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Paleostrain stratigraphic analysis of calcite twins across the Cambrian–Ordovician unconformity in the Tethyan Himalaya, Spiti and Zanskar valley regions, India

Timothy S. Paulsen [a,*], Christie M. Demosthenous [a], Paul M. Myrow [b], Nigel C. Hughes [c], S.K. Parcha [d]

[a] *Department of Geology, University of Wisconsin, Oshkosh, WI 54901, USA*
[b] *Department of Geology, Colorado College, Colorado Springs, CO 80903, USA*
[c] *Department of Earth Sciences, University of California, Riverside, CA 92521, USA*
[d] *Wadia Institute of Himalayan Geology, Dehra Dun, Uttranchal 248001, India*

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Abstract

Calcite strain analyses were conducted on low-grade Cambrian and Carboniferous limestone samples collected above and below the Cambrian–Ordovician unconformity in the Spiti and Zanskar valley regions of the NW Himalaya in order to compare strain patterns in rocks that bracket an enigmatic early Paleozoic tectonic episode. All samples record a layer-parallel shortening strain at a high angle to folds and faults in the Tethyan Himalayan fold-thrust belt. In the Carboniferous samples, we relate these layer-parallel strains to the onset of Cenozoic deformation within the Tethyan Himalayan fold-thrust belt. The Cambrian sample from the Spiti area contains a layer-parallel shortening strain even though the Cambrian–Ordovician unconformity is angular. This suggests that the twinning strains in the Cambrian sample may have formed at the onset of early Paleozoic folding and subsequent erosion, and that early phases of Cenozoic shortening were coaxial to early Paleozoic shortening. The maximum shortening axis in the Carboniferous samples, which is probably parallel to the early thrust transport direction in the Tethyan Himalayan fold-thrust belt, is parallel to the NE movement of India with respect to Eurasia in the Middle Eocene, suggesting that it might closely correspond to the India/Eurasian slip direction during this time period.

Keywords: Himalaya; Unconformity; Calcite twin; Strain; Early Paleozoic; Cenozoic

1. Introduction

An early Paleozoic deformation episode has long been recognized in the Tethyan Himalaya (Fig. 1; Hayden, 1904), but the tectonic significance of this event and its influence on the Cenozoic development of the Himalayan orogen remains a fundamental problem in Himalayan tectonics (DeCelles et al., 2000; Gehrels et al., 2003; Myrow et al., 2006a, 2006b). Previous authors have related early Paleozoic structural, stratigraphic and magmatic assemblages to terrane accretion (DeCelles et al., 2000), fold-thrust belt tectonism (Gaetani and Garzanti, 1991; DeCelles et al., 2000; Gehrels et al., 2003, 2006), and rifting (Murphy and Nance, 1991; Hughes and Jell, 1999; Wyss, 1999; Miller et al., 2001; Wiesmayr and Grasemann, 2002) along the Tethyan continental margin of northern Indian. The lack of consensus on the nature of early Paleozoic tectonism exists because spatial and temporal patterns of early Paleozoic deformation are poorly constrained, which is due, in part, to the fundamental problem of distinguishing early Paleozoic structures from Cenozoic structures in the Himalaya. In some instances, early Paleozoic intrusions and the Cambrian–Ordovician unconformity cross-cut structures within the

* Corresponding author. Tel.: +1 920 424 7002; fax: +1 920 424 0240.
E-mail address: paulsen@uwosh.edu (T.S. Paulsen).

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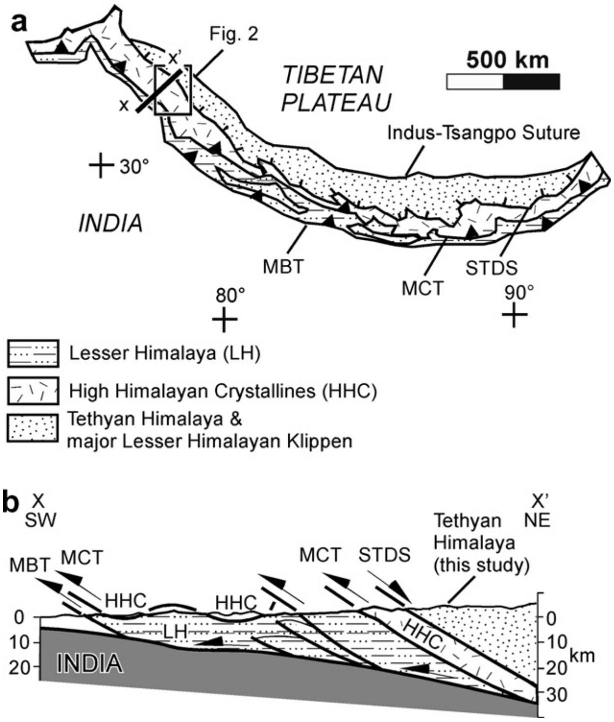

Fig. 1. (a) Simplified regional map of the Himalaya showing major tectonic features within the range (modified from Myrow et al., 2003). (b) Simplified cross section of the northwest Himalaya (modified from Vannay et al., 2004). HHC, High Himalayan Crystallines; LH, Lesser Himalaya; MBT, Main Boundary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

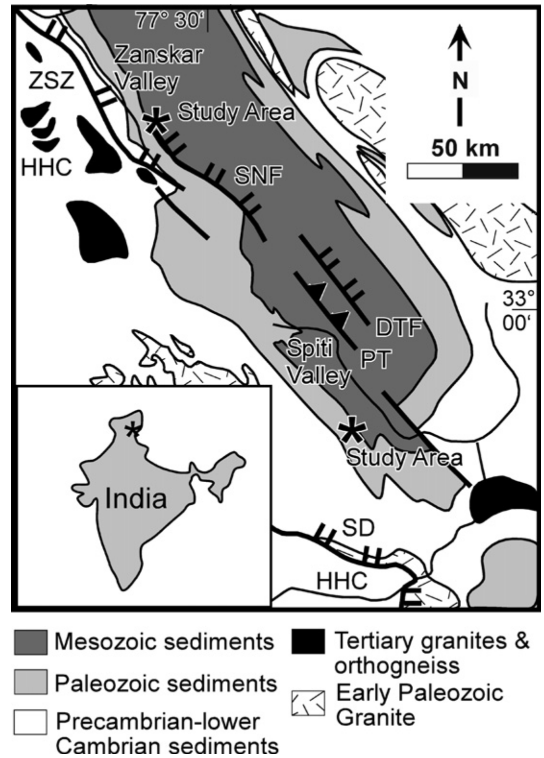

Fig. 2. Geology of the Spiti–Zanskar basin area showing the location of sampling sites in Spiti and Zanskar (after Wyss et al., 1999). Inset shows the location of the map on a regional scale in India (from Draganits et al., 2004). Fig. 1 shows the location of the map area within the Himalaya. DTF, Dutung-Thaktote fault; HHC, High Himalayan Crystallines; PT, Parang La Thrust; SNF, Sarchu Normal Fault; SD, Sangla Detachment; ZSZ, Zanskar Shear Zone.

Himalaya, providing a basis for identifying such structures as early Paleozoic in age (Wiesmayr and Grasemann, 2002; Gehrels et al., 2003, 2006). Unfortunately, such contacts are generally rare in the Himalaya, and as a result, our knowledge of the early Paleozoic strain patterns and their relation to Cenozoic strain patterns remains limited. To address these uncertainties, we approached the problem of early Paleozoic deformation in a new way, namely by conducting a paleostrain stratigraphic analysis of rocks that bracket the early Paleozoic deformation episode. Our approach is similar in concept to a paleostress stratigraphic analysis (Kleinspehn et al., 1989), which uses fault populations in different age stratigraphic intervals to analyze polyphase tectonism in basins. Here, we use calcite twin populations in different age stratigraphic intervals (e.g., Craddock et al., 1993, 1997; van der Pluijm et al., 1997) to analyze strains associated with early Paleozoic and subsequent tectonism along the northern Indian continental margin. The results provide new three-dimensional strain ellipsoidal pattern data from rocks involved in both early Paleozoic deformation and early phases of Cenozoic thrusting during the India–Eurasia collision.

2. Geologic background

This study focuses on calcite strain analyses of rocks collected from the Spiti and Zanskar areas of the Tethyan Himalayan fold-thrust belt in NW India (Figs. 1 and 2; Myrow et al., 2006a, 2006b). The dominant structures in the study areas are faults, folds, and cleavage 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; Corfield and Searle, 2000; Fuchs, 1987; Wiesmayr and Grasemann, 2002; Myrow et al., 2003; Gehrels et al., 2003; Neumayer et al., 2004). In our study areas in Spiti and Zanskar, the structural grain of the fold-thrust belt, as defined by the trends of folds, cleavage, and cleavage–bedding intersections, trends NW/SE and N/S, respectively (Figs. 3 and 4; Dezes, 1999; Wyss et al., 1999; Wiesmayr and Grasemann, 2002; Neumayer et al., 2004). Sedimentary rocks deformed within the Tethyan Himalayan fold-thrust belt range in age from Neoproterozoic to Eocene and are generally of low metamorphic grade. High-grade gneisses of the Greater Himalaya bound these low-grade rocks to the south and are separated from the low-grade rocks of the fold-thrust belt by the Sangla Detachment in Spiti, and the Zanskar Shear Zone in Zanskar (Fig. 2; Vannay and Grasemann, 1998; Dezes et al., 1999; Wyss et al., 1999; Wiesmayr and Grasemann, 2002; Vannay et al., 2004; Neumayer et al., 2004). The Sangla Detachment

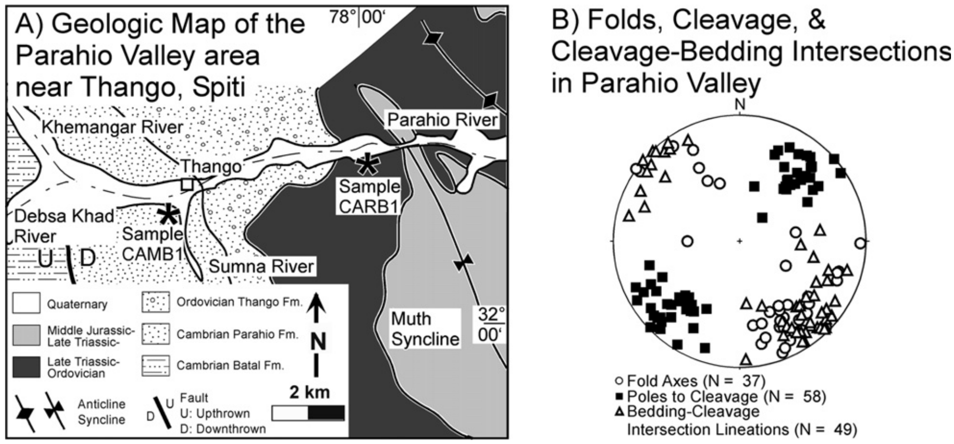

Fig. 3. (A) Geologic map showing sample localities in Spiti (compiled and modified from Fuchs, 1982; Bhargava and Bassi, 1998; Wiesmayr and Grasemann, 2002). (B) Lower hemisphere equal area plot of fold axes, poles to cleavage, and bedding–cleavage intersection lineations within the Tethyan Himalayan fold-thrust belt in the Parahio Valley area (data from Myrow et al., 2006a).

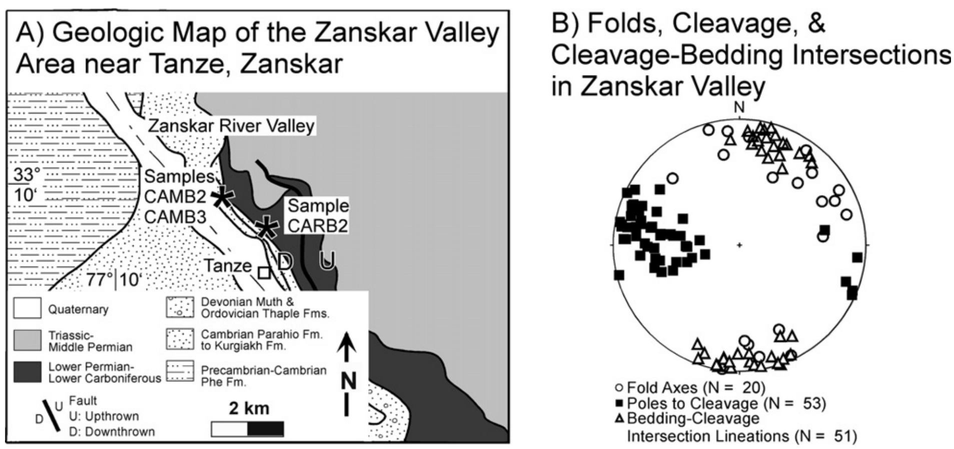

Fig. 4. (A) Geologic map showing sample localities in Zanskar (from Dezes, 1999). (B) Lower hemisphere equal area plot of fold axes, poles to cleavage, and bedding–cleavage intersection lineations within the Tethyan Himalayan fold-thrust belt in the Zanskar Valley area.

and Zanskar Shear Zone are two of a series of north-dipping, extensional shear zones that are generally referred to as the South Tibetan detachment system (Fig. 1; Burchiel et al., 1992). The northern boundary of the Tethyan Himalayan fold-thrust belt is the south-dipping Cenozoic Great Counter Thrust, which marks most of the Indus-Tsangpo suture zone, separating rocks of the Indian and Eurasian plates to the south and north, respectively (Yin and Harrison, 2000).

Our study areas in Spiti and Zanskar contain two of the most important and best-preserved early Paleozoic stratigraphic sections in the Himalaya. Coarse conglomerate of the Ordovician Thango Formation and its equivalent, the Thaple Formation, caps the Cambrian–Ordovician unconformity in the Spiti and Zanskar areas, respectively (Figs. 3–5; Garzanti et al., 1986; Bagati et al., 1991; Bhargava and Bassi, 1998; Myrow et al., 2006a, 2006b). In Zanskar, the conglomerate overlies the latest Middle Cambrian Kurgiakh Formation (Gaetani et al., 1986; Whittington 1986; Jell and Hughes, 1997; Hughes 2002), whereas in Spiti, the unconformity cuts down section such that the conglom-

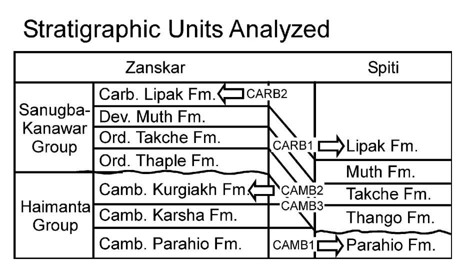

Fig. 5. Stratigraphic units (following Bhargava and Bassi, 1998) sampled and analyzed in the Spiti and Zanskar areas (modified from Myrow et al., 2006b).

erate rests on older rocks of the Middle Cambrian Parahio Formation (Fig. 5; Reed, 1910; Jell and Hughes, 1997; Myrow et al., 2006a). The Cambrian rocks record passive margin sedimentation along the northern Indian continental margin and probably represent the distal equivalents of Cambrian deposits in the Lesser Himalaya (Myrow et al., 2003, 2006a, 2006b; Hughes et al., 2005). Early Paleozoic uplift and erosion of the Cambrian rocks occurred after the earliest Late Cambrian (<500 Ma; Jell 1986; Jell and

Hughes 1997; Myrow et al., 2006b), based on the age of the youngest rocks below the unconformity, but certainly no later than Late Ordovician based on the minimum age of the overlying Ordovician conglomerate (Paterson, 2004; Myrow et al., 2006b). The specific age of the Thango Formation is poorly constrained because fossils offering precise age determinations have yet to be described from that unit. The well-preserved trace fossil *Phycodes circinatum* figured by Bhargava and Bassi (1998, fig. 2.14) is Ordovician in age, but is not necessarily early Ordovician (A. Seilacher, pers. comm. 2005, *contra* Bhargava and Bassi, 1998, p. 24). Paleocurrents from the Ordovician conglomerate indicate transport to the north and northeast, consistent with an uplifted source area to the south to southwest (Garzanti et al., 1986; Bagati et al., 1991). The nature of this uplifted source area remains unknown, in part because of deformation and high-grade metamorphism represented by the High Himalayan Crystalline Sequence in the Greater Himalaya (Myrow et al., 2006b). The carbonate-bearing Takche Formation overlies the Thango and Thaple formations and records a change to a shallow shelf setting (Bhargava and Bassi, 1998), followed by the development of a coastal environment represented by the quartzitic Devonian Muth Formation (Fig. 5; Draganits, 2000). The Lipak Formation succeeds the Muth Formation and records deposition in a low-energy carbonate platform setting that temporally overlapped with the earliest stages of late Paleozoic rifting along the northern Indian continental margin (Fig. 5; Draganits et al., 2005). The Lipak Formation is thought to be mostly early Carboniferous in age although lower parts may be late Devonian (Bhargava and Bassi, 1998, p. 40).

The Spiti area assumes regional significance in the problem of early Paleozoic Himalayan tectonics because it is one of the few areas where folds and faults can be observed to be locally cross-cut by the Cambrian–Ordovician unconformity, and thus be unambiguously classified as early Paleozoic in age. In the Spiti area, the Cambrian–Ordovician unconformity is angular, with an angular discordance ranging from 15° to 40° (Fuchs, 1982, p. 332; Wiesmayr and Grasemann, 2002; Draganits et al., 2004; Myrow et al., 2006a). The unconformity cross-cuts a normal or strike-slip fault with a normal stratigraphic throw of ~70 m (Wiesmayr and Grasemann, 2002). The unconformity also cross-cuts mesoscopic (1–2 m wavelength) and macroscopic (kilometer wavelength) folds that were open and upright prior to Cenozoic folding (Wiesmayr and Grasemann, 2002). Other possible early Paleozoic deformation has been reported in Zanskar, where Dezes (1999) ascribed upright kilometer-scale folds in Cambrian strata to early Paleozoic orogenesis. However, these folds are overlain by the Permian Panjal Traps, which only constrains them as being pre-Permian in age. The early Paleozoic folds in Spiti and the possible early Paleozoic folds in Zanskar trend NW/SE and N/S, respectively, parallel to Cenozoic folds in the Tethyan Himalayan fold-thrust belt. The parallelism of Cenozoic and early Paleozoic folds suggests that Cenozoic deformation may have been roughly coaxial to the early Paleozoic deformation, but the general lack of data left this issue open for debate.

3. Approach to study

To compare strain patterns of rocks across the Cambrian–Ordovician unconformity, we collected oriented Cambrian and Carboniferous limestone samples in both the Spiti and Zanskar areas. Both the Cambrian and Carboniferous samples were affected by Cenozoic deformation associated with the Eocene evolution of the Tethyan Himalayan fold-thrust belt, but because the Carboniferous rocks post-date late Cambrian/early Ordovician deformation they provide a standard with which to compare the strain patterns of the Cambrian rocks. In Spiti, we analyzed one sample from the Middle Cambrian Parahio Formation and one from the Lower Carboniferous Lipak Formation in Parahio Valley (Figs. 3 and 5). In Zanskar, we analyzed two samples from the Middle Cambrian Kurgiakh Formation and one from the Lower Carboniferous Lipak Formation in Zanskar Valley (Figs. 4 and 5). Unlike other parts of the Himalaya, the early Paleozoic stratigraphic successions in these areas are well preserved because Cenozoic metamorphism in the sample areas has been weak. Illite crystallinity measurements indicate that peak metamorphic temperatures probably did not exceed diagenetic conditions in Spiti, and very weak metamorphic conditions (low epizone conditions) in Zanskar (Dezes, 1999; Wiesmayr and Grasemann, 2002). This agrees with the average twin width and twin intensity in our samples, which suggest twinning occurred at temperatures <200 °C (Burkhard, 1993; Ferrill et al., 2004).

4. Calcite strain analysis

A calcite twinning analysis is ideal for a paleostrain stratigraphic study in the Spiti and Zanskar areas because calcite acts as an extremely sensitive strain gauge by twinning at low critical resolved shear stresses (~10 MPa; Burkhard, 1993). The calcite strain gauge technique also represents a powerful tool for identifying non-coaxial strains that are 45–90° from each other (Teufel, 1980). In addition, calcite twinning analyses have been demonstrated to be an effective means for distinguishing paleostrain histories by examining twinning strains in different age stratigraphic intervals (e.g., van der Pluijm et al., 1997). In some cases such analyses appear to have successfully identified twinning strains as old as the early Proterozoic (Craddock et al., 1993, 1997).

We followed the standard procedure of cutting and analyzing two orthogonal thin sections from each sample (Groshong et al., 1984), and measured and analyzed all of the twin sets, excluding bent twins, in 25 grains within each thin section. Twins were measured in cement and fossil grains where present. Our twin measurements include thin twins (i.e., dark lines with no visible twinned material) and thick twins (i.e., twins with visible twinned material). We used an average value of 0.5 μm for the thickness of thin twins in our calculations. We used CSG22 strain-gauge software (Evans and Groshong, 1994) to determine strain ellipsoidal axis orientations for the samples using the calcite strain gauge technique (Groshong, 1972, 1974). The calcite strain gauge technique calculates strain axis orientation and magnitude as a function of twin orientation and thickness, and these vary depending on lithology, grain size, and porosity (Groshong, 1972; Groshong et al., 1984). Table 1 provides the details of the calcite data. The CSG22 software also calculates compression axes for each twin set (Turner, 1953); compression axes are at 45° to each twin set and at 71.5° to the grain's *c*-axis. Fig. 6 shows the three principal strain axes along with contours of compression axis densities for each of the cleaning procedures outlined below.

We applied two data cleaning procedures to the entire data set (ALL) as noise reduction techniques (Groshong, 1974). We removed from ALL 20% of the largest magnitude deviations (largest deviations removed, LDR), which should eliminate the grains with the largest inhomogeneous strains and possible measurement errors (Groshong, 1974). We also separated and analyzed the positive and negative expected values from ALL, and then removed 20% of the largest magnitude deviations from each of these data sets (Groshong, 1974; Teufel, 1980). Positive expected values (PEV) are those twin sets whose orientations are consistent with the overall strain tensor calculated for a twinned calcite aggregate. Twin sets that are not favorably oriented for twinning with respect to the strain tensor are unexpected and thus are referred to as negative expected values (NEV). If the NEV percentage is still high following LDR cleaning (>40%), then the NEV probably reflects an additional non-coaxial strain (Teufel, 1980).

Twinning strains calculated for the Carboniferous and Cambrian samples using all of the data (ALL) from each sample are similar; the strains range from 3% to 12%, *X*/*Z* ratios range from 1.05 to 1.24, and intermediate axial lengths are roughly 1.00, indicating plane strain (Table 1). The differential stress magnitudes that caused calcite twinning in each sample (Jamison and Spang, 1976) are similar for the Carboniferous and Cambrian samples and are listed in Table 1; the differential stress magnitudes range from 94 to 121 MPa for the Carboniferous samples and from 79 to 105 MPa for the Cambrian samples. LDR and PEV data show similar strain axis orientations and magnitudes with respect to ALL. The cleaned data (LDR, PEV, and NEV) show a decrease in NEV percentage with respect to ALL; LDR data range from 7% to 19% NEV; PEV and NEV data range from 0% to 14% NEV. LDR and PEV data show unimodal compression axis maxima that intersect bedding great circle traces and have a similar bearing as the maximum shortening axes ($e1$; Fig. 6). NEV data for samples CAMB1 and CAMB3 show well-defined compression axis maxima that have a similar bearing as the maximum shortening axes ($e1$). NEV data for the rest of the samples have scattered compression axes that lack well-defined maxima. NEV data for samples CARB2, CAMB1, and CAMB2 show $e1$ axes with the same orientations as the $e3$ axes for ALL, LDR, and PEV data, indicating a nearly orthogonal flip between the $e1$ and $e3$ axes for these samples. NEV data for samples CARB1 and CAMB3 have $e1$ axes with the same orientations as the $e2$ axes for ALL, LDR, and PEV data, indicating a nearly orthogonal axis flip between the $e1$ and $e2$ axes.

5. Discussion

Our strain analyses indicate that the Cambrian and Carboniferous samples contain similar twinning strains. In Spiti, the Carboniferous sample (CARB1) and the Cambrian sample (CAMB1) show nearly similar $e1$ axis trends (Fig. 7; LDR and PEV $e1$ = NE/SW; NEV $e1$ = NW/SE). In Zanskar, the Carboniferous sample (CARB2) and Cambrian sample CAMB2 show similar $e1$ axis orientations (Fig. 7; LDR and PEV $e1$ = E/W; NEV $e1$ = N/S). The remaining Zanskar Cambrian sample (CAMB3) differs from the other Zanskar samples in that the E/W shortening ($e1$) is recorded by the NEV data rather than the PEV data, which in turn records the N/S $e1$ (Fig. 7). Although the NEV data in the samples display systematic principal shortening strain orientations following LDR cleaning, all of the samples have low NEV percentages (9–19%; Table 1) of less than 40%, indicating that the samples do not record non-coaxial polyphase deformation (Teufel, 1980). The nearly orthogonal flip between the $e1$ and $e3$ axes (samples CARB2, CAMB1, and CAMB2) and $e1$ and $e2$ axes (samples CARB1 and CAMB3) also makes polyphase deformation dubious (Fig. 6; Burkhard, 1993). The NW/SE (Spiti) and N/S (Zanskar) shortening strains seen in the NEV data are therefore probably related to inhomogeneous strains and/or measurement errors. In Zanskar sample CAMB3, the PEV records the N/S shortening strain, indicating that: (1) inhomogeneous strains dominate that sample and that the cleaning procedure did not adequately remove the inhomogeneous strain, or alternatively, (2) there has been a 90° rotation of strain axes during deformation (e.g., Willis and Groshong, 1993; Craddock and Relle, 2003).

What is the origin of the NE/SW and E/W twinning strains in Spiti and Zanskar, respectively? To answer this question we first focus on calcite twinning age constraints. Cross-cutting relations imply that twinning must be younger than the rocks that contain them and thus the twinning strains within the Cambrian and Carboniferous rocks must at least post-date the earliest Late Cambrian (<500 Ma; Jell, 1986; Jell and Hughes, 1997; Myrow et al., 2006b) and post-date the early Carboniferous (Bhargava and Bassi, 1998, p. 40), respectively. Twinning strains in these samples could be the product of a single post-early Carboniferous deformation or the product of two or more distinct deformation episodes. In general, there are six possible tec-

Table 1
Detailed results of calcite twin analyses using the calcite strain gauge technique

Location	Age/unit/sample ID	Cleaning procedure	*N*	NEV (%)	SEM	Strain orientation (B, P)			Principal strains			Differential stress (MPa)
						*e*1	*e*2	*e*3	*e*1 (%)	*e*2 (%)	*e*3 (%)	
Spiti	Carboniferous	ALL	56	9	1.209	053°, 12°	155°, 46°	312°, 42°	−9.42	−.42	9.84	121
	Lipiak Fm.	LDR	45	9	0.879	056°, 30°	298°, 39°	172°, 36°	−9.14	−.13	9.01	
	CARB1	PEV	41	5	0.816	049°, 7°	147°, 49°	312°, 40°	−9.52	−.13	9.65	
		NEV	4	0	0.000	129°, 25°	001°, 52°	232°, 26°	−17.7	.84	16.92	
Spiti	Cambrian	ALL	73	43	1.619	019°, 17°	126°, 44°	274°, 41°	−9.82	−1.77	11.59	105
	Parahio Fm.	LDR	59	19	1.160	026°, 25°	158°, 55°	285°, 23°	−8.58	−.06	8.64	
	CAMB1	PEV	34	0	1.070	019°, 24°	190°, 65°	287°, 4°	−8.37	.52	7.84	
		NEV	25	8	1.364	118°, 13°	013°, 46°	220°, 41°	−9.99	3.83	6.15	
Zanskar	Carboniferous	ALL	74	24	0.394	092°, 4°	195°, 72°	001°, 18°	−3.20	.85	2.35	94
	Lipiak Fm.	LDR	60	10	0.298	090°, 5°	210°, 80°	359°, 8°	−8.60	−.06	8.60	
	CARB2	PEV	45	0	0.239	089°, 6°	203°, 74°	357°, 14°	−3.91	.74	3.16	
		NEV	15	7	0.630	004°, 6°	133°, 80°	273°, 7°	−3.62	−.03	3.70	
Zanskar	Cambrian	ALL	55	20	1.189	082°, 4°	182°, 68°	351°, 22°	−3.27	−1.89	5.16	79
	Kurgiakh Fm.	LDR	44	7	0.598	080°, 6°	180°, 58°	346°, 32°	−4.88	.05	4.83	
	CAMB2	PEV	36	0	0.506	263°, 10°	153°, 62°	358°, 26°	−6.55	.14	6.41	
		NEV	9	11	2.347	008°, 26°	165°, 62°	273°, 9.5°	−9.93	−.27	10.20	
Zanskar	Cambrian	ALL	50	30	1.732	211°, 17°	115°, 16°	345°, 66°	−6.56	−.99	7.55	83
	Kurgiakh Fm.	LDR	40	17	1.268	206°, 4°	115°, 18°	309°, 71°	−8.51	1.28	7.23	
	CAMB3	PEV	28	14	1.181	198°, 19°	105°, 10°	347°, 68°	−9.50	3.32	6.19	
		NEV	12	0	1.438	268°, 1°	176°, 51°	359°, 39°	−10.15	1.99	8.17	

N, number of twin sets analyzed; ALL, all twins from the sample; LDR, 20% largest magnitude deviations removed; PEV, positive expected values; NEV, negative expected values; SEM, standard error of the analysis; *e*1, *e*2, and *e*3 are the maximum, intermediate, and minimum principal strains with shortening strain being negative; B and P, bearing and plunge.

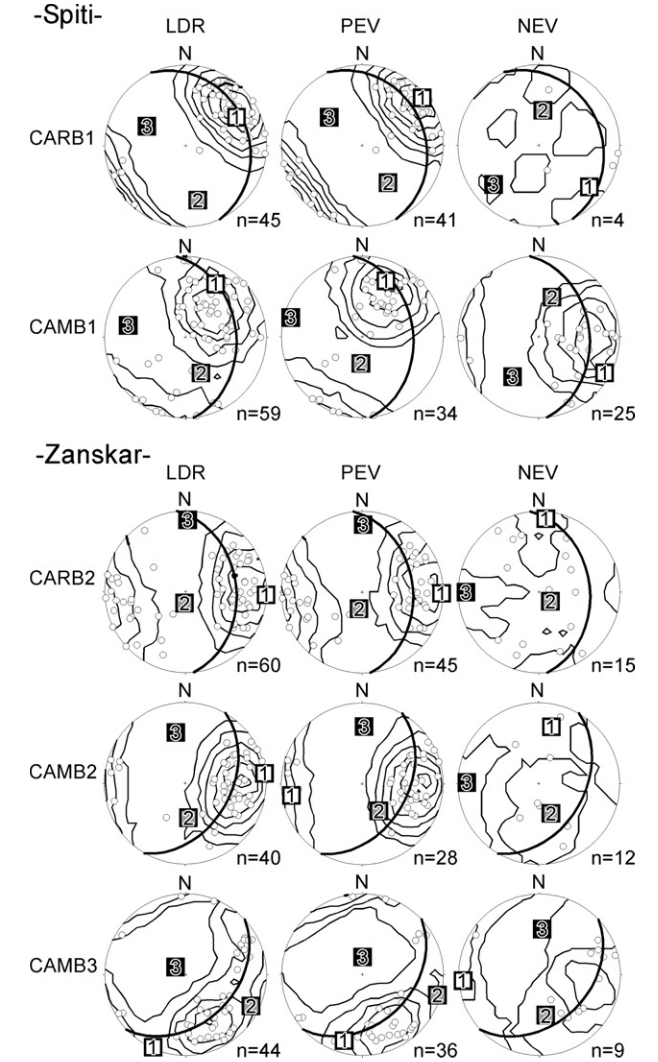

Fig. 6. Lower hemisphere equal area plots of the calcite strain gauge results for Cambrian and Carboniferous samples from Spiti and Zanskar. Numbers refer to strain ellipsoidal axes determined from the calcite strain analyses; $1 = e1$ (shortening), $2 = e2$ (intermediate), and $3 = e3$ (extension). Note the similarity in strain axis orientations for the Cambrian and Carboniferous samples. Equal area plots for all of the data (not shown) show similar strain and compression axes as LDR and PEV. Open circles = compression axes; Kamb contours of compression axes; great circles show bedding; LDR, largest deviations removed; PEV, positive expected values; NEV, negative expected values.

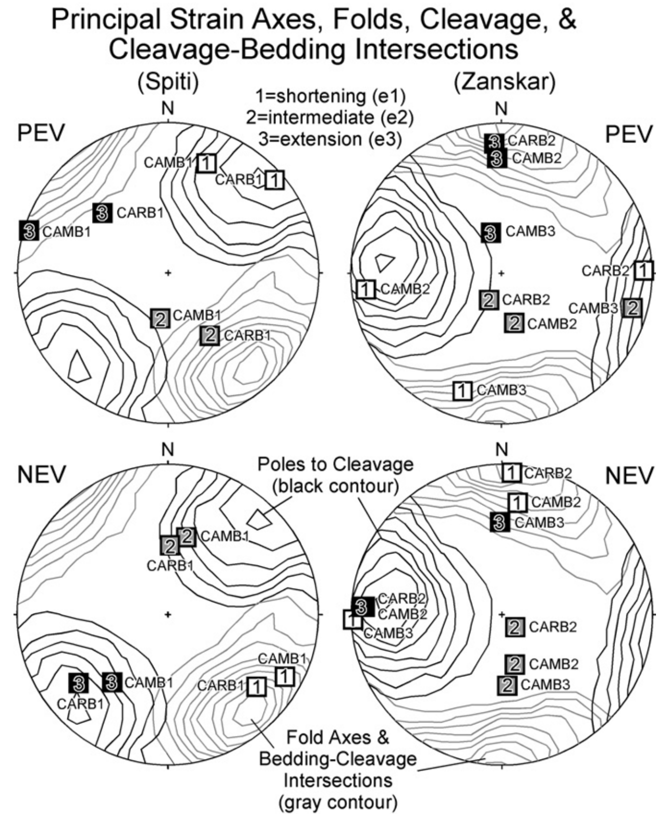

Fig. 7. Lower hemisphere equal area plots showing the spatial relation of the principal strain axes from calcite strain gauge results to Kamb contour plots of the orientations of folds, cleavage, and cleavage–bedding intersection lineations in the Spiti and Zanskar areas. Numbers refer to strain ellipsoidal axes determined from the calcite strain analyses. Note the similarity in $e1$ axis orientations for Carboniferous and Cambrian samples in the Spiti and Zanskar areas. If Cambrian rocks contain an early Paleozoic twin, then the twinning strains are roughly coaxial to the post-early Carboniferous twinning strains in the Carboniferous samples.

tonic events that could have produced twinning strains in our samples: (1) earliest Late Cambrian (<500 Ma) to Late Ordovician Himalayan orogenesis (e.g., Gehrels et al., 2003), (2) early Paleozoic Ross-Delamerian orogenesis (Stump, 1995; Boger and Miller, 2004), (3) late Paleozoic Gondwanide orogenesis (Cox, 1978; Johnson, 1991), (4) early Carboniferous rifting (Draganits et al., 2005), (5) Triassic extension (Draganits et al., 2005), and (6) Cenozoic Himalayan orogenesis (Yin and Harrison, 2000).

India was part of Gondwana in the Paleozoic, during which the early Paleozoic Ross-Delamerian and late Paleozoic/early Mesozoic Gondwanide orogenies occurred along the Panthalassan margin of Gondwana (Cox, 1978; Johnson, 1991; Boger and Miller, 2004). It is possible that some of the twinning strains formed in response to far-field stress transmission from these distant orogenic belts, but calcite twinning due to the transmission of stress over hundreds of kilometers predicts that calcite twins will record relatively low differential paleostress magnitudes on the order of tens of MPa (Craddock et al., 1993, 1997; van der Pluijm et al., 1997). The differential stress magnitudes determined from calcite twin fabrics in our rocks are higher than this and are similar to differential stress magnitudes previously reported for rocks from orogenic belts, such as fold-thrust belts in the Canadian Rockies (Jamison and Spang, 1976), the Appalachians (Craddock et al., 1993, 1997; van der Pluijm et al., 1997), and the Sevier fold-thrust belt (Craddock, 1992; Craddock and van der Pluijm, 1999) of North America.

The NE/SW (Spiti) and E/W (Zanskar) shortening strains are probably not related to twinning in a purely extensional environment during late Paleozoic rifting or late Triassic extension along the northern Indian continental margin (Brookfield, 1993; Draganits et al., 2005) because this predicts steeply plunging $e1$ axes (Lomando and Engelder, 1984), which we do not see in our samples. Our compression axis maxima cluster around the bedding great circle traces (Fig. 6), indicating that twinning records a layer-parallel shortening strain. There is evidence from conjugate cataclastic bands in the lower Devonian Muth Formation in Spiti for pre-Himalayan layer-parallel shortening, which has been postulated to be associated with either early Carboniferous rifting or Late Triassic extension (Draganits et al., 2005). However, the deformation bands record layer-parallel E/W shortening and N/S extension, whereas the twinning strains in Spiti record NE/SW layer-parallel shortening, indicating that the twinning strains are probably not related to whichever extensional episode produced the deformation bands.

Did the twinning strains develop due to fold-thrust belt deformation associated with the Cenozoic India/Eurasian collision? Previous calcite twinning studies from other fold-thrust belts indicate that calcite twinning commonly occurs during the earliest phases of fold-thrust belt deformation, prior to major faulting and folding, and tends to strain harden such that the original layer-parallel shortening strain is preserved during subsequent deformation (Kilsdonk and Wiltschko, 1988; Craddock et al., 1988; Evans and Dunne, 1991; Craddock, 1992; and references therein). LDR and PEV data in our samples show unimodal compression axis maxima that intersect bedding great circle traces and have a similar bearing as the maximum shortening axes ($e1$; Fig. 6), suggesting that they developed, at least in part, from layer-parallel shortening. The slight deviation of the maximum shortening axis from bedding for PEV data from samples CARB2 and CAMB2 may be due to strains related to folding, which can cause the maximum shortening direction to deviate from bedding such that it plunges toward the core of the fold (Groshong, 1975). In extreme cases, folding strains can cause a rotation of the shortening strain direction such that it no longer shows down-dip shortening (Willis and Groshong, 1993), which provides a possible explanation for the anomalous N/S maximum shortening direction displayed by the CAMB3 PEV data. Folding strains notwithstanding, the NE/SW and E/W layer-parallel shortening strains identified in this study trend at a high angle to Cenozoic folds, cleavage, and cleavage–bedding intersection lineations in the Tethyan Himalayan fold-thrust belt (Fig. 7; Dezes, 1999; Wiesmayr and Grasemann, 2002; Neumayer et al., 2004). We therefore conclude that the layer-parallel shortening strains (in the Carboniferous samples) likely formed during initial layer-parallel shortening associated with the Cenozoic India/Eurasian collision (Figs. 8 and 9).

Like the Carboniferous samples, the Cambrian samples have NE/SW (Spiti) and E/W (Zanskar) $e1$ axes associated with compression axis maxima that cluster around the bedding great circle traces (Fig. 6), indicating that the twinning records a layer-parallel shortening strain. At first glance, it would appear that the simplest scenario to explain the similarity in Carboniferous and Cambrian twinning strains would be that the Cambrian samples also record Cenozoic

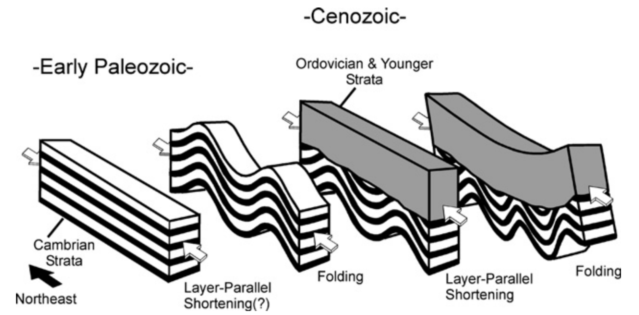

Fig. 8. Coaxial layer-parallel shortening strains in the Cambrian and Carboniferous samples may be the result of roughly coaxial early Paleozoic and Cenozoic deformation episodes (after Wiesmayr, 2000).

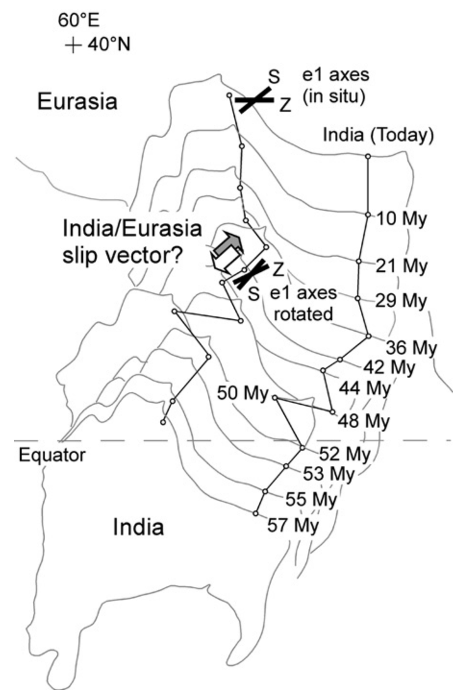

Fig. 9. Reconstruction showing India's movement with respect to Eurasia for the last 57 million years (after Patriat and Achache, 1984). Lines connecting open dots represent the relative movement of two points on the Indian continent with respect to Eurasia. The trend of the $e1$ axes (S, Spiti; Z, Zanskar) for the Carboniferous rocks probably reflects the Middle Eocene thrust direction of the Tethyan Himalayan fold-thrust belt. Corrective rotation of the $e1$ axes to account for vertical axis rotations since the Middle Eocene suggests that the thrust slip direction was parallel to the relative movement of India with respect to Eurasia and that it may record the India/Eurasian slip direction during this time period.

thrusting, rather than early Paleozoic deformation. Although we cannot rule out the possibility that the twinning fabrics are Cenozoic in age, relations in the Spiti area suggest that they could be, at least in part, early Paleozoic in age. In the Spiti area, the Cambrian–Ordovician unconformity is angular (~15°; Wiesmayr and Grasemann, 2002). This angularity implies that the Cambrian strata likely had an initial dip at the onset of Cenozoic thrusting. Early shortening associated with Cenozoic deformation would be expected to have imparted non-layer-parallel shortening strains in the Cambrian rocks below the unconformity if these rocks had not been twinned, and thus strain hardened, prior to Cenozoic deformation. The layer-parallel shortening strains in the Cambrian samples therefore may have formed during early Paleozoic deformation, prior to early Paleozoic folding and subsequent erosion. Once the early Paleozoic twinning occurred, it could have strain hardened such that the original twinning fabric was preserved during subsequent deformation. A high differential stress oriented at 45–90° to the earlier twinning strain would be required to superimpose a second twinning strain (Teufel, 1980; see Craddock et al., 1988 and references therein). The low NEV percentages (<20%) of the Cambrian samples following LDR cleaning suggests that if the Cambrian samples do contain an early Paleozoic twin, then Cenozoic shortening was <45° to early Paleozoic shortening (Fig. 8; Teufel, 1980). This possibility is supported by the orientations of the few early Paleozoic folds that have been recognized in the areas, which suggest roughly coaxial early Paleozoic and Cenozoic folding (Dezes, 1999; Wiesmayr and Grasemann, 2002).

This is the first study to our knowledge that uses mechanically twinned calcite to investigate strain patterns in the Himalaya. The maximum layer-parallel shortening strain recorded by calcite twins in fold-thrust belts is in most cases parallel to the thrust transport direction (Kilsdonk and Wiltschko, 1988; Craddock et al., 1988; Craddock, 1992, and references therein). The Cenozoic twinning strains in the Carboniferous samples may therefore provide new data on the early thrust transport direction of the Tethyan Himalayan fold-thrust belt during the early stages of the India/Eurasia collision. Illites from sedimentary rocks have ^{40}Ar–^{39}Ar cooling ages of 43.5 ± 1.5 Ma (Spiti) and 44 ± 5 Ma (Zanskar), suggesting Cenozoic thrusting and thus, twinning, at least in the Carboniferous samples, occurred in the Middle Eocene (Bonhomme and Garzanti, 1991; Wiesmayr and Grasemann, 2002). The calcite data do not account for clockwise vertical axis rotations (~27.5° in Spiti and ~45° in Zanskar) of the Tethyan Himalayan fold-thrust belt with respect to India (Klootwijk et al., 1985; Schill et al., 2001), or for the ~18° counterclockwise rotation of India with respect to Eurasia since the Middle Eocene (Fig. 9; Patriat and Achache, 1984). Corrective rotations of the strain axes to account for these movements suggest a NE/SW Middle Eocene thrust transport direction, which is parallel to the relative movement of India with respect to Eurasia (Fig. 9; Patriat and Achache, 1984), suggesting that it may reflect the India/Eurasian slip direction during this time period (Dewey et al., 1989).

6. Conclusions

Calcite twinning analyses show that Cambrian rocks, which were deformed during an early Paleozoic deformation episode in the Tethyan Himalaya, NW India, contain shortening strains that are roughly parallel to shortening strains in Carboniferous rocks that post-date this event. Twinning strains within Carboniferous rocks are likely related to the onset of Cenozoic thrusting within the Tethyan Himalayan fold-thrust belt and may record shortening parallel to the Middle Eocene slip direction of the India/Eurasian collision zone. Although a Cenozoic age for twinning fabrics in early Paleozoic samples cannot be ruled out, relations in the Spiti area suggest that they could be early Paleozoic in age and that Cenozoic shortening may have been roughly parallel to early Paleozoic shortening within this sector of the Himalaya.

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