66 a consistent component could be isolated in low AF fields, however, matching the present field direction (Fig. 6c). At fields higher than about 30-50 mT a gyromagnetic remanence was acquired, evidenced by deflection of the remanence towards the direction perpendicular to the last AF field direction (e.g. Stephenson, 1980).

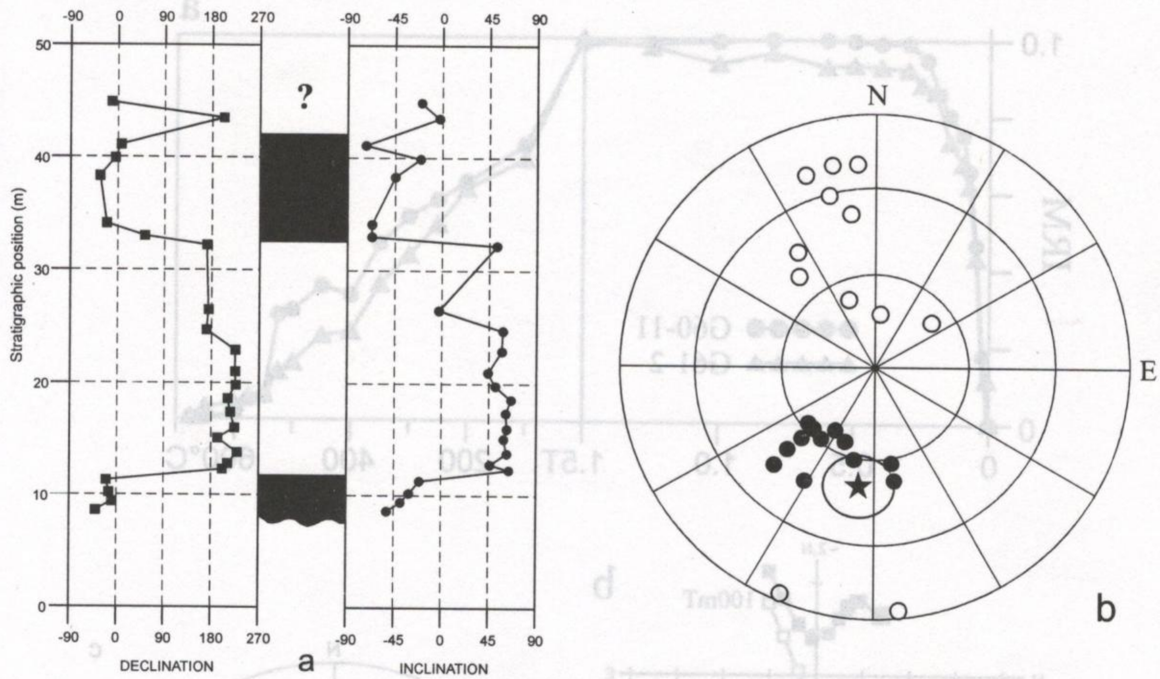

Fig. 5: Results from the Late Campanian Zhepure Shanbei Fm (T3/4): (a) Declinations, inclinations of tilt corrected ChRM directions and magnetic polarity pattern along the stratigraphic succession, (b) Equal area projection of tilt corrected ChRM. Open and closed symbols denote negative and positive inclinations respectively. The mean direction (normal and reverse specimens) is shown by the star with α95 confidence limit.

Zhepure Shan Formation, Member V (ZSFmV; Early to Mid-Eocene)

IRM curves (Fig. 7a) identify magnetite as the dominating magnetisation carrier with varying contribution of haematite. The presence of maghemite can be concluded from the thermal decay of SIRM between 300-400°C.

During heating above about 400°C, mineral alteration is indicated by an increase of susceptibility. AF treatment provides more stable demagnetisation curves than thermal, and thus was selected as the standard procedure. Two sites, H72 and H73/74, have generally very low NRM intensities, and no valuable results could be obtained for this reason. The remaining 6 sites show a well defined two component behaviour during AF demagnetisation (Fig. 7b,c). Soft magnetic remanences of various directions were completely removed in fields up to about 20 mT. The second, more stable component (ChRM) directs towards the origin and is reduced to near zero in fields up to 100 mT indicating magnetite as the carrier of the ChRM. For part of the specimens the last steps may be again affected by gyroremanence acquisition (Fig. 7c), but also for these samples the second component can be determined from the range between about 20-50 mT.

Site H71 shows highly scattered ChRM directions and is rejected for further consideration. For the other 5 sites, 32 out of 50 specimens yield reliable ChRM results. The remaining 18 specimens show too low intensities after the 20 mT step for identification and determination of the ChRM direction. The ChRM directions of all specimens and the site mean directions are plotted in Fig. 7d,e respectively. Values are listed in Table 1. The slight decrease in dispersion upon bedding correction (from k=41.3 to k=34.8 for site level) suggests a post-tectonic origin for the ChRM component. Stepwise unfolding yields a maximum k-value near 0% of unfolding. Nevertheless, the significance of the fold test is below the 95% level after McFadden (1990). All individual specimen directions show

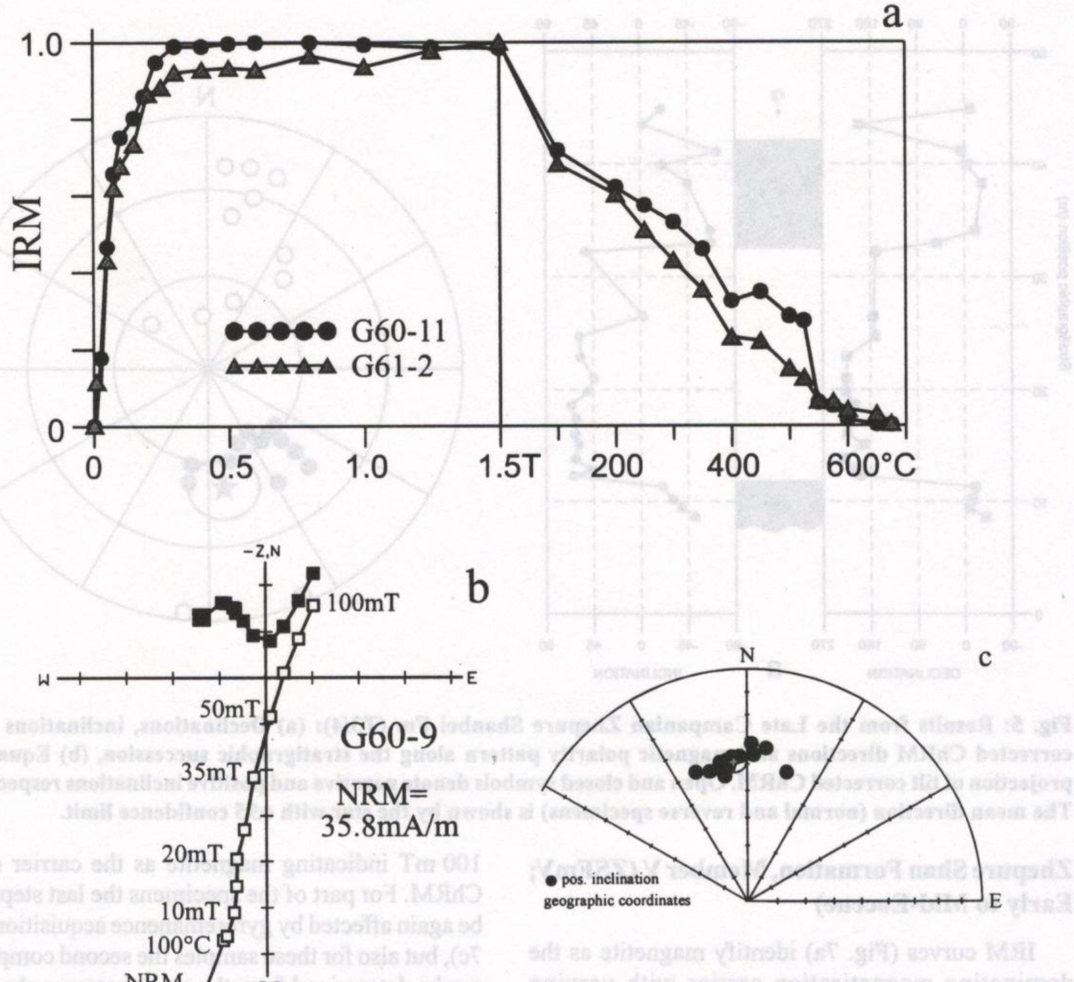

Fig. 6: Results from the late Palaeocene Zhepure Shanpo Formation: (a) IRM acquisition curves and thermal demagnetisation of a SIRM, (b) Orthogonal vector projection, (c) Equal area projection of the soft magnetic component.

reverse polarities excluding remanence acquisition in the present field.

DISCUSSION AND CONCLUSION

In Fig. 8, palaeolatitudes derived from the ChRM directions determined in this paper are compared with reference curves calculated for the sampled location. The reference curves show expected palaeolatitudes for a stable India based on present-day geography (assuming absence of relative movements between the Tingri area and stable India). Different reference curves result from the apparent polar wander path (APWP) published by Besse and Courtillot (1991) (Ref. A), and from ocean floor anomalies with a fixed hot spot system (Klootwijk et al. 1991, Patriat and Achache 1984) (Ref. B). The figure also includes palaeomagnetic results of Gamba/Duela in southern Tibet by Patzelt et al. (1996), which support the existence of a 'Greater India'. The palaeolatitude of the ZSbF coincides approximately with the reference curves A and B and does not support a 'Greater India'. Within its confidence limits, it allows a northern extent of maximum a few hundred kilometres only. However, the ZSbF result is based on a single

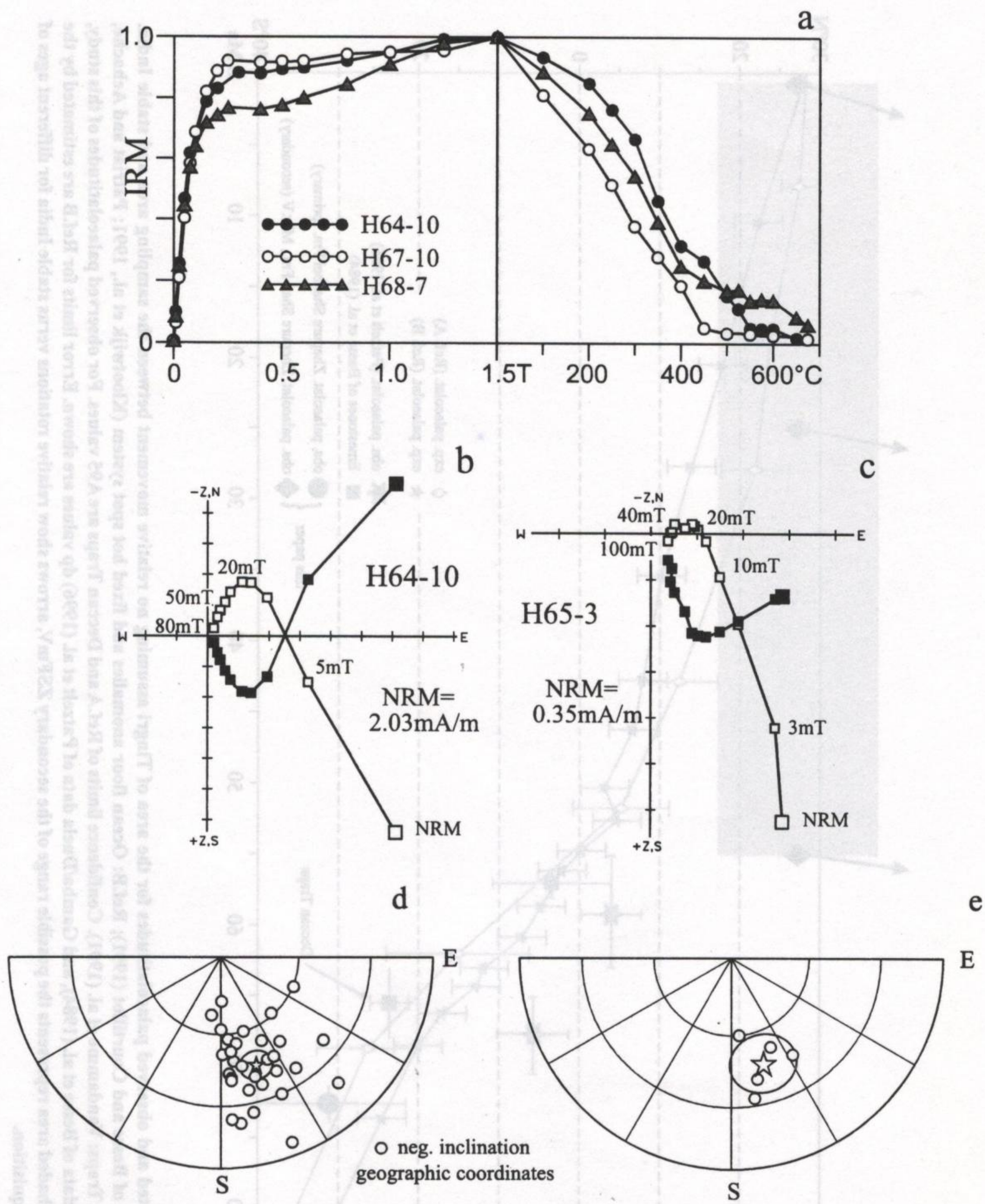

Fig. 7: Results from the early to mid-Eocene Zhepure Shan Formation, Mbr V: (a) IRM acquisition curves and thermal demagnetisation of a SIRM. (b,c) Orthogonal vector projections of representative samples. (d,e) Equal area projection of in situ ChRM directions on specimen (left side) and site level (right side). The mean direction is shown by a star with α95 confidence limit.

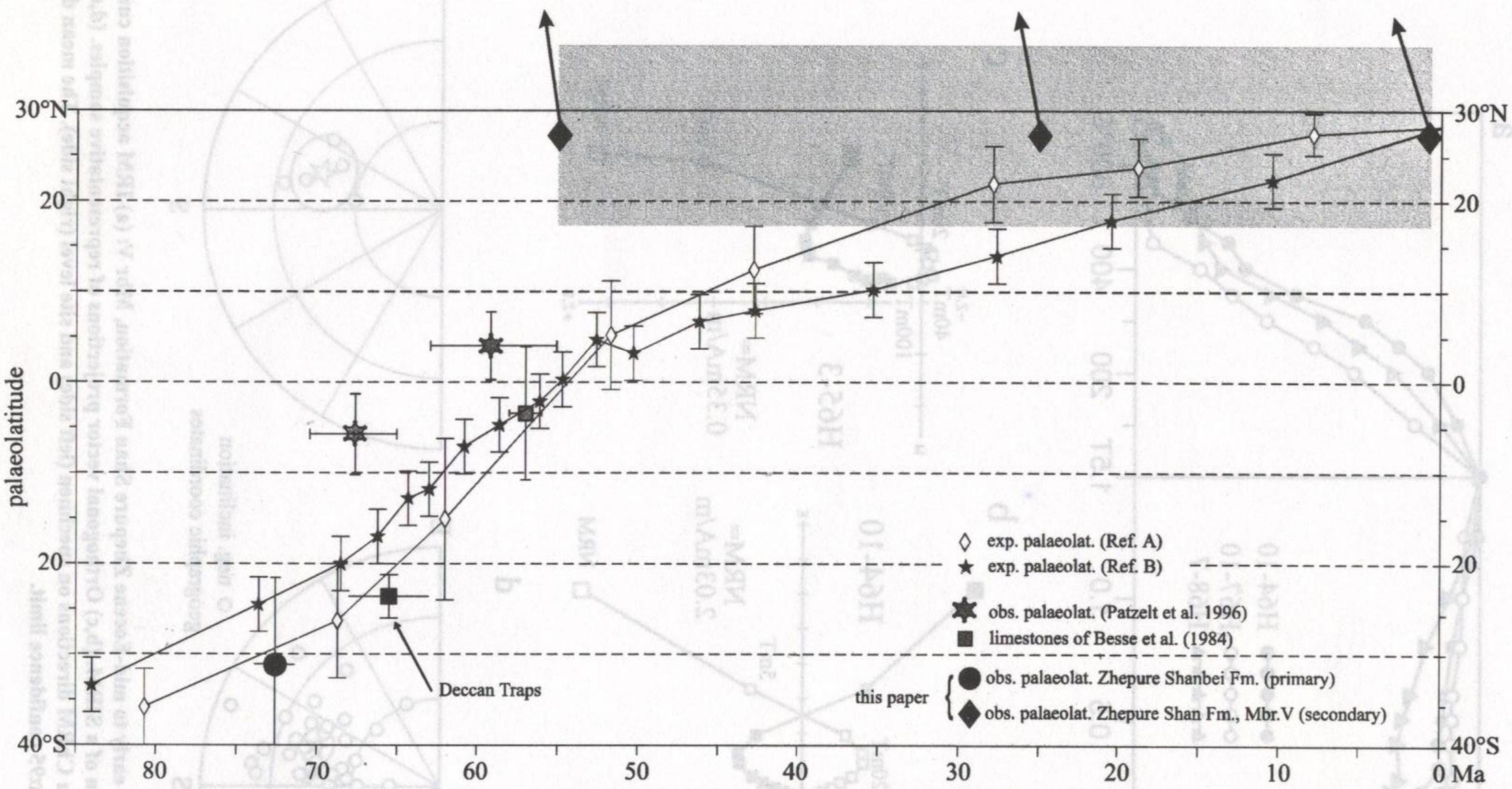

Fig. 8 : Expected and observed palaeolatitudes for the area of Tingri assuming no relative movement between the sampling area and stable India. Ref.A: APWP of Besse and Courtillot (1991); Ref.B: Ocean floor anomalies and fixed hot spot system (Klootwijk et al., 1991; Patriat and Achache, 1984); Deccan Traps: Vandamme et al. (1991). Confidence limits of Ref.A and Deccan Traps are A95 values. For observed palaeolatitudes of this study, for the Tingri data of Besse et al. (1984), and Gamba/Duela data of Patzelt et al. (1996) dp values are shown. Error limits for Ref.B are estimated by the authors. The shaded area represents the possible range of the secondary ZSFmV, arrows show relative rotations verus stable India for different ages of remanence acquisition.

location and the significance is further reduced by incomplete separation of the ChRM. Because this incomplete separation mainly affects the declination, rotations around vertical axis can not be interpreted.

In addition to statistical results, a secondary origin of the ZSFmV component is supported by the lack of a plausible meaning for the tilt corrected inclination. The reverse polarity proves that it is a palaeoremanence with a possible age of remanence acquisition between the Brunhes/Matuyama boundary (about 0.7 Ma) and the rock age. A palaeolatitude of the ZSFmV can be derived from the in situ inclination. Within possible remanence acquisition ages and confidence limits (shaded area in Fig. 8) this palaeolatitude could coincide with the reference curves (between 0.7 Ma to about 40 Ma / 25 Ma for Ref. A / Ref. B) but also a 'Greater India' matching that of Patzelt et al. (1996) is possible. The determination of the remanence age and models for a 'Greater India' are also dependent on inclination steepening by the MCT ramping, which is found to be in a range of 10-20° in the Annapurna and Everest areas (Appel et al., 1991; Rochette et al., 1994). Inclination steepening by an angle a would increase the difference between the observed and expected inclinations by the value of a. At the present stage there are too many unknown factors for a sound interpretation in terms of palaeolatitudes. Future geological indications and more detailed MCT ramping studies might provide better constraints for fixing the remanence age, and the palaeomagnetic data should be saved for this reason.

Contrary to our results, Besse et al. (1984) reported primary remanences from the ZSFmV based on three limestone sites (22 specimens) and one sandstone site (6 specimens) passing the fold test. Rejection of the sandstone site, which seems to be questionable, does not significantly change the mean direction but leads to higher $\alpha95$. Within the corrected confidence limit, the palaeolatitude is not contradictory to the 'Greater India' of Patzelt et al. (1996) (Fig. 8) assumed that the age given by Besse et al. (1984) is correct (late Palaeocene; numerical value of 57 Ma). However, according to informations provided by Besse et al. (1984) and Besse and Cortillot (personal communication) their samples have been drilled from the Zhepure Shan Formation, member V, and the age should be younger (Fig. 3). The answer to the problem of the rock age, and to the fact that a primary remanence could not be separated for the ZSFmV as Besse et al. (1984) did, must remain open here.

Rotation angles versus stable India can be derived from the difference of observed declinations and expected declinations (assuming no relative rotations versus stable India). The primary remanence of Besse et al. (1984) (No. 5 in Fig. 1) and our secondary ZSFmV component (No. 4 in Fig. 1, for an age of 25 Ma) yield nearly identical rotation angles. Accordingly, no rotation around a vertical axis is evidenced between the rock age and the remanence acquisition age of the secondary component. Klootwijk et al. (1985), Appel et al. (1991) and Patzelt et al. (1996) used rotation angles versus stable India to calculate the magnitude of rotational underthrusting. The rotation angles of the Tingri area do not fit very well to the rotation pattern measured in the Tethyan Himalaya and the Everest leucogranites (Fig. 1). An indication to local block rotations can be concluded, which would affect modelling rotational underthrusting. Such local effects have been reported also from the Zanskar Range in the northwestern Himalaya (Appel et al., 1995). Further work to separate block rotations on different scales are encouraged for this reason.

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