Eohimalayan fold and thrust belt in the NW-Himalaya (Lingti-Pin Valleys): Shortening and depth to detachment calculation

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KEYWORDS
Spiti
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† Following the tragic death of Julian Neumayer in an ice-avalanche in the mountains of Peru at the end of May 2003, this manuscript was completed by his co-author friends.

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Abstract

Structural field data processed with forward and backward balancing software provide a rigorously balanced cross section of the deformed Tethyan Himalaya sediments of the Higher Himalayan tectonic unit (Spiti and Lingti Valleys, NW-Himalayas). The dominant local Eocene Eohimalayan deformation phase (D2) has two deformation styles, depending on lithologic/competence contrasts: Large scale SW-vergent fault-propagation folding and SW-directed thrusting in the basal part of the stratigraphy, below a local detachment horizon, located at the upper boundary of the Devonian Muth Formation. The stratigraphically higher part of the sequence is deformed by short wave-length low amplitude detachment folding. The calculated shortening of the D2 deformation event in the Lingti Valley (c. 36%) is comparable with shortening values from the Pin Valley (~30%).

Calculated geometries indicates a flat lying openly folded basal detachment at a depth of about 10 km, coinciding with the approximated local depth of the South Tibetan Detachment System in this area. We infer a shallow dipping continuation of the Higher Himalayan Crystalline metamorphic rocks below the Tethyan Himalaya in Spiti. The South Tibetan Detachment System most plausibly represents an Eohimalayan thrust reactivated in the Miocene as a normal fault thereby facilitating the extrusion of the Higher Himalayan Crystalline wedge, as hitherto suggested.

Eohimalayan structures in the SW are overprinted by a shallowly NE dipping axial planar cleavage (D3). In the Lingti Valley, conjugate cataclastic normal faults indicate Late Miocene to recent age W-E extension (D4). These normal faults possibly indicate the northwards continuation of the Kaurik-Chango Fault.

1. Introduction

The collision of India with Asia, starting roughly 55-50 Ma ago (Garzanti and van Haver, 1988; Searle et al., 1997), resulted in more than 2000 km of shortening between India and Asia and in the decrease of the convergence rate from previously nearly 20 cm/a to recently about 5 cm/a (Dewey et al., 1989). Long-term rates in the Himalayas are only in the order of about 2 cm/a, while the remainder is probably accommodated by distributed deformation and zones of high deformation throughout Tibet, Tien Shan and Altai, an area of > 1000km N-S width. The evidence of the total shortening between India and Asia since its collision comes mainly from magnetic anomaly, palaeomagnetic and volumetric balancing studies (see Johnson, 2002). The few published balanced cross sections focus on profiles mainly south of the crystalline core of the Himalayan range (e.g. Schelling and Arita, 1991; Srivastava and Mitra, 1994; DeCelles et al., 2001) suggesting that shortening in the order of 60-70% occurred since the Miocene.

These shortening budgets leave a considerable deficit, when compared with the overall convergence of India and Asia, probably because pre-Miocene shortening is largely neglected by these studies. Comparatively few balanced sections exist from the Tethyan Himalayas north of the crystalline core (e.g. Corfield and Searle, 2000). In the Tethyan the Eocene deformation phase immediately followed the collision, the so called Eohimalayan phase, forming a huge fold and thrust belt in the Tethyan sediments; the former Palaeozoic and Mesozoic passive margin on the Indian continent (Searle et al., 1988). Balanced sections in the Tethyan Himalayas are clearly crucial to constrain the amount of Eohimalayan shortening, highlight the mechanisms of deformation within the fold and thrust belt and define a detachment horizon for the Tethyan sediments; a horizon that may have been either reactivated or overprinted by Miocene tectonics events.

Recently, Wiesmayr and Grasemann (2002) presented a detailed balanced cross section along the SW- NE trending Pin Valley (Spiti, NW Himalayas) constraining the geometry and evolution of the Eohimalayan fold-thrust belt in this area (Figs. 1 and 2). Ar/Ar data from micas formed in axial planes contemporaneously to folding, indicated an EarlyMiddle Eocene age for the SW directed crustal thickening deformation by large scale folding and thrusting. Additionally, the balanced model demonstrated that the amount of shortening of the fold-thrust belt is about 30%, and that this has been partitioned into large scale, SW vergent fault-propagation folds and translation along imbricate thrusts in the lower part of the sedimentary sequence and into short wave-length lower amplitude folding above local detachment horizons within the higher stratigraphic succession. The present work extends the Wiesmayr and Grasemann (2002) section in the Pin Valley by 20 km towards ENE into the Lingti Valley (Fig. 1) and thereby provides a test of the deformation phases, the amount and style of shortening, and, most critically, the depth of the constructed detachment. This demonstrates that although most of the Eohimalayan tectonic characteristics are quite similar. The presence of younger brittle deformation structures in the Lingti Valley indicates a different structural position in the tectonometamorphic evolution of the Himalayan orogen.

2. Regional Geology

The ongoing collision between India and Asia causes deformation, crustal thickening and surface uplift of the Himalayan orogen. Indian upper continental crust has been sheared off and thrust along major, hundreds of meters thick thrust zones in south-westward direction. These thrust zones divide the Himalayan orogen into ist major tectonic units (Fig. 1); from North to South, Transhimalaya, Indus-Yarlung Suture Zone, Higher Himalaya, Lesser Himalaya and Sub Himalaya (Gansser, 1964; Yin and Harrison, 2000; Hodges, 2000 and references cited therein): The Transhimalaya tectonic unit comprises granitic rocks, cropping out directly to the North of the Indus-Yarlung Suture Zone, which defines the surface trace of the actual boundary between Indian and Asian crust in the Himalayan orogen. The igneous rocks of the Transhimalaya originated from Andean-type magmatism related to the subduction of the Tethyan oceanic crust beneath Asia, in front of the actual collision of India and Asia. South of the Indus-Yarlung Suture Zone, the Higher Himalaya forms the northernmost tectonic unit of the Indian crust. The Higher Himalaya is situated above the Main Central Thrust, upon which the Higher Himalaya is thrust SW-wards over the Lesser Himalayan tectonic unit. The Higher Himalaya is divided into two sub-units, into the Higher Himalaya Crystalline in lower parts of the tectonic unit and the overlying Tethyan Himalaya. The Higher Himalaya Crystalline, lying structurally directly above the Main Central Thrust, comprises metamorphosed, Proterozoic sedimentary rocks intruded by two generations of granites, with respective intrusion ages of around 485 Ma old, 20 Ma and younger (Le Fort, 1986; Miller et al., 2001). The South Tibetan Detachment System (Burg et al., 1984; Burchfield et al., 1992) represents the generally accepted tectonic boundary to the overlying Tethyan Himalaya. It consists of low-grade metamorphosed, mainly marine sandstones, shales, dolomites and limestones. These sediments have been deposited upon the northern Indian continental margin and range from Precambrian to Eocene in age. The Lesser Himalaya consists of Precambrian to early Tertiary metasediments including a 1.8 Ga basement and is thrust over the Subhimalayas along the Main Boundary Thrust. The Sub-Himalaya at the southern margin of the wedge is the outermost tectonic unit of the orogen and comprises mainly sandstones and conglomerates derived from the erosion of the rising Himalayas in the North. The Sub-Himalaya overthrusts Quaternary sediments of the Indus-Ganges plains upon the still active Main Frontal Thrust, which accommodates a major part of the present shortening between India and Asia.

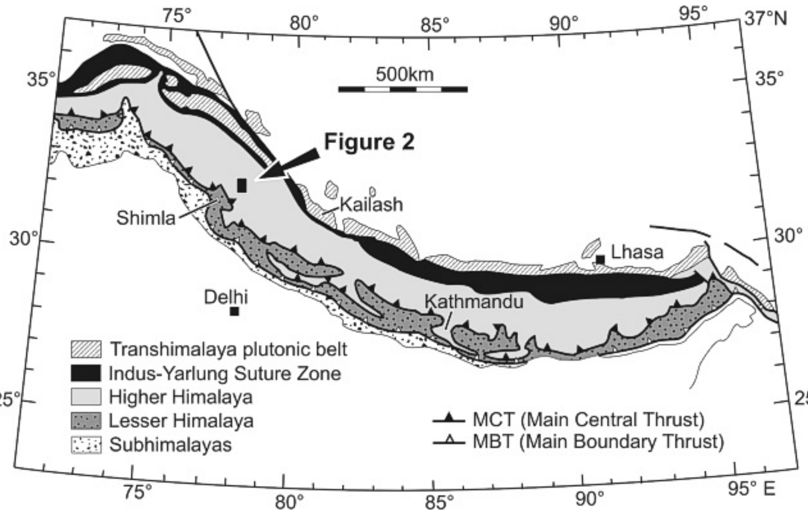


Figure 1: Simplified tectonic map of the Himalayan orogen (after Gansser, 1964; modified by Schuster, 1999), with five major tectonic units 1) Subhimalayas, 2) Lesser Himalaya, 3) Higher Himalayas 4) Indus Yarlung Suture Zone and 5) the Transhimalaya. Arrow indicates position of studied location in Spiti shown in a detailed geological map in Figure 2.

Our investigated section is located in the Tethyan Himalayas (Pin and Lingti Valleys, Spiti, NW India) (Fig. 2), where a classical stratigraphic section (Griesbach, 1891; Hayden, 1904; Bhargava and Bassi, 1998) of more than 5 km from late Proterozoic to Mesozoic passive margin sedimentary sequence has been folded into spectacular km-scale syn- and anticlines (Fuchs, 1982). Here, in the outer part of the Tethyan fold and thrust belt, shortening is generally considered to be older than movement along the Main Central Thrust (i.e. pre-Miocene) and several nappe structures have been described by numerous authors (see Steck, 2003 and references cited therein).

For the purpose of balanced cross section constructions and to correspond to the scheme of Wiesmayr and Grasemann (2002), the sedimentary sequence has been divided into five units, firstly competence units A, B, C, D, which make up the Upper Fold Belt and secondly the Basal Fold-Thrust Belt (Fig.3). This division is based on the litho-stratigraphy as well as mechanical competence during deformation. As part of their competences contrast during folding, the units are separated by local detachments from one another, of which the local detachment on top of the Muth Formation is the most prominent. This local detachment divides the sedimentary sequence into two parts, which we call the Upper Fold Belt and the Basal Fold-Thrust Belt, and which exhibit different deformation styles (Fig. 6). Details on the litho-stratigraphy of this area are given in Fuchs (1982), Garzanti et al. (1995) and Draganits (2000). The lowermost competence unit, the Basal Fold-Thrust Belt comprises (1) the Precambrian-Cambrian Haimanta Group consisting of alternating metagreywackes, metapelites and metasiltstones overlain by dolomites and shales. These are unconformably overlain by (2) the Ordovician Shian Formation with transgressive conglomerates at the base and thick, massive quartzites on top. The quartzites are conformably overlain by (3) the mixed siliciclastic/carbonatic Pin Formation (Ordovician/Silurian), which is disconformably overlain by (4) the pure quartzites of the Devonian Muth Formation.

This Basal Fold-Thrust Belt rocks are overlain by Competence Unit A consisting of rheologically incompetent shales and siltstones with minor sandstones, which are alternate with carbonates and range from Carboniferous to the Carnian in age. Competence Unit B consists of a thick carbonate succession. (Carnian-Norian). Competence Unit C consists of predominating shales and mudrocks ranging from Norian-Rhaetian. Competence Unit D consists of a more than 600m thick competent carbonate succession that underlies arkoses and quartzarenites (Dogger). Competence Units A-D, the Upper Fold Belt, represent an alternation of rheologically incompetent and competent horizons (Figs. 3 and 6).

3. Deformation phases

Three significant deformation events (D1, D2 and D3) that affected

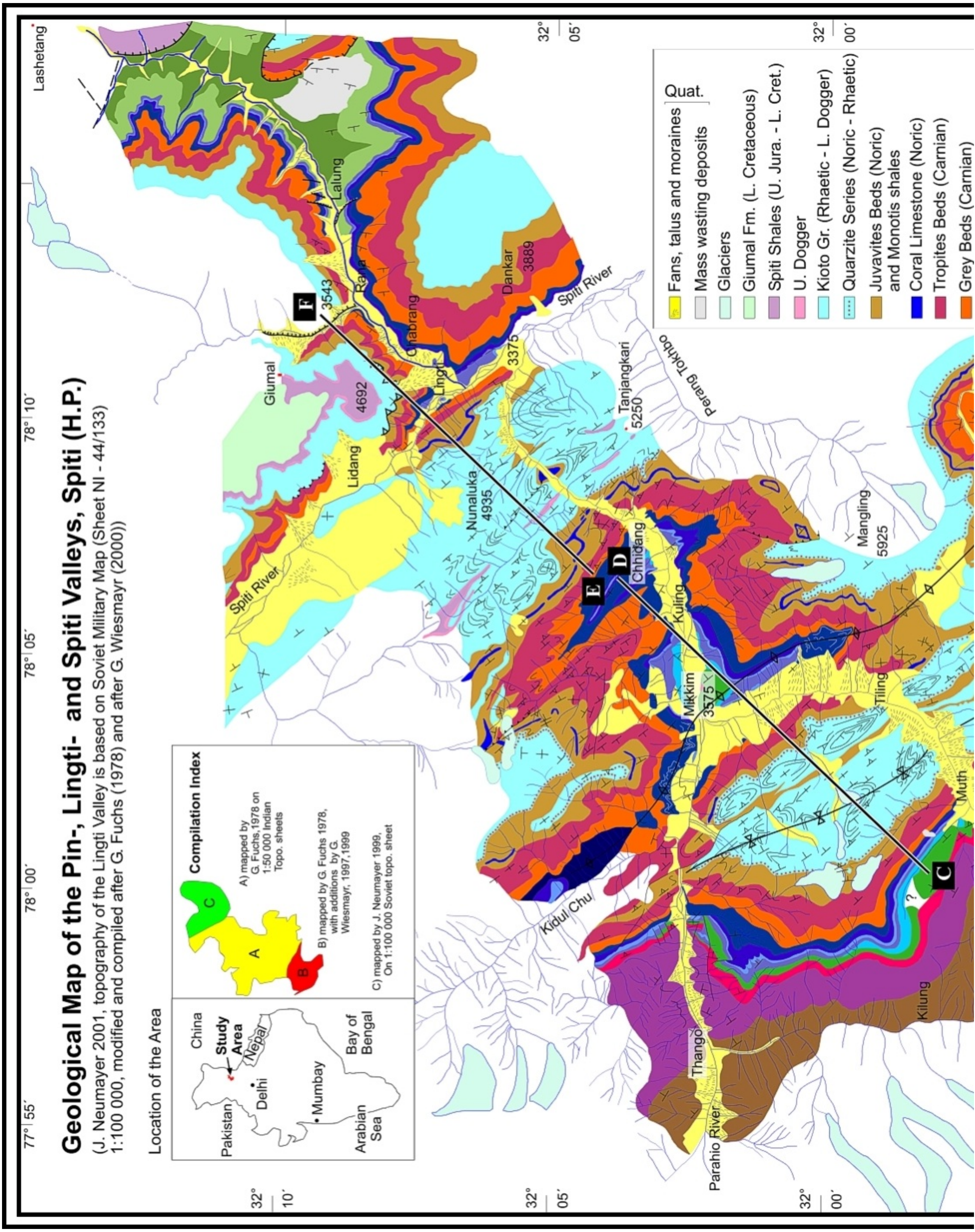
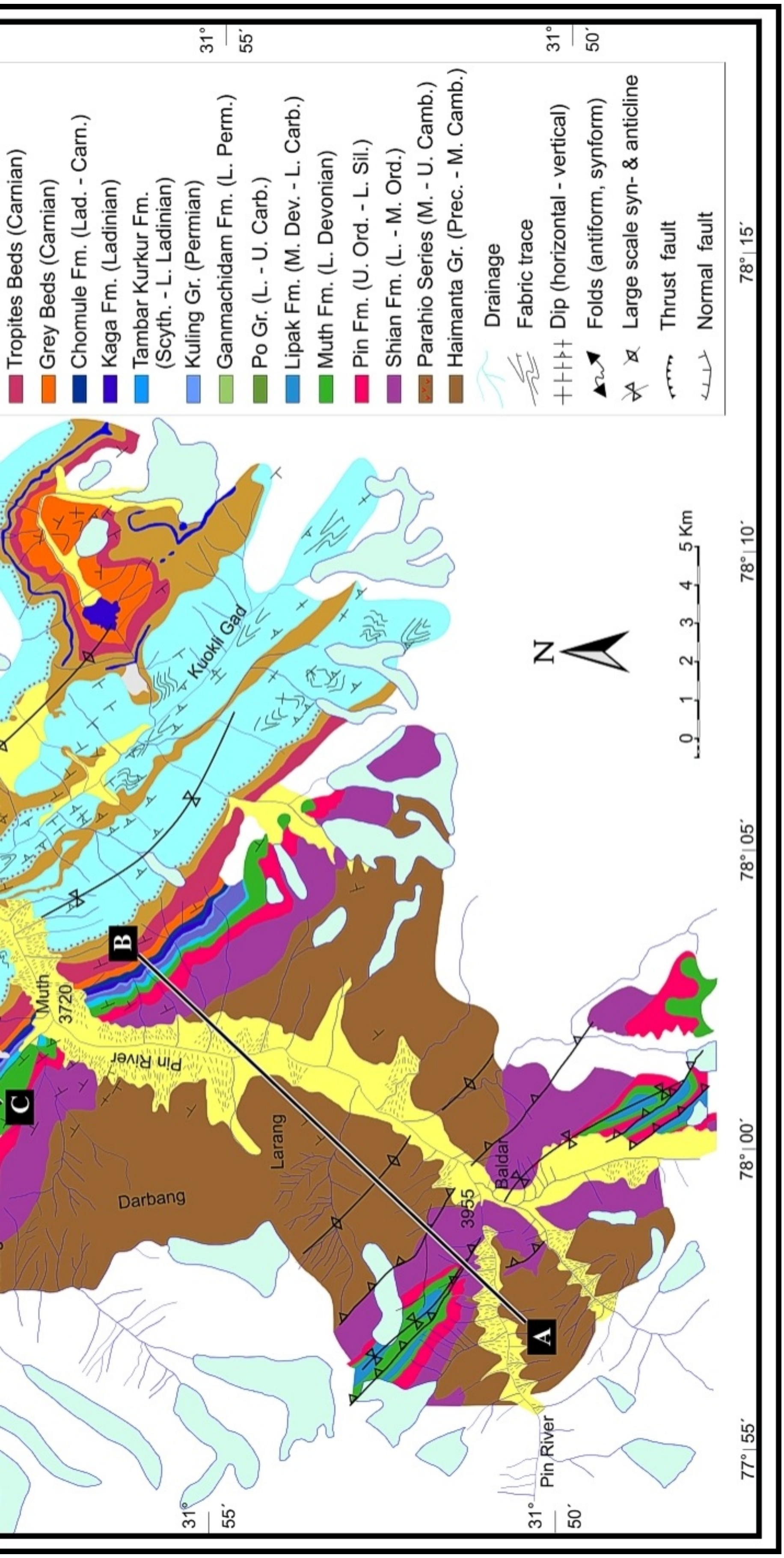


Figure 2: Geological map of Pin-, Lingti- and Spiti Valley (Himachal Pradesh) compiled and modified after Fuchs (1982) and Wiesmayr (2000). Sections AB and CD of Wiesmayr and Grasemann (200



mann (2002) have been continued towards NE into the Lingti Valley (section EF). Complete balanced section is shown in Figure 6.

the major style of the fold-and thrust belt are discriminated, in agreement with the results of Wiesmayr and Grasemann (2002): D1 comprises remnants of a pre-Himalayan deformation event; D2 represents the dominant large scale folds and thrusts formed as part of the Eohimalayan event; D3 is related to the Miocene extrusion of the Higher Himalayan Crystalline structurally lying below the Tethyan Himalaya. Note, that D1 and D3 are only recorded in the southwestern parts of the section in the Pin Valley, but the newly recognised D4, recording brittle W-E extension, has only been observed in the Lingti Valley (Fig. 4).

3.1. Pre-Ordovician deformation (D1)

The angular unconformity between the Cambrian successions of the Haimanta Group and the overlying Ordovician Shian Formation (Fig. 4) has long been recognized (Hayden, 1904), but its tectonic history and relationship to the widespread intrusion of Cambro-Ordovician granites is still debated (Miller et al., 2001 and references therein). The erosive contact of fluvial conglomerates with marine slates, siltstones and carbonates together with a depositional gap, indicate surface uplift and erosion. The angle of the angular unconformity is about 15° in the Pin Valley, but reaches nearly 90° in Kumaon (Griesbach 1891). In addition to local, short wavelength folding and general very open folding with km-scale wavelengths, Wiesmayr and Grasemann (2002) found some indications of extensional tectonics, sealed by the unconformity. This litho-stratigraphic level and thus the unconformity is not exposed in the extended northeastern part of the cross section presented here (Fig. 4).

3.2. Eohimalayan deformation (D2)

The SW vergent, large-scale folding whose steep axial surfaces and SW directed thrust faults dominates the finite deformation recorded in the Tethyan Himalayas in the Pin and Lingti Valleys.

The rocks in the Pin Valley record a penetrative axial surface cleavage with contemporaneously recrystallized illites growing in cleavage domains. Several sizes of fractions of these illites gave Ar/Ar ages between 42 and 45.8 ± 0.7 Ma (Wiesmayr and Grasemann, 2002), and are interpreted as formation ages suggesting that folding occurred during the Middle Eocene. The Basal Fold-Thrust Belt and the competent units of the Upper Fold Belt have been deformed by flexural slip folding. Slickensides related to this folding mechanism are typically coated with chlorite slickenfibres (Fig. 4). Less competent units (Competence Units A and C) are deformed by non-parallel folding resulting in distinct thickness variations between the hinges and fold limbs. These folds are imbricated along several SW directed thrusts with evidence for brittle/ductile deformation mechanism (Fig. 5a, b). Folding and faulting are clearly interrelated and are best explained by fault propagation fold models, described in detail below.

In the northeastern parts of the section deformation occurred mainly in the brittle field by faulting, cataclastic deformation and pressure solution/precipitation. Second order folds in the Upper Fold Belt frequently have a box shape with steep NE and SW dipping sets of axial surfaces (Fig. 4 and 5c). Fold hinges are sharp, frequently showing kink type geometries. Refold structures developed ($D2_1$ and $D2_2$ in Fig. 4) due to the progressive development of the second order folds and migration of axial surfaces.

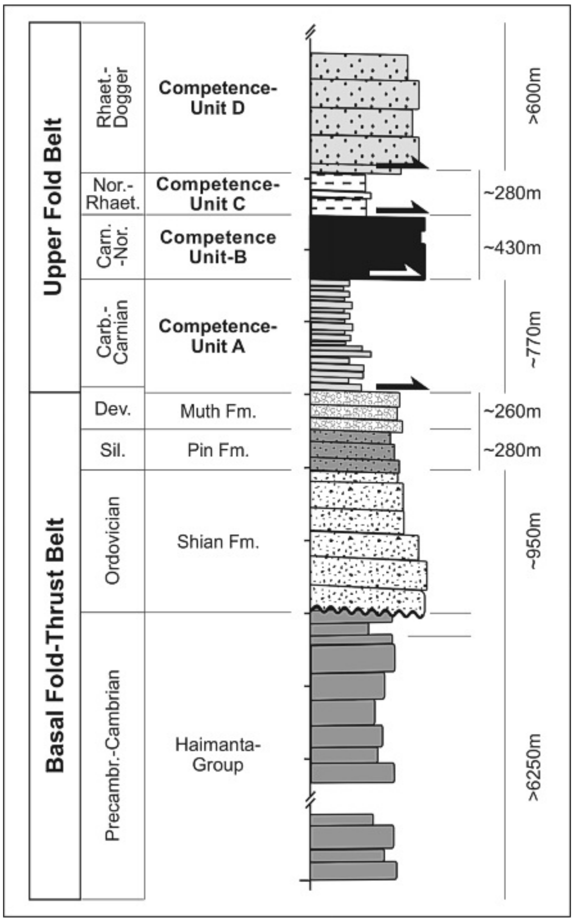


Figure 3: Simplified stratigraphic column of the Tethyan Himalayas in Spiti modified after Fuchs (1982), Garzanti et al. (1995), Draganits (2000) and Wiesmayr and Grasemann (2002). Following suggestions of Wiesmayr and Grasemann (2002) entire column is divided in two major components: A Basal Fold - Thrust Belt (Precambrian-Devonian), which behaves as a coherent unit and an Upper Fold Belt, which consists of four competence units A-D, separated by local detachments.

3.3. Neohimalayan deformation (D3)

In the SW parts of the complete Pin and Lingti Valley section, the D2 axial surfaces are overprinted by a later foliation moderately dipping towards the NE (Fig. 4). This foliation is interpreted as being related to the Miocene extrusion of the underlying Higher Himalayan Crystalline (Wiesmayr and Grasemann, 2002). Only structurally higher levels are exposed in the NE parts of the Pin and Lingti Valley and therefore D3 is not recorded in the rocks investigated in this study.

3.4. Neotectonic deformation (D4)

An additional extensional deformation event overprinting all other structures has been found that is restricted to the Lingti Valley; it is not been recorded in the Pin Valley rocks. It shows increasing intensity towards the NE part of the Lingti Valley section. The brittle normal faults strike roughly N-S to NNW-SSE and are present either as steeply dipping conjugate sets or as bookshelf-type extensional faults (Fig. 4 and 5d). A further group of extensional faults, striking NW-SE and dipping towards NE, can be discriminated within the collected fault plane measurements. Some of these faults show polyphase slickensides, evidencing earlier thrusting kinematics overprinted by normal displacement. These faults have therefore been interpreted as D2 thrusts, formed during Eohimalayan shortening, subsequently reactivated as normal faults during D4.

In the Lingti Valley, these faults are frequently associated with zones of brittle deformation that comprise incohesive fault breccias and fault gouge. Faulting of Quaternary lake sediments as well as soft-sediment deformation structures resulting from liquefaction and fluidization of these sediments are both probably related to D4 deformation (see also Bhargava and Bassi, 1998). In the Leo Pargil area (SE of the Pin and Lingti Valley), similar structures have been interpreted by Ni and Barazangi (1985) as seismites related to activity of the steeply W-dipping Kaurik-Jango normal fault. Some of the lake sediments have been dated between 20,000 4,000 years (Ni and Barazangi, 1985).

Based on (1) the similar kinematic orientation and (2) the nearby position of Leo Pargil to the SE, we speculate that the brittle deformation in the Lingti Valley is part of the hanging wall extension of the Kaurik-Jango fault recording neotectonic activity on this area.

4. Balanced Cross Section

The balanced cross section of this investigation represents a continuation towards the NE into the Lingti Valley of the Pin Valley balanced cross section of Wiesmayr and Grasemann (2002). Based on the observation that D2 is the major deformation event responsible for the large scale structures in the Pin and Lingti Valleys, a section was chosen parallel to the main transport direction of the D2 deformation. Because D2 folds are sub-cylindrical flexural slip folds, no material has been substantially transported into or out of the sections (plane strain). Because (1) D3 is not recorded in this part of the Pin Lingti Valley overall section and (2) with the except of a larger normal fault at the NE termination of the section (Fig. 6), brittle deformation D4 has only minor impact on the finite deformation and can be neglected for the construction of the balanced cross section.

As mentioned above, D2 folding and faulting are clearly interrelated and are both reasonably described by fault propagation folds models followed by translation along imbricate thrusts or breakthrough thrusting along the synclinal axial surface. Based on the idea that only a limited suite of structures generally occur within the same tectonometamorphic unit (Hansen, 1971), the assumed fault propagation fold models and the balancing techniques strictly follow those of Wiesmayr and Grasemann (2002) as these were

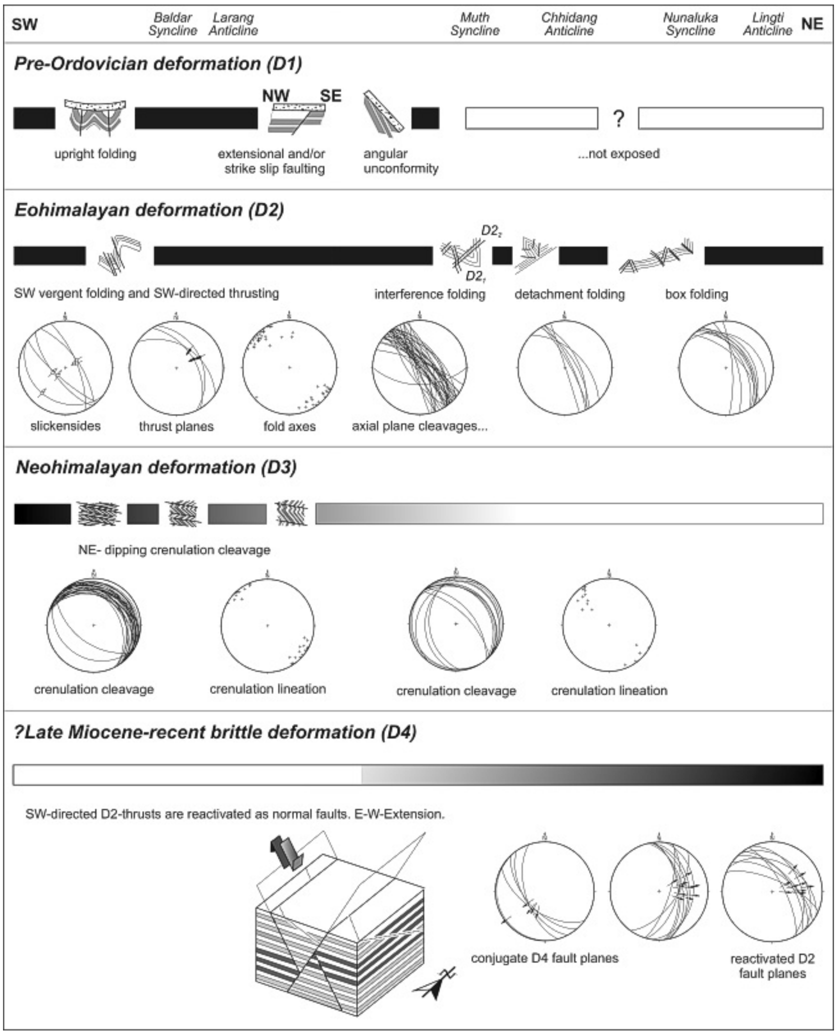


Figure 4: Schematic deformation history of the aggregate cross section; Key geographic points along upper row; Horizontal shaded bars indicate regional variations in intensities of deformation events. Structures related to pre-Ordovician deformation D1 are only exposed in SW parts of cross section. Eohimalayan D2 phase is dominant deformation event responsible for large scale structures forming the fold and thrust belt in whole area of Tethyan Himalaya. Neohimalayan deformation D3 is caused by extrusion of Higher Himalayan Crystalline below Tethyan Himalayas. Overprint is more pronounced in SE parts of section, structurally closer to extruding metamorphic units. Pronounced brittle deformation phase (D4) is only observed in NE parts of section, and probably related to exhumation of high-grade metamorphic rocks of the Leo Pargil Horst to the SE.

successfully employed for the overall tectonometamorphic unit. Line length, area balancing and forward modelling of fault related folds were calculated with the analytical modelling software 2DMove Vers. 3.1 from Midland Valley. In this paper, only the NE part of the composed section, i.e. Nunaluka Syncline Lingti Anticline in the Lingti Valley (Fig. 6), is described in detail.

The large scale antiform-synform fold train has been forward modelled by deforming the Basal Fold-Thrust Belt into a simple step fault propagation fold with an interlimb half angle of γ= 65° and a ramp angle of α= 38°. The structure has been subsequently modified by breakthrough thrusting along steepening imbricate faults parallel to the synclinal axial plane. These faults displace the hanging wall for another 2.7 km.

Deformation in the Upper Fold Belt has been backward modelled (Mitra and Namson, 1989) by (1) comparing restored line lengths in competent beds (Competence Units B and D), which deformed by parallel folding, while maintaining original thickness and line length, and (2) conservation of area in lithologies recording significant thickness change (Competence Units A and C). Pin lines (pin 1 and 2 in Fig. 6) have been placed normal to the competent beds at points where non-coaxial and heterogeneous deformation was minimal, and SW of the major D4 extensional fault (Fig. 6), in order to preserve cross sectional area. The original length of beds between these two pin lines of 10.74 km has been shortened to 6.82 km corresponding to a shortening of 36.59%. Although deformation is decoupled at the base of Competence Unit A, this shortening compares perfectly to the displacement recorded in the fault-propagation fold modelled in the Basal Fold-Thrust Belt.

5. Discussion

By re-evaluating the balanced cross section by Wiesmayr and Grasemann (2002) and continuing the section towards NE, a detailed deformation history of the Tethyan Zone in the NW-Himalaya can be derived (Fig. 7):

Except for the Cambro/Ordovician deformation (D1) (Fig. 7a), which is not exposed in the NE part of the section (Lingti Valley), the oldest observed deformation structures are related to the dominant Eohimalayan, large scale, SW directed fault-propagation folding and faulting (D2). Thin skin-type thrusting has been created by low-angle subduction of the Higher Himalayan Crystalline along a detachment (Fig. 7b). We term this detachment the Sangla Thrust, because of its similar structural position to the Sangla Detachment in the Baspa Valley, where it locally represents the boundary between the Higher Himalaya Crystalline and Tethyan Himalaya, with relict thrusting kinematic indicators (Vannay and Grasemann, 1998; Vannay and Grasemann, 2001). Based on Ar/Ar formation ages of contemporaneously recrystallized illite in axial surfaces of D2 folds, Wiesmayr and Grasemann (2002) concluded an age for that deformation of about 42-45 Ma. Although D2 is generally considered to be 5-10 Ma younger, Eohimalayan S to SW directed large-scale folding and faulting are nevertheless typically observed in much of the Tethyan Himalaya (e.g. Fuchs, 1981; Searle et al. 1990; Steck, 2003). In our sections however, there is no evidence of an earlier N to NE directed thrusting in comparison to the regional tectonics described in Steck et al. (1999) and Godin (2003). The shortening represented by the D2 deformation event that we calculate here for the NE part of the PinLingti Valley section (~35%) is slightly higher than calculations from the SW part (~30%, Wiesmayr and Grasemann, 2002) but much less than estimations from other

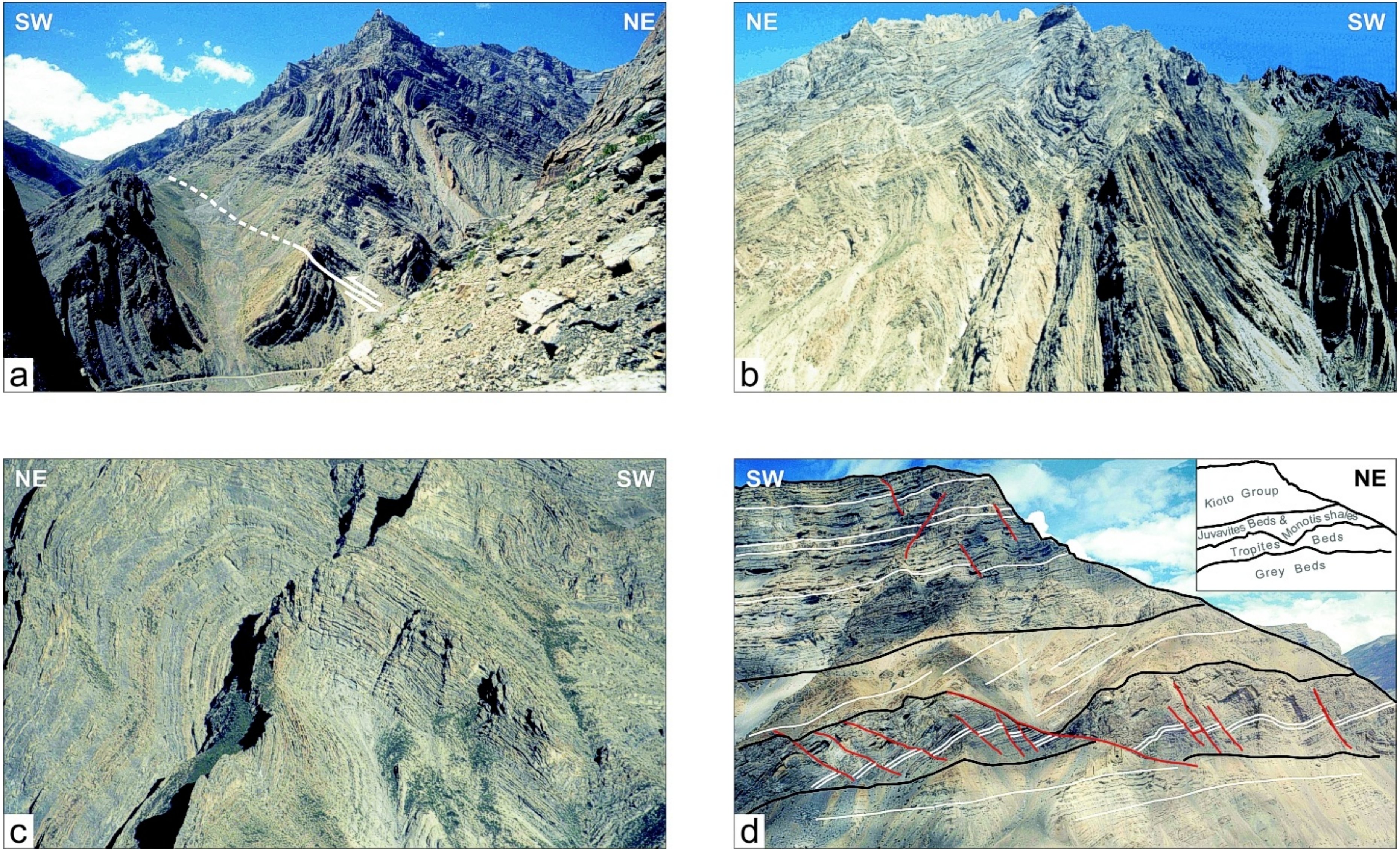


FIGURE 5: Field photographs showing representative structures related to deformation phases in Figure 4. a) SW vergent large scale D2 syncline-anticline fold train (Nunaluka Syncline) within Competence Unit D (Kioto Group), subsequently translated by SW directed thrust, leaving syncline in footwall (looking NW to Nunaluka peak; vertical scale is 1500m), see also Fig. 6. b) Same D2 syncline-anticline fold train as shown in Figure 5a) (Nunaluka Syncline), but without translation along imbricate thrust (looking SE to Tanjangkari peak; vertical scale is 1700m). c) Second order folds within Chhidang Anticline within Competence Unit A (Grey Beds) comprising SW dipping axial surfaces (looking SE; horizontal scale is c. 250m). d) D4 brittle normal faults within Competence Units A-D, directly NE of Lingti Anticline. While E-W extension is very well pronounced by mesoscopic scale bookshelf-type extensional faults within Competence Unit B (Tropites Beds), it is less pronounced in Comptence Unit D (Kioto Group), forming conjugate sets of normal faults. In less competent Competence Units A (Grey Beds) and C (Juvavites Beds and Monotis Shales) are much less evident (looking NW, vertical scale is c.1000m).

authors of around 60%, which generally consider larger sections mainly including Neohimalayan deformation (Johnson, 2002 and references cited therein).

In the Pin Valley, S-SW extrusion of the crustally imbricated Higher Himalayan Crystalline above the Main Central Thrust and below the Sangla Detachment normal fault (Vannay and Grasemann, 2001) caused the formation of a shallow NE dipping foliation (D3) in the Tethyan Himalaya. No D3 foliation is present in the Lingti Valley however, probably due to its higher structural position (Fig. 7c).

The aggregate Pin Lingti Valley section balanced cross section suggests a much more shallowly dipping Higher Himalayan Crystalline wedge than previously suggested by Wiesmayr and Grasemann (2002). We therefore speculate that the amphibolite facies metasediments that, together with abundant syntectonically crosscutting Middle Miocene granitic dykes (pers. comm. Ch. Hager and Ch. Janda, 2001) are exposed at the Leo Pargil Horst (Ni and Barazangi, 1985) SE of the Lingti Valley, are part of rocks of the Higher Himalayan Crystalline wedge, that have been passively exhumed by the subsequent D4 extensional event. This idea is supported by preliminary unpublished observations of B. Grasemann from the Leo Pargil Horst, where SW-dipping amphibolite facies mylonites with kinematic indicators (-and σ-type mantled feldspar porphyroclasts) indicate an apparently NE directed thrusting, that is subsequently overprinted by greenschist facies normal faulting kinematics (Fig. 7d). Accepting that the orientation of the amphibolite facies mylonites is a result of subsequent open folding, the mylonites from the Leo Pargil Horst may represent originally NE-directed normal faults that can be correlated with the South Tibetan Detachment System (Burg et al., 1984; Burchfield et al., 1992). This interpretation is supported by Rb/Sr white mica data from the upper part of footwall W of Leo Pargil showing Early Miocene cooling ages (pers. comm. C. Hager, C. Janda and M. Thöni, 2003). Geometrically, this model implies that (1) the Higher Himalayan Crystaline wedge extends much further to the NE than previously thought and consequently (2) the proposed junction with the Main Himalayan Thrust is also situated further to the NE than previously thought (Vannay and Grasemann, 2001). The idea that the Higher Himalayan Sequence forms the core of a long, low-viscosity crustal channel, which extends far to the N probably extending under the Tibetan plateau, has already been suggested by Grujic et al. (2002) for the Bhutan Himalayas at the eastern end of the Himalayas.

All structures in the NE parts of the presented section are pervasively overprinted by a roughly W-E brittle extension (D4). The initiation of this extension is poorly constrained and might have started in the Late Miocene after extrusion of the Higher Himalayan Crystalline, and there are many pieces of evidence, that extension in this area may still be active. Based on remote sensing techniques Ni and Barazangi (1985) mapped faults, that offset the local geomorphology and Quaternary sediments around the Leo Pargil Horst. These authors relate these faults to minor shallow intraplate seismic events and the Kinnaur earthquake of January 19, 1975 (magnitude 6.8) and its aftershocks, all of whose epicentres lie W of the Leo Pargil Horst. This earthquake was the largest event known to occur in the Tethyan Himalaya during the past 70 years. Fault plane solutions of the Kinnaur earthquake and its two largest aftershocks record a clear W-E extension perfectly matching with our fault plane plots from the Lingti Valley (Fig. 4). Furthermore, the Kinnaur earthquake caused deformation of Quaternary sediments by faulting and liquefaction. Detailed studies of fluvio-lacustrine sediments along the Spiti River and its tributaries SE of the presented section (i.e. the area between the Lingti Valley and the Leo Pargil) revealed that at least nine major earthquakes occurred during the late Pleistocene-Holocene (Mohindra and Bagati, 1996). At a larger scale, the conjugate normal faults of the D4 W-E extensional event may be explained by pull-apart structures related to the Karakoram Fault (Ni and Barazangi, 1985) or to orogenic collapse

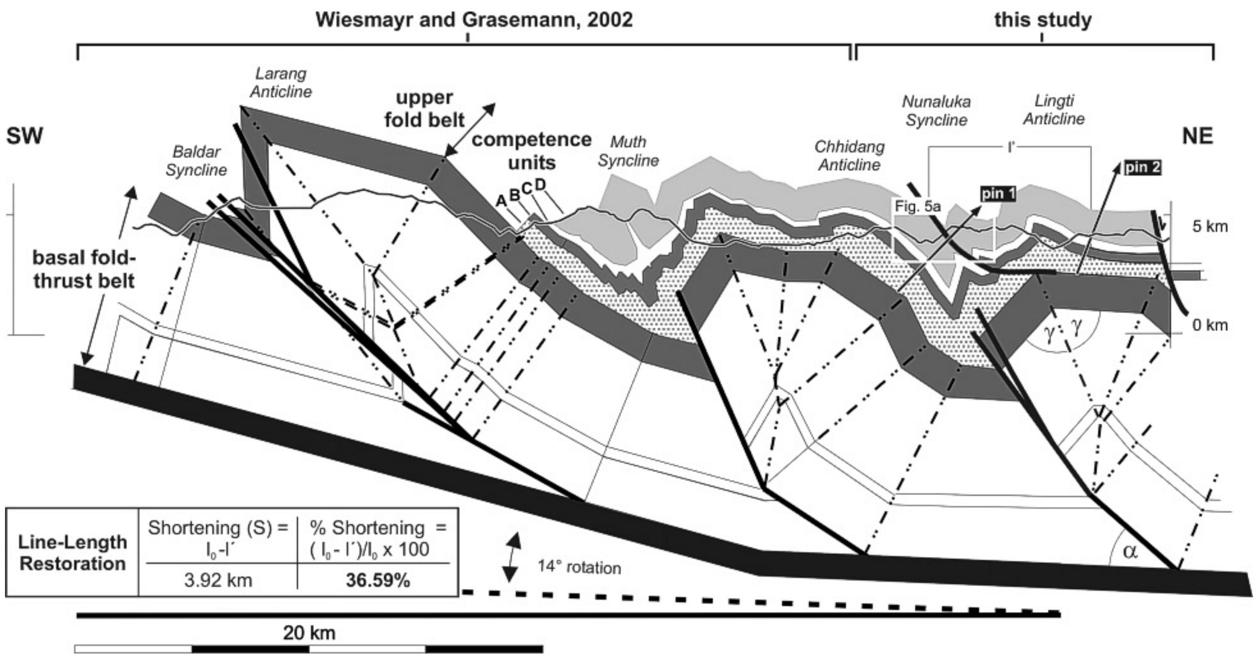


Figure 6: Aggregate balanced cross section of this study together with Wiesmayr and Grasemann (2002). Basal Fold – Thrust belt is forward modelled using complex fault propagation fold kinematics. The Upper Fold Belt subdivided in competence units A-D was area and line length balanced. Shortening of aggregate section was estimated between pin lines 1 and 2 resulting in roughly 36% shortening, slightly higher than estimation of Wiesmayr and Grasemann (2002) in the south-western parts of section (~30%).

structures related to E-W extension of the Himalaya-Tibet system (Garzione et al., 2003).

6. Conclusions

The presented balanced cross section lengthens the Pin Valley profile of Wiesmayr and Grasemann (2002) to the NE into the Lingti Valley. Their interpretations of the geometry and deformation mechanisms of the Eohimalayan southwest directed fold and thrust belt, as well as the amount of shortening, is confirmed. Additional important new results have been obtained:

1) In the Lingti Valley, no deformation associated with the extrusion of the Higher Himalayan Crystalline is recorded.

2) The geometries of the aggregate balanced cross sections imply that the Higher Himalayan Crystalline wedge extends much further to the NE than previously thought. This observation is strikingly consistent with the geometry of the Higher Himalayan Crystalline constrained by geophysical investigations in Southern Tibet (Nelson et al. 1996). It provides further support for low-viscosity Higher Himalayan Crystalline crustal channel models, extending probably far to the N under the Tibetan plateau (Grujic et al., 2002).

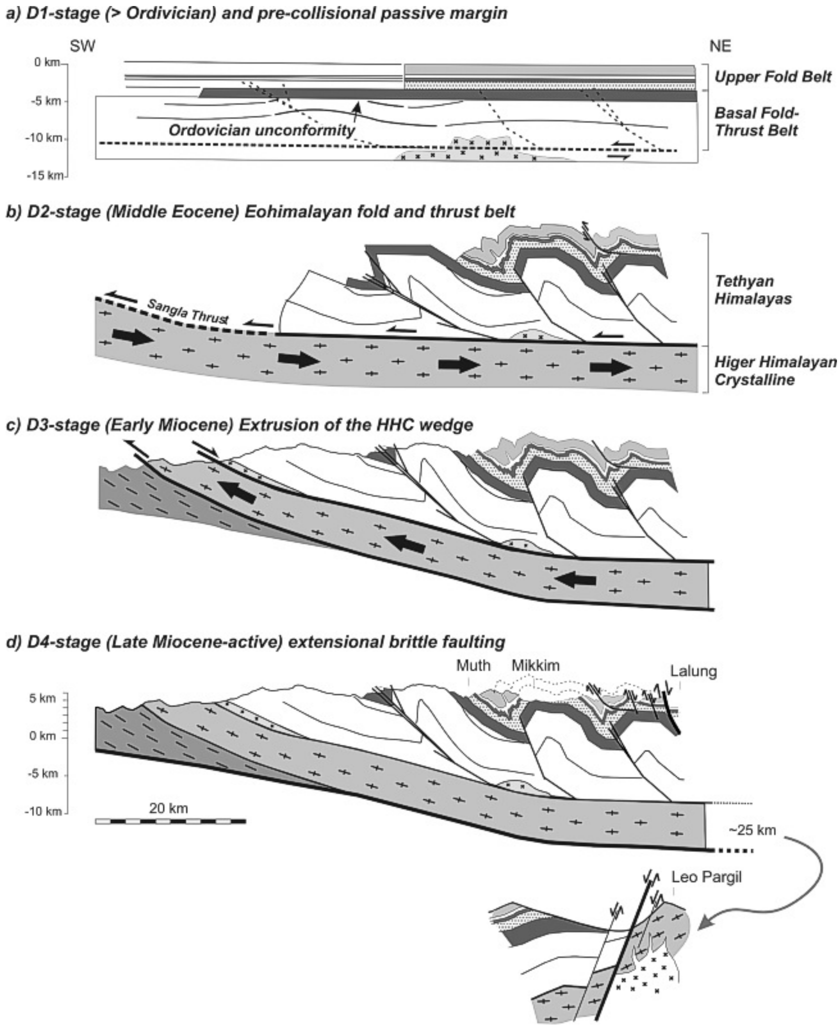


Figure 7: SW-NE cross sections showing progressive deformation of Tethyan Himalaya in Pin and Lingti Valleys. See text for details.

3) Conjugate brittle faults and reactivation of Eohimalayan thrusts, (not recorded in the SW parts of the aggregate section), suggest a significant W-E extension following the extrusion of the Higher Himalayan Crystalline. Epicenters of seismic events, focal plane solutions of major earthquakes and deformation of Quaternary sediments suggest that extension is still active in this area. These normal faults possibly represent a northward continuation of the Kaurik-Chango Fault related to the exhumation of the high-grade metamorphic rocks of the Leo Pargil Horst.

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References

Bhargava, O.N. and Bassi, U.K., 1998. Geology of Spiti-Kinnaur, Himachal Himalaya. Geological Survey of India Memoirs 124, 1-210.

Burchfield, B.C., Zhiliang, C., Hodges, K.V., Yuping, L., Royden, L.H., Changrong, D. and Jiene, X., 1992. The South Tibetan Detachment System, Himalayan Orogen. Extension Contemporaneous With and Parallel to Shortening in a Collisional Mountain Belt. Geological Society of America Special Paper 269, 41 pp.

Burg, J.P., Brunel, M., Gaspais, D., Chen, G.M. and Liu, G.H., 1984. Deformation of leucogranites of the crystalline main central thrust sheet in southern Tibet (China). Journal of Structural Geology 6, 535-542.

Corfield, R.I. and Searle, M.P., 2000. Crustal shortening estimates across the north Indian continental margin, Ladakh, NW India. In: P.J. Treloar, M.P. Searle, Jan, M.Q., (Eds.), Tectonics of the Nange Parbat Syntaxis and the Western Himalaya. Geological Society, London, Special Publications, London, pp. 395-410.

DeCelles, P.G., Robinson, D.M., Quade, J., Ojha, T.P., Garzione, C.N., Copeland, P. and Upreti, B.N., 2001. Stratigraphy, structure, and tectonic evolution of the Himalayan fold-thrust belt in western Nepal. Tectonics 20, 487-509.

Dewey, J.F., Cande, S. and Pitman III, W.C., 1989. Tectonic evolution of the India/Eurasia Collision Zone. Eclogae Geologicae Helvetiae 82, 717-734.

Draganits, E., 2000. The Muth Formation in the Pin Valley (Spitit, N-India): Depositional Environment and Ichnofauna of a Lower Devonian Barrier Island System. PhD Thesis, University of Vienna, Vienna, 144 pp.

Fuchs, G., 1981. Outline of the geology of the Himalaya. Mitteilungen der Österreichischen Geologischen Gesellschaft 74-75, 101-127.

Fuchs, G., 1982. The geology of the Pin valley in Spiti, H.P., India. Jahrbuch der Geologischen Bundesanstalt 124, 325-359.

Gansser, A., 1964. Geology of the Himalayas. Interscience Publishers, London, 289 pp.

Garzanti, E. and van Haver, T., 1988. The Indus clastics: forearc basin sedimentation in the Ladakh Himalya (India). Sedimentary Geology 59, 237-249.

Garzanti, E., Jadoul, F., Nicora, A. and Berra, F., 1995. Triassic of Spiti (Tethys Himalaya, N India). Rivista Italiana di Paleontologia e Stratigrafia 101, 267-300.

Garzione, C.N., DeCelles, P.G., Hodkinson, D.G., Ojha, T.P. and Upreti, B.N., 2003. East-west extension and Miocene environmental change in the southern Tibetan plateau: Thakkhola graben, central Nepal. Geological Society of America Bulletin 115, 3–20.

Godin, L., 2003. Structural evolution of the Tethyan sedimentary sequence in the Annapurna area, central Nepal Himalaya. Journal of Asian Earth Sciences 22, 307-328.

Griesbach, C.L., 1891. Geology of the Central Himalayas. Memoirs of the Geological Survey of India 23, 1-232.

Grujic, D., Hollister, L.S. and Parrish, R.R., 2002. Himalayan metamorphic sequence as an orogenic channel: insight from Bhutan. Earth and Planetary Science Letters 198, 177-191.

Hansen, E., 1971. Strain Facies. Minerals, Rocks and Inorganic Materials, Monograph Series of Theoretical and Experimental Studies 2, Springer, Berlin, 207 pp.

Hayden, H.H., 1904. The geology of Spiti. Geological Survey of India Memoirs 36, 122-201.

Hodges, K.V., 2000. Tectonics of the Himalaya and southern Tibet from two perspectives. Geological Society of America Bulletin 112, 324-350.

Johnson, M.R.W., 2002. Shortening budgets and the role of continental subduction during the India-Asia collision. Earth-Science Reviews 59, 101-123.

Le Fort, P., 1986. Metamorphism and magmatism during the Himalayan collision. In: Coward, M.P., Ries, A.C. (Eds.), Collision Tectonics. Geological Society Special Publication 19, 159-172.

Miller, C., Thöni, M., Frank, W., Grasemann, B., Klötzli, U., Guntli, P. and Draganits, E., 2001. The early Palaeozoic magmatic event in the Northwest Himalaya, India; source, tectonic setting and age of emplacement. Geological Magazine 138, 237-251.

Mitra, S., Namson, J., 1989. Equal area balancing. American Journal of Science 289, 563-599.

Mohindra, R., Bagati, T.N., 1996. Seismically induced soft-sediment deformation structures (seismites) around Sumdo in the lower Spitit valley (Tethys Himalaya). Sedimentary Geology 101, 69-83.

Nelson, K. D., 27 others. 1996. Partially molten middle crust beneath southern Tibet: synthesis of project INDEPTH results. Science 274, 1684-1688.

Ni, J. and Barazangi, M., 1985. Activ tectonics of the Western Tethyan Himalaya above the underthrusting Indian Plate: the Upper Sutlej River Basin as a pull-apart structure. Tectonophysics 112, 277-295.

Schelling, D., Arita, K., 1991. Thrust tectonics, crustal shortening, and the structure of the far-eastern Nepal, Himalaya. Tectonics 10, 851-862.

Schuster, R., 1999. Die geodynamische Entwicklung von SW-Tibet. PhD Thesis, University of Vienna, Vienna, 273 pp.

Searle, M.P., Cooper, D.J.W., Rex, A.J., 1988. Collision tectonics of the Ladakh - Zanskar Himalaya. Philosophical Transactions of the Royal Society, London A326, 117-150.

Searle, M.P., Pickering, K.T. and Cooper, D.J.W., 1990. Restoration and evolution of the intermontane Indus molasse basin, Ladakh Himalaya, India. Tectonophysics 174, 301-314.

Searle, M.P., Corfield, R.I., Stephenson, B. and McCarron, J., 1997. Structure of the North Indian continental margin in the Ladakh-Zanskar Himalayas: implications for the timing of obduction of the Spontang ophiolite, India-Asia collision and deformation events in the Himalaya. Geological Magazine 134, 297-316.

Srivastava, P. and Mitra, G., 1994. Thrust geometries and deep structure of the outer and lesser Himalaya, Kumaun and Garhwal (India): implications for evolution of the Himalayan fold-and- thrust belt. Tectonics 13, 89-109.

Steck, A., Epard, J.L. and Robyr, M., 1999. The NE-directed Shikar Beh Nappe: A major structure of the Higher Himalaya. Eclogae Geologicae Helvetiae 92, 239-250.

Steck, A., 2003. Geology of the NW Indian Himalaya. Eclogae Geologicae Helvetiae 96, 147-196.

Vannay, J.-C. and Grasemann, B., 1998. Inverted metamorphism in the High Himalaya of Himachal Pradesh (NW India): phase equilibria versus thermobarometry. Schweizerische Mineralogisch Petrographische Mitteilungen, 78, 109-135.

Vannay, J.-C. and Grasemann, B., 2001. Himalayan inverted metamorphism and syn-convergence extension as a consequence of a general shear extrusion. Geological Magazine 138, 253-276.

Wiesmayr, G. and Grasemann, B., 2002. Eohimalayan fold and thrust belt; implications for the geodynamic evolution of the NW-Himalaya (India). Tectonics 21, 1-18.

Wiesmayr, G., 2000. Eohimalayan structural evolution of the fold and thrust belt in the Tethyan Himalaya (Spiti, N-India). Diploma Thesis, University of Vienna, Vienna, 95 pp.

Yin, A., Harrison, T.M., 2000. Geologic Evolution of the Himalayan-Tibetan Orogen. Annual Review of Earth and Planetary Sciences 28, 211-280.

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