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The Tethyan Himalaya: palaeogeographical and tectonic constraints from Ordovician palaeomagnetic data

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Abstract: To test whether the Tethyan Himalaya were part of the northern margin of India in the early Palaeozoic we have produced the first primary palaeomagnetic data (bedding-corrected declination 267.5°, inclination 63.0°, $\alpha_{95} = 10°$; pole latitude 20.2°N, longitude 28.6°E) from low metamorphic grade Ordovician red beds in the Tethyan Himalaya (Shian Formation). The palaeomagnetic data are of excellent quality, and a statistically positive fold test combined with a comparison with late Cambrian–Ordovician Gondwana poles suggests a primary hematite-bearing magnetization, acquired between 470 and 500 Ma. This is in excellent agreement with stratigraphic, faunal and provenance age estimates, and the palaeomagnetic data demonstrate that the Tethyan Himalaya must have been located in proximity to the Indian craton during early Ordovician times, and are therefore consistent with a continuous margin at that time. The Shian Formation pole overlaps with 470–500 Ma Gondwana poles, but an even better fit can be obtained by invoking a post-Ordovician clockwise rotation of $13° \pm 4°$. Such a rotation is similar in both sense and magnitude to clockwise rotations recorded in primary Triassic sequences as well as Palaeogene palaeomagnetic overprint data from the Tethyan Himalaya: rotations of the Tethyan Himalaya compared with cratonic India are thus probably all of post late Eocene age. Triassic and Early Ordovician data do not imply any crustal shortening between Tethyan Himalaya and cratonic India. However, in the Early Ordovician, India was rotated 90° compared with its present orientation, and any enlargement of India would not be detected by palaeomagnetic data.

An understanding of the Cenozoic evolution of the Himalaya relies on knowledge of the pre-deformational history of rock bodies along the northern Indian continental margin (Yin & Harrison 2000). The presence of a belt of high-grade metamorphic rocks that make up the High Himalayan Crystalline Sequence in the Greater Himalaya has therefore presented a longstanding challenge for Himalayan geologists (Fig. 1; DeCelles *et al*. 2000; Myrow *et al*. 2003). Metamorphic rocks of the Greater Himalaya are bounded to the north by the South Tibetan Fault System, a north-dipping normal fault system that has low-grade Neoproterozoic to Eocene rocks of the Tethyan Himalaya fold–thrust belt in its hanging wall (Burchfiel *et al*. 1992). The metamorphic rocks of the Greater Himalaya have, in turn, been thrust south along the Main Central Thrust where they overlie a thick Precambrian to a probably middle Cambrian succession that is unconformably overlain by Permian and younger strata in the Lesser Himalaya. The early Palaeozoic palaeogeographical relationship between these three lithotectonic zones is debated and this controversy is highlighted in the recent literature by two different models for Himalayan orogenesis. In the first model, the three lithotectonic zones represent proximal (Lesser Himalaya) to distal (Tethyan Himalaya) parts of a continuous margin thrust southwards during Cenozoic collision of northern India with Asia (Searle 1986; Brookfield 1993; Hughes & Jell 1999; Corfield & Searle 2000; Myrow *et al*. 2003). In the second model, parts of the Greater Himalaya and/or Tethyan Himalaya were located outboard of Gondwanaland in the early Palaeozoic and subsequently accreted to the northern Indian margin (e.g. Cocks & Fortey 1988; DeCelles *et al*. 2000; Yoshida & Upreti 2006). Recent workers have challenged the terrane model by demonstrating that many Cambrian sections in the Tethyan Himalaya show striking similarities along and across the strike of the orogen, as would be expected with a continuous margin model (Myrow *et al*. 2003, 2006*a*,*b*, 2009*b*; Hughes *et al*. 2005). The possibility of terranes in the Himalaya has fundamental importance for understanding the evolution of the Himalaya (Yin & Harrison 2000). Nevertheless, the question of whether rocks in the Tethyan Himalaya were part of continental India and within core Gondwanaland in the early Palaeozoic has not been tested palaeomagnetically. Indeed, there is a general paucity of reliable primary palaeomagnetic data from the Tethyan Himalaya, and this has hampered palinspastic restorations of the original extent of the northern Indian margin, which is fundamental for models describing the evolution of the Himalaya and the Tibetan Plateau (Patzelt *et al*. 1996; Yin & Harrison 2000, and references therein).

This study focuses on palaeomagnetic analyses of Early to Middle Ordovician rocks collected from Parahio Valley in the Spiti area, Himachal Pradesh, of the Tethyan Himalayan fold–thrust belt in NW India (Figs 1 and 2; Myrow *et al*. 2006*a*,*b*). Our purpose was to determine whether early Palaeozoic rocks of the Tethyan Himalaya were part of the northern margin of India

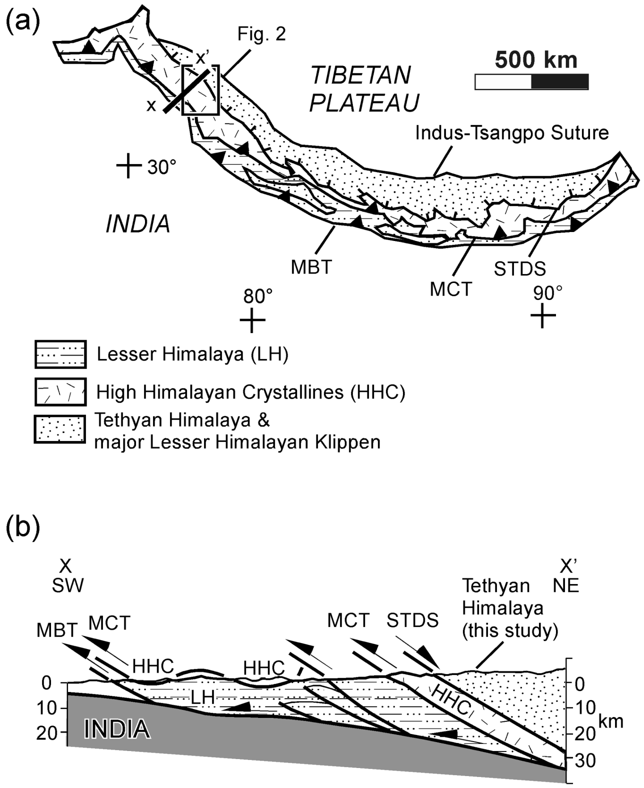


Fig. 1. (**a**) Simplified regional map of the Himalaya showing major tectonic features within the range (from Paulsen *et al*. 2007; originally modified from Myrow *et al*. 2003). Location of Figure 2 is shown. (**b**) Simplified cross-section of the NW Himalaya (from Paulsen *et al*. 2007; originally modified from Vannay *et al*. 2004). HHC, High Himalayan Crystallines; LH, Lesser Himalaya; MBT, Main Boundary Thrust; MCT, Main Central Thrust; STDS, South Tibetan Detachment System.

during the early Palaeozoic, and to attempt to place constraints on the original extent of the Tethyan shelf prior to Cenozoic collision of India with Eurasia. The dominant structures in the Parahio Valley area of Spiti are NW–SE-trending faults and folds related to thrusting in the Tethyan Himalayan fold–thrust belt, which displaced a northward thickening wedge of strata southward over an equivalent but thinner succession of strata during Eocene convergence of India with Eurasia (Searle 1986; Fuchs 1987; Corfield & Searle 2000; Wiesmayr & Grasemann 2002; Myrow *et al*. 2003; Neumayer *et al*. 2004; Gehrels *et al*. 2006). Sedimentary rocks deformed within the Tethyan Himalayan fold–thrust belt range in age from Neoproterozoic to Eocene (Bhargava & Bassi 1998). Unlike other parts of the Himalaya, the early Palaeozoic stratigraphic succession in this area is well preserved because Cenozoic metamorphism has been weak, making the rocks good candidates for a palaeomagnetic analysis.

Red beds were collected as oriented hand samples at six sites around a NW–SE-trending anticline near Thango in the Parahio Valley (Fig. 2b). Overall, folds within the study area are upright to inclined, cylindrical, and have amplitudes and wavelengths that range from a few metres to several kilometres (Wiesmayr & Grasemann 2002; Neumayer *et al*. 2004; Myrow *et al*. 2006*b*). Bedding-parallel slip surfaces commonly occur on the limbs of folds, indicating that they formed predominantly by flexural slip (Wiesmayr & Grasemann 2002; Neumayer *et al*. 2004; Myrow *et al*. 2006*b*). The fold we sampled plunges *c*. 45° SE, which is similar to, but is on the steep side of the range of fold plunges documented in the area. Folds typically have horizontal or shallow to moderate (*c*. 5–40°), NW- and SE-plunging axes (Wiesmayr & Grasemann 2002; Neumayer *et al*. 2004; Myrow *et al*. 2006*b*) that are similar to the trends and plunges of pi axes (*c*. 0–30°) defined by bedding pole great circle girdles and of cleavage–bedding intersection lineations (*c*. 20°) (Myrow *et al*. 2006*b*).

No fossils were recovered from the beds at the sample sites but they are from the Shian Formation, also known locally as the Thango Formation. In the Parahio Valley, the *c*. 1000 m thick Shian Formation (Draganits 2000) unconformably overlies Cambrian rocks that are no older than *c*. 510 Ma (Myrow *et al*. 2006*b*), providing a maximum depositional age for our samples. However, Cambrian rocks as young as 500 Ma are known elsewhere in the Spiti–Zanskar region (Myrow *et al*. 2006*a*), making it most unlikely that the samples analysed herein are older than 500 Ma, a conclusion confirmed by detrital zircon analyses (see below). Furthermore, the Shian Formation contains

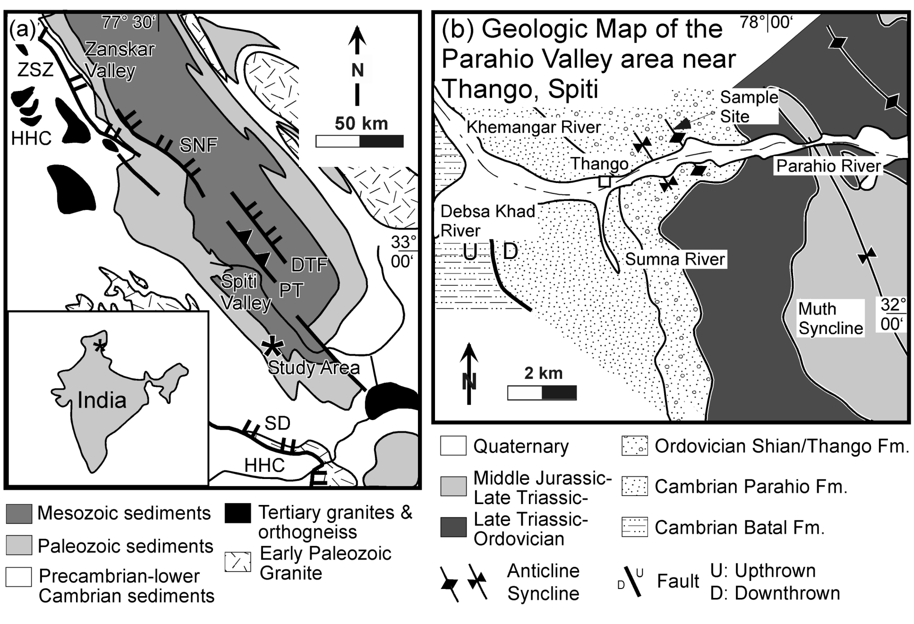


Fig. 2. (**a**) Geology of the Spiti–Zanskar basin area showing the location of sampling site in Spiti (after Wyss *et al*. 1999). Inset shows the location of the map on a regional scale in India (modified from Draganits *et al*. 2004; Paulsen *et al*. 2007).
(**b**) Geological map showing sample site in Parahio Valley in Spiti (compiled and modified from Fuchs 1982; Bhargava & Bassi 1998; Wiesmayr & Grasemann 2002; Myrow *et al*. 2006*b*; Paulsen *et al*. 2007). DTF, Dutung–Thaktote Fault; HHC, High Himalayan Crystallines; PT, Parang La Thrust; SNF, Sarchu Normal Fault; SD, Sangla Detachment; ZSZ, Zanskar Shear Zone.

the distinctive trace fossil *Phycodes circinatum*, collected *c*. 650 m above its base (Bhargava & Bassi 1998, fig. 2.14), and this form is diagnostic of Ordovician age (A. Seilacher, pers. comm.). The Shian Formation is conformably overlain by the Pin Formation (also locally known as the Takche Formation), which contains a varied fauna. The latter formation has recently been subdivided into three members: the Farka Muth Member, the Takche Member and the Mikkim Member (Suttner 2007), of which the base of the second member (*c*. 90 m above the formation base) appears to be latest Ordovician in age, based on the occurrence of conodonts representative of the *Amorphognathus ordovicicus* Zone (Suttner *et al*. 2007). This conclusion is consistent with data from other taxa such as trilobites (Paterson 2004), sponges (Maithy *et al*. 1999), cephalopods (Suttner & Kröger 2006), bryozoans (Suttner & Ernst 2007) and ostracodes (Schallreuter *et al*. 2008). The base of the Pin Formation is thus no older than about 450 Ma.

Accordingly, local age constraints suggest that the depositional age of the analysed samples is within the range 450–500 Ma. We have selected the intermediate value of 475 Ma as the approximate age of our samples because they come from low within the Shian Formation, above the unconformity with the Cambrian. This is supported by detrital zircon analyses from the base of the Shian Formation, which show the presence of a significant number of concordant grains with ages around 500 Ma (Myrow *et al*. 2009*a*). Probably several million years would be required for the unroofing, transportation and incorporation of these grains. Limestone-bearing Middle Ordovician fossils have been reported along the strike of the Himalaya (Burchfiel *et al*. 1992) in the Everest region, indicating that a carbonate platform had developed in the Himalayan region at around 475 Ma (Myrow *et al*. 2009*b*). Hence we consider 475 Ma as a reasonable depositional age estimate, but the actual value could be somewhat older or younger (see below).

Palaeomagnetic results

The natural remanent magnetization (NRM) was measured on a JR6A magnetometer at the Geological Survey of Norway (Trondheim), and NRM stability was tested by thermal demagnetization (MM-TD-60 furnace). Fifty-eight samples were demagnetized in 16 temperature steps and characteristic remanence components were calculated with the LineFind algorithm of Kent *et al*. (1983) as implemented in the Super-IAPD software (Torsvik *et al*. 2000). To identify the magnetic mineralogy we used a horizontal translation bridge to determine Curie temperatures, a pulse magnetizer for isothermal remanent magnetization (IRM) acquisition curves, and a vibrating sample magnetometer (VSM) for hysteresis loops.

NRM intensities average to $3.6 \pm 1.4\,\mathrm{mA\,M^{-1}}$, and most samples are characterized by 10–20% intensity decay below 600 °C followed by more discrete unblocking between 600 and 680 °C. Most samples (52 out of 58) behaved very well during demagnetization, and are characterized by almost univectorial (albeit somewhat irregular) decay toward the origin of the vector plots (Fig. 3a and b). Subordinate low unblocking components (<200–300 °C) can be present but they are scattered and are not considered futher.

Thermal demagnetization spectra suggest hematite as the principal remanence carrier in all samples. This is also supported by IRM curves (Fig. 4a) that are not saturated in the maximum available field (1.3 T) and Curie temperatures (Fig. 4b) close to 680 °C. Thermomagnetic curves are erratic because of low intensities, and heating and cooling curves are irreversible (Fig. 4b). The irreversible behaviour is caused by heating-related alterations, as clearly shown by the VSM hysteresis loop experiments performed on the same sample before and after heating (Fig. 4c). Both VSM and IRM analysis are indicative of high-coercivity mineral phase, which supports the thermomag-

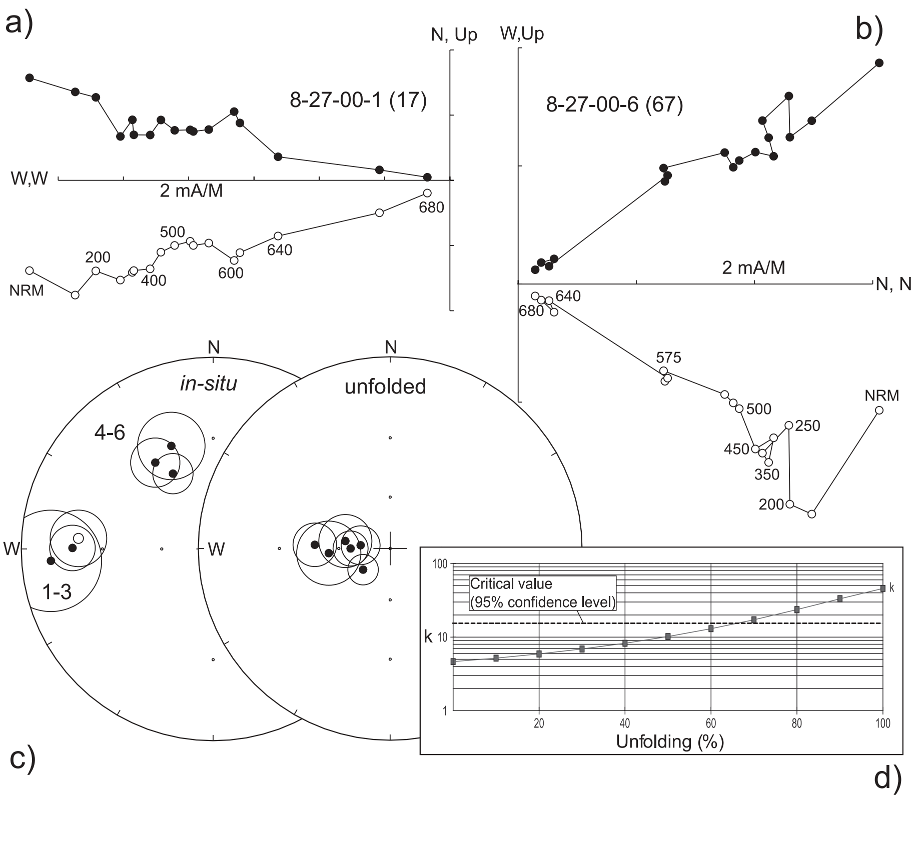


Fig. 3. (**a**, **b**) Thermal demagnetization of site 1 (8-27-00-1; limb 1) and site 6 (8-27-00-6; limb 2) samples (not bedding corrected). In orthogonal vector plots, filled (open) circles denote points in the horizontal (vertical) plane. Numbers on the curves are temperature in °C. (**c**) Site mean directions shown in *in situ* (not corrected for bedding) and bedding-corrected coordinates (unfolded). In stereo-plots, filled (open) symbols denote positive (negative) inclinations. Mean directions are shown with α_{95} confidence circles (Table 1). (**d**) Stepwise unfolding (10% increments) of site means showing uniform increase in precision (*k*) with unfolding. Positive fold test according to both the classic McElhinny (1964) fold test and the limb fold test of McFadden & Jones (1981).

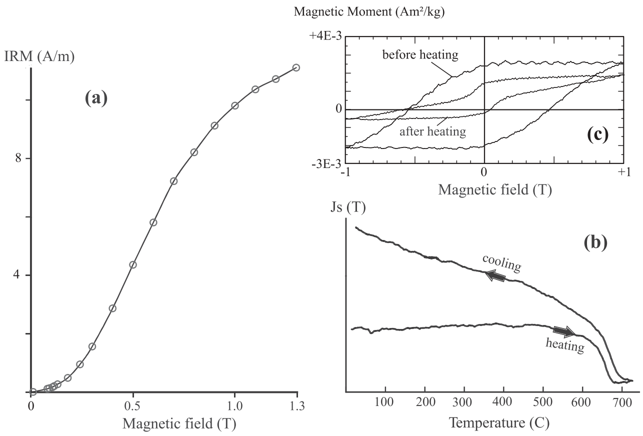


Fig. 4. (**a**) Examples of isothermal remanent magnetization (IRM). (**b**) 'Saturation' magnetization (J_s) v. temperature; (**c**) hysteresis loops measured at room temperature for a sample before and after heating to 720 °C.

netic and thermal demagnetization result. We therefore conclude that hematite is the bulk remanence carrier.

High unblocking remanence components from limb 1 (sites 1–3) show westerly directed declinations with shallow-dipping inclinations (*in situ* coordinates). Conversely, limb 2 (sites 4–6) is characterized by NNW declinations and shallow positive inclinations (Fig. 3c). After bedding correction, within- and between-limb dispersion decreases, and the six sites (two limbs) pass a fold test at the 95% confidence level (McElhinny 1964; McFadden & Jones 1981). The remanence is thus pre-folding (Fig. 3d), assumed to be primary and carried by detrital and/or early diagenetic hematite. Bedding-corrected site mean directions (Fig. 3c) show westerly declinations (mean 267.5°) with steep positive inclinations (mean 63.0°). The inclinations yield a local palaeolatitude of 44.5°S at the time of remanence acquisition.

Gondwanan and Tethyan Himalayan poles

To test whether the Tethyan Himalaya represents the early Palaeozoic passive margin of India (e.g. Myrow *et al*. 2006*a*,*b*) we compare the Shian Formation pole (Table 1) with reliable late Cambrian–Ordovician poles from Gondwana (Fig. 5a), and an apparent polar wander (APW) path for Gondwana from 500 to 220 Ma (Fig. 5b). Early Palaeozoic Gondwana poles come from Africa, Australia, East Antarctica, Madagascar and South America, but all poles and the APW path are rotated to an Indian reference frame using appropriate plate movements (Torsvik & Van der Voo 2002; Torsvik *et al*. 2008).

The Shian Formation pole overlaps with 460–500 Ma mean poles from Gondwana (Table 2; Fig. 5b), and given the positive fold test (albeit probably of Eocene folding age), we consider it likely that the remanence is primary. Conversely, if the pole is secondary (but pre-fold) then it must represent a complete Devonian (*c*. 400–370 Ma) or Permian (*c*. 300–250 Ma) magnetic resetting that was subsequently rotated respectively 50° or 130° counter-clockwise around a vertical axis. We find this unlikely, as there is no geological evidence for such a major resetting and subsequent rotation. Indeed, using stratigraphic thicknesses and average geothermal gradients and sediment densities for passive margins, Draganits *et al*. (2005) estimated that temperatures within the Devonian Muth Formation (located *c*. 250 m stratigraphically above the top of the Shian Formation), probably did not exceed *c*. 90 °C before Cenozoic Himalayan orogenesis. There are two post-Ordovician extensional events known to have affected the northern Indian margin prior to Cenozoic Himalayan orogenesis (Draganits *et al*. 2005). The first was in the Carboniferous, during Neotethyan rifting (pre-drift), and associated with the Early Permian eruption of the Panjal Traps flood basalts. Although the Panjal Traps basalts are present over 100 km to the NW in south Zanskar (Draganits 2000), they are absent in the Spiti Valley, with the possible exceptions of a few mafic dykes (Hayden 1904; Fuchs 1982), and we observed no evidence for intrusions or contact metamorphism in the area. The second was a Late Triassic extensional subsidence event, which does not fit the timing of possible resetting events outlined above. The timing of the main thermal event known to have affected the Spiti region comes from illite data from deformed slates that suggest temperatures *c*. 180 °C, and yield ^{40}Ar–^{39}Ar cooling ages of 43.5 ± 1.5 Ma, suggesting a Middle Eocene deformation age (Wiesmayr & Grasemann 2002).

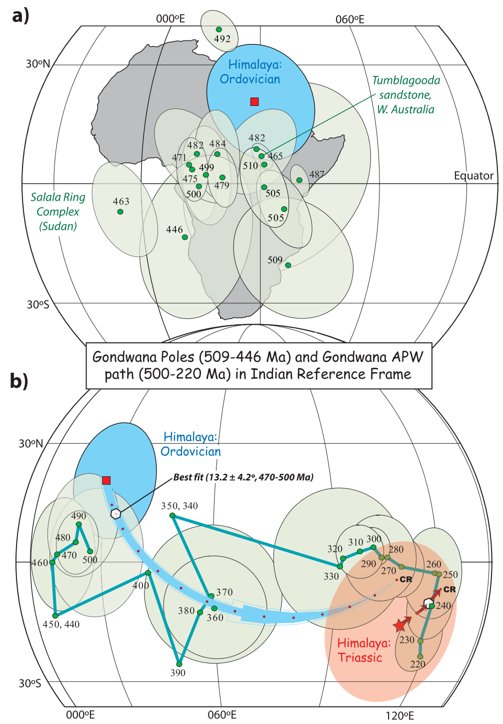
As the Shian Formation pole is essentially from one locality, it should be considered with some caution; nevertheless, we wish to point out the following important characteristics.

(1) The Shian pole plots somewhat to the NE of the majority of Gondwana poles and compares best with 480–500 Ma Gondwana mean poles (Fig. 5b; Table 2). These are running mean poles with a window length of 20 Ma and include raw

Table 1. *Site and sample mean directions from the Shian Formation and a palaeomagnetic pole calculated from the bedding-corrected site mean (positive fold test)*

Site/limb	Strike (°)	Dip (°)	*n*	*k*	α_{95}	Dec (°)	Inc (°)	*T*Dec (°)	*T*Inc (°)
1/1	018	60E	8	40.8	8.8	270.4	17.5	231.9	69.7
2/1	009	67E	9	29.9	11.2	274.5	−19.7	272.8	47.1
3/1	356	45E	8	11.2	17.3	265.8	9.4	265.7	54.4
4/2	094	45S	7	37.8	10.0	331.9	42	269.9	66.7
5/2	099	56S	10	11.5	14.9	337.9	29.8	279.4	63.4
6/2	076	49S	10	19.4	11.3	326.2	33.1	276.3	72.4
Site means			6			298.3	21.9	267.5	63.0
						α_{95} = 34.9, *k* = 4.6		α_{95} = 10.0, *k* = 45.9	
Sample means			52			301.1	24.3	268.6	65.3
						α_{95} = 10.2, *k* = 4.8		α_{95} = 5.6, *k* = 48.2	
Pole (bedding-corrected site mean)						Latitude 20.2°N, longitude 28.6°E; d*p*/d*m* = 12.4/15.7°			

Strike and dip, strike and dip for bedding; *n*, number of sites or samples; *k*, precision parameter; α_{95}, 95% confidence circle around the mean direction; Dec and Inc, mean declination and inclination; *T*Dec and *T*Inc, mean declination and inclination corrected for bedding (100% unfolded); d*p*/d*m*, semi-axes of the cone of 95% confidence about the pole. Mean sampling coordinates 32°02'N, 77°58'E (3871 m elevation).



poles in the 463–509 Ma range. Excluding the somewhat anomalous 463 Ma Salala Ring Complex pole (Fig. 5a) from Africa improves the fit with the mean 470 Ma Gondwana pole (the second set of values for 470 Ma in Table 2), and great circle distances (GCD) between the Shian Formation pole and Gondwa-

Fig. 5. (**a**) Late Cambrian and Ordovician palaeomagnetic poles with d*p*/d*m* confidence ovals (green shading) from Gondwana rotated to an Indian reference frame (509–446 Ma raw poles listed by Torsvik & Van der Voo (2002) with plate movements revised by Torsvik *et al.* (2008)). These poles are compared with the Ordovician Shian Formation pole from the Tethyan Himalayas (blue shaded d*p*/d*m* oval). (**b**) Late Cambrian to Early Triassic Gondwana apparent polar wander (APW) path compared with our Ordovician pole and a Triassic mean pole from western Dolpo, Thakkhola and Manang (Crouzet *et al.* 2003, table 4). It should be noted that we have rotated this mean pole around a vertical axis centred around a mean sampling location and not according to clockwise inclined rotations derived from younger secondary pyrrhotite poles (see Crouzet *et al.* 2003), which would bring the mean pole to the wrong section (Late Carboniferous–Early Permian) of the Gondwana APW path. The Tethyan Himalaya poles are shown with d*p*/d*m* ellipses whereas Gondwana mean poles (AGE ± 10 Ma) are shown with A95 ovals. A95 ovals are not shown if they exceed 30° or the mean pole is based on only one pole. The effect of clockwise rotations (CR) around a vertical axis is shown for both poles in 10° increments (blue and red arrows).

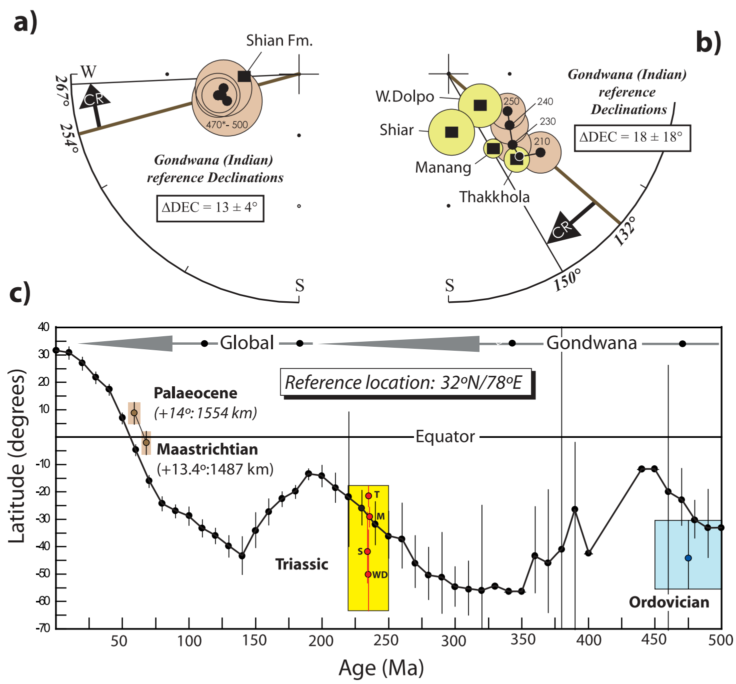


Fig. 6. (**a**) Ordovician mean directions from Gondwana rotated to an Indian reference frame (calculated from Torsvik & Van der Voo 2002; Torsvik *et al.* 2008, table 3) and compared with the Shian Formation direction (black square). Gondwana mean directions are calculated without the 463 Ma Salala Ring Complex (470–500 Ma; Table 2). (**b**) Primary Triassic directions (with yellow α_{95} ovals) from the Western Dolpo (WD), Thakkhola (T), Manang (M) and Shiar (S, Crouzet *et al.* 2003, table 4) compared with Gondwana reference data. The average reference declination is a mean of 250–210 Ma directions. In stereo-plots closed symbols denote positive inclinations. Reference directions are shown with brown *A*95 circles. All data are recalculated to a common location in Spiti (32°N, 78°E). CR, clockwise rotation compared with Gondwana reference frame. (**c**) Stable India reference latitude curve (recalculated to Spiti location) based on Gondwana (500–220 Ma; Torsvik & Van der Voo 2002) and global (190–0 Ma; Torsvik *et al.* 2008) palaeomagnetic reference frames. It should be noted that Ordovician and Triassic data from the Tethyan Himalaya on average yield lower latitudes than stable India but they statistically overlap. Conversely, Maastrichtian (*c.* 68 Ma) and Palaeocene (*c.* 59 Ma) data from the Tethyan Himalaya (Gamba and Duela regions) plot systematically to the north of the reference curve and imply 1500 km of younger shortening between the Tethyan Himalaya and cratonic India (see also Patzelt *et al.* 1996).

na mean poles in the 470–500 Ma range then vary between 18 and 13° (mean GCD = 16.5 ± 2.5°).

(2) The fit with 470–500 Ma Gondwana poles can be improved if we consider local clockwise rotations of the order of 8–18°. Over this time range a clockwise rotation of 13.2 ± 4.2° produces the best fit, with mean GCD reduced to 13.4 ± 2.0°. Such a rotation, both in magnitude and sense (clockwise), is comparable with primary palaeomagnetic data from Triassic (Figs 5b and 6a,b, 18 ± 18°) as well as many Palaeogene data (Crouzet *et al*. 2003) from the Tethyan Himalaya. However, it should be pointed out that these results come from different parts of the Tethyan Himalaya that may have experienced different rotational histories. Furthermore, the sampling sites of this study are distributed around a moderately plunging fold axis (*c*. 45°) that could cause declination deviations if, for example, the plunge of the fold is primarily due to non-coaxial refolding of an earlier-formed roughly horizontal NW–SE anticline. For example, un-plunging the fold-axis followed by stepwise unfolding leads to a declination of 274.4° and subsequently a best-fit clockwise rotation of 20.1° compared with Gondwana. Our data

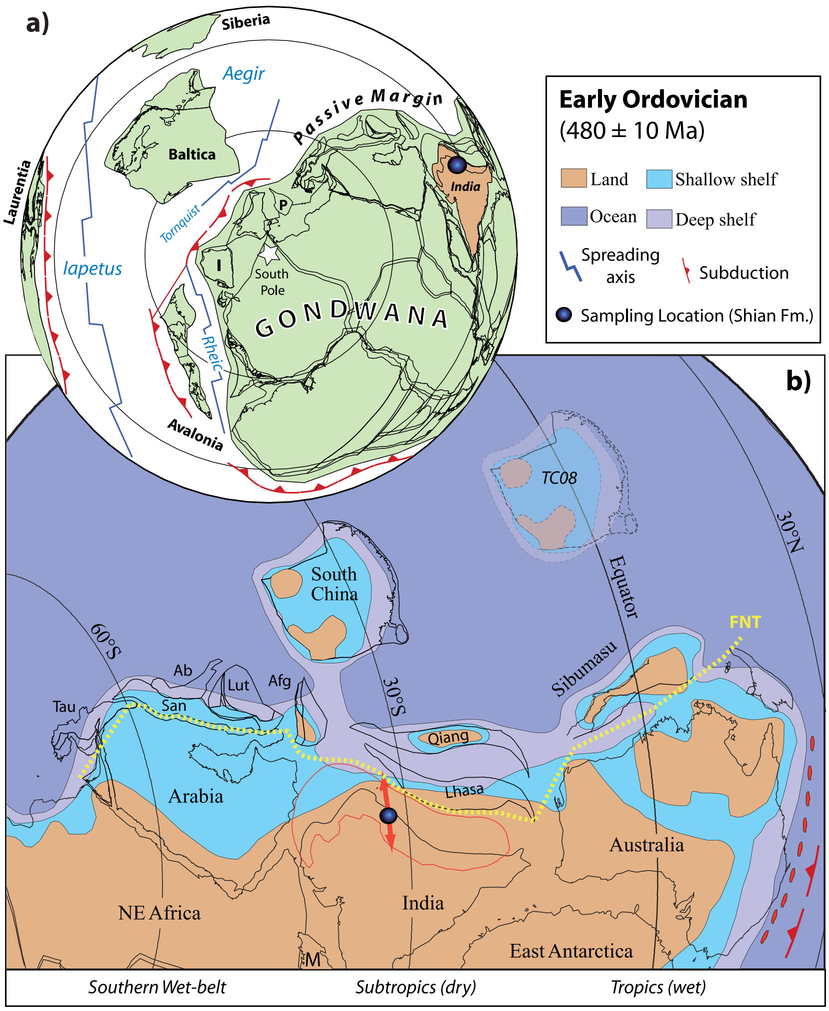


Fig. 7. (**a**) Reconstruction of most of Gondwana (stable India shown in brown along with Spiti sampling location) and its relationship to some major continents in early Ordovician time (480 ± 10 Ma). Avalonia has just started to drift off the margin of Gondwana (opening of the Rheic Ocean) and later collided with Baltica in the Late Ordovician. The Gondwana margin from Spain (Iberia, I) to Bohemia (Perunica, P) was an active margin by this time whereas the Gondwana margin from the Turkey (Taurides) to Australia was a passive margin throughout the Ordovician. (**b**) Detailed *c*. 480 Ma palaeogeography of NE Gondwana and adjacent terranes. Ab, Alborz terrane; Afg, Afghan terranes; M, Madagascar; Qiang, Qiangtang terrane; San, Sanand terrane; Tau, Taurides terrane. In this reconstruction (modified from Torsvik & Cocks 2008) the sampling location in north India (Shian Formation) is shown as a blue circle. Taken at face value the Shian Formation gives a southerly latitude that is too high compared with stable India (see Fig. 6c); this is considered very unlikely (will fall on top of the Arabian Peninsula or must move west of Lut–Afghan terranes) but the latitude falls within error of the current position of the Shian Formation with respect to cratonic India. The position of South China is problematical from palaeomagnetic data: a Middle Cambrian pole (Yang *et al*. 2004) suggests a low-latitude position (marked TC08, Torsvik & Cocks 2009), whereas an Early Ordovician pole (Fang *et al*. 1990) suggests intermediate southerly latitudes. The position of South China adjacent to the Afghan terranes is based on the latter pole but South China is moved somewhat closer toward the equator (but within the uncertainties, $\alpha_{95} \sim 17°$, of the original pole). In this Early Ordovician reconstruction, India has been enlarged 500–700 km (Greater India), but at this time India was rotated almost 90° compared with its present orientation, and any enlargement of India would not be detected by palaeomagnetic data. Thus the Tethyan Himalaya (based on the Shian Formation pole) can theoretically be placed at any palaeolongitude (see red arrow centred on our sampling location). FNT, future Neotethys.

Table 2. *Mean palaeomagnetic poles for Gondwana (in cratonic Indian coordinates) from 500 to 450 M*a

Age (Ma)	*A*95	*P*Lat	*P*Long	*n*	GCD	GCD^R	ΔDEC	Δ*P*Lat	SOL
450 ± 10	18*	−13.0	11.2	1	37.4	33.3	21.2	32.8	No
460 ± 10	99.0	0.0	12.1	2	25.9	24.3	10.8	24.2	Yes
470 ± 10	13.8	2.0	14.2	5	22.9	21.4	10.3	21.4	Yes
470 ± 10*	9.7	4.2	19.2	4	18.4	16.0	14.6	16.0	Yes
480 ± 10	7.7	4.9	21.3	7	16.9	13.9	12.2	13.9	Yes
490 ± 10	12.7	9.3	21.8	7	12.8	11.8	8.0	11.1	Yes
500 ± 10	15.7	2.5	26.5	7	17.8	11.7	18.0	11.1	Yes
510 ± 10	7.6	−8.8	31.5	9	29.1	20.8	21.9	14.8	No
Mean									
(includes raw poles 465–509 Ma; Fig. 5a)									
470*–500 Ma					16.5 ± 2.5	13.4 ± 2.0	13.2 ± 4.2	13.0 ± 2.4	Yes

*The 470 Ma mean pole for Gondwana calculated without the *c*. 463 Ma Salala Ring Complex (see Fig. 5a).
*A*95, 95% confidence circle around the mean pole (value for 450 ± 10 Ma = α_{95}); *P*Lat and *P*Long, pole latitude and longitude; *n*, number of poles; GCD, great circle distance (shortest distance on a sphere) between Gondwana (‘India’) reference poles and the Shian Formation Pole (Table 1); GCD^R, GCD corrected for a clockwise rotation of 13.2°; ΔDEC, rotation of the Shian Formation Pole compared with Gondwana reference poles (positive values represent clockwise rotation); ΔPLat, palaeolatitude difference; SOL, statistical overlap (yes/no) between the Shian Formation pole and Gondwana mean poles.

do not allow us to determine whether the SE plunge of the fold that we sampled is related to a single deformation phase or multiple non-coaxial deformation phases. Wyss *et al*. (1999) reported non-coaxial folds to the NW of the Parahio Valley area, but such deformation has yet to be identified in the area of our study, where the rocks appear to be primarily deformed by SW-directed thrusts and SW-vergent folds that developed during the formation of the Tethyan Himalayan fold–thrust belt (Wiesmayr & Grasemann 2002; Neumayer *et al*. 2004; Myrow *et al*. 2006*b*; Paulsen *et al*. 2007).

(3) The Shian Formation pole yields somewhat higher latitudes (11–16° too far south; Δ*P*Lat in Table 2) than expected if the Tethyan Himalaya was part of northern India. Inclination error is a recognized phenomenon in sedimentary rocks (e.g. Kodama 1997; Rochette & Vandamme 2001; Kent & Tauxe 2005); it is latitude dependent but it also depends on rock type and remanence acquisition or shallowing mode. Fifty per cent of the late Cambrian–Ordovician Gondwana poles come from sedimentary rocks; we therefore recalculated all Gondwana sedimentary poles and the Shian pole using a flattening value (f) of 0.55, and undertook the same comparative analysis as in Figure 5. However, this leads to a statistically worse fit and thus inclination errors (or non-dipole field contributions) cannot explain the systematic but small and statistically insignificant differences between the Shian Formation and Gondwana reference poles.

The Tethyan Himalaya plays a key role in reconstructing the original extent of Greater India, and Patzelt *et al*. (1996) have estimated 1500 km shortening between Tethyan Himalaya and cratonic India. This is based on the observation that Maastrichtian (*c*. 65–71 Ma) and Palaeocene (*c*. 55–63 Ma) data from Tethyan Himalaya yield systematically more northerly latitudes than cratonic India (Fig. 6c). Interestingly, Triassic (*c*. 220–250 Ma) and the older Shian Formation poles do not show this pattern; the bulk of these poles even plot at more southerly latitudes than cratonic India but within error they overlap (Fig. 6c). Possible explanations include: (1) Ordovician and Triassic data (including the reference frame data; see large latitude error bars in Fig. 6c) are less precise or of poorer quality; (2) the Greater India margin underwent considerable extension after Late Triassic time (Draganits *et al*. 2005) or younger times (Patzelt *et al*. 1996); or a combination of these two causes. However, we note that in Ordovician times (Fig. 7), India was rotated 90° (westerly declinations in Fig. 6a) with respect to its present orientation; any ‘northerly’ extension of India would therefore have been oriented palaeo-east–west, and the Tethyan Himalaya can be placed anywhere ‘north’ of present-day India (ancient longitude being not detectable with palaeomagnetic data). Conversely, latitude discrepancies between the Triassic data (SE declinations in Fig. 6b) and the cratonic India reference curve should be theoretically noticeable if the relatively large Late Cretaceous–Early Tertiary shortening estimates (*c*. 1500 km) are correct.

Palaeogeographical implications

The palaeomagnetic data from the Tethyan Himalaya demonstrate that the Shian Formation must have been located at intermediate southerly latitudes, and close to or at the northern margin of cratonic India during the Early Ordovician. At this time, Gondwana and peri-Gondwanan terranes stretched from the south pole to low northerly latitudes, and were separated from major continents such as Baltica and the low-latitude Laurentian and Siberian continents (Fig. 7a). Figure 7b shows a detailed palaeogeographical reconstruction of NE Gondwana and peri-Gondwanan terranes at around 480 Ma (modified from Torsvik & Cocks 2009). From south to north, we have placed the Taurides (parts of Turkey–Syria), Sanand–Alborz–Lut (most of Iran), Afghan, Tibetan (Qiangtang, Lhasa) and the Sibumasu terranes as linked to core Gondwana, but most of these drifted off the Gondwana margin during the Late Permian opening of the Neotethys (Stampfli & Borel 2002; Torsvik & Cocks 2004; future Neotethys line marked FNT in Fig. 7b). Placement of the Lhasa and Qiatang terranes of Tibet adjacent to the Himalaya provides a complementary passive margin to western Australia, but there is not strong support for this based on independent data for the early Palaeozoic. No unequivocal Cambrian sedimentary rocks are known from these terranes, although a small Middle Cambrian trilobite fauna from the Yunlung Collage in western Yunnan may represent the south-eastward part of the Qiantang terrane (Hughes *et al*. 2002). Some workers have suggested that the combined Lhasa and Qiantang blocks collided with the Himalaya margin during a Cambrian–Ordovician event (Hughes & Jell 1999; Yin & Harrison 2000), but evidence for this is scant.

The position of South China is also problematical. Strong stratigraphic and faunal similarities link South China to the Himalayan margin in Neoproterozoic, Cambrian and Ordovician time (Chen 1984; Kumar 1984; Chen & Rong 1992; Jell & Hughes 1997; Jiang *et al*. 2002, 2003; Hughes *et al*. 2005).

Unfortunately, the location of South China from palaeomagnetic data is equivocal. There are only two reliable Cambro-Ordovician poles: one Middle Cambrian pole (Yang *et al*. 2004) suggests a low-latitude position (TC08 in Fig. 7b), whereas the Early Ordovician pole by Fang *et al*. (1990) suggests an intermediate southerly latitude for South China. A position that may be consistent with both a low-latitude setting and relative proximity to India might be associated with the NW margin of Australia (Yang *et al*. 2004). Alternatively, a higher southern latitude position adjacent to the Afghan (Fig. 7b) or Pakistan is plausible (Cocks & Torsvik 2002; Jiang *et al*. 2003). Both alternatives are shown in Figure 7b with India enlarged some 500–700 km (Greater India) in the Early Ordovician; subsequent extension events (see Draganits *et al*. 2005) in the Permo-Carboniferous (Neotethys rifting) and the Late Triassic (major subsidence event in the Tethyan Himalaya) may have enlarged Greater India several hundred kilometres prior to Cenozoic collision and subsequent shortening and southward thrusting of the Tethyan Himalaya.

Conclusions

The Shian Formation red beds reveal well-defined remanence components carried by hematite. A positive fold test combined with a comparison of the Shian Formation pole with Late Cambrian–Ordovician poles from Gondwana strongly suggests a primary magnetization acquired some time between 470 and 500 Ma. This is in excellent agreement with stratigraphic, faunal and provenance (detrital zircons) age estimates, which provide an upper and lower age limit of 500 Ma and 450 Ma, respectively. The Shian Formation pole overlaps with Gondwana poles in the 470–500 Ma range but an improved fit can be obtained by invoking a post-Ordovician clockwise rotation of $13 \pm 4°$. The sense and magnitude match well with rotations seen in both primary Triassic and secondary Palaeogene palaeomagnetic data, and thus we can conclude that no substantial rotation of the Tethyan Himalaya (compared with cratonic India) occurred between Ordovician and Eocene times.

The data presented in this paper strongly suggest that the Tethyan Himalaya were, within error, in close proximity to the Indian craton during early Ordovician time. This is consistent with the continuous margin model, and refutes a version of the accreted terrane model that places the Tethyan Himalaya outboard of Gondwana in the early Ordovician. However, because other versions of the accreted terrane model associate the Tethyan region with India in the Ordovician (e.g. DeCelles *et al*. 2000) our result does not discriminate completely between these models. It does, however, place an important temporal constraint upon any attempt to isolate the Himalayan margin from the Indian craton: it must have been over by the earliest Ordovician.

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