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Ductile extrusion of the Higher Himalayan Crystalline in Bhutan: evidence from quartz microfabrics

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Abstract

Quartz textures measured from deformed quartz tectonites within the Lesser Himalaya and Higher Himalaya Crystalline of Bhutan show similar patterns. Orientation and distribution of the quartz crystallographic axes were used to confirm the regional shear sense: the asymmetry of *c*-axis and *a*-axis patterns consistently indicates top-to-the-south shearing. The obliquity of the texture and the inferred finite strain (plane strain to moderately constrictional), suggest the strain regime had a combination of rotational and irrotational strain path. In most of the samples from the Bhutan Himalaya, the inferred deformation mechanisms suggest moderate- to high-temperature conditions of deformation that produced the observed crystallographic preferred orientation. Much higher temperature of deformation is indicated in the quartz veins from a leucogranite.

The observed ductile deformation is pervasively developed in the rocks throughout the investigated area. The intensity of deformation increases only slightly in the vicinity of the Main Central Thrust. Simultaneous southward shearing within a large part of the Higher Himalaya Crystalline near and above the Main Central Thrust and normal faulting across the South Tibetan Detachment, is explained by the tectonically induced extrusion of a ductily deforming wedge. The process of extrusive flow suggested here can be approximated quantitatively by channel flow models that have been used to describe subduction zone processes. Channel flow accounts for some observed phenomena in the Himalayan orogen such as inverted metamorphic sequences near the Main Central thrust, not related to an inversion of isotherms, and the syntectonic emplacement of leucogranites into the extruding wedge, locally leading to an inversion of isotherms due to heat advection.

1. Introduction

Since the recognition of the fundamental tectonic framework of the Himalayas (Gansser, 1964) considerable advances have been made. Several questions remain, however, without a satisfactory answer:

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(1) The Main Central Thrust is a major intra-crustal ductile thrust zone that is associated with inverted metamorphic isograds both above — in the Higher Himalaya Crystalline and below — in the Lesser Himalaya (e.g., Gansser, 1964; Hodges et al., 1988). Different models have been put forward to explain this phenomenon (for summaries see Windley, 1983 and Barnicoat and Treloar, 1989). Some of them are based on the implicit assumption that inverted metamorphic gradients record an inverted distribution of isotherms at the time of metamorphism (Le Fort, 1975; Brunel and Kienast, 1986; Molnar and England, 1990), the others imply post-metamorphic folding of isograds (Hodges et al., 1988; Searle et al., 1988; Jain and Manickavasagam, 1993). None of these models is completely satisfactory, and the reliability of the available geothermobarometric data has been questioned recently (e.g., Hubbard, 1994; Davidson et al., 1995).

(2) The South Tibetan Detachment (e.g., Burg et al., 1984; Herren, 1987; Pêcher, 1991; Burchfiel et al., 1992) is a major north-dipping low-angle normal fault with up to 15–18 km of throw and 80 km of heave (e.g., Burchfiel and Royden, 1985; Searle, 1995). This normal faulting appears to be incongruous with the south directed thrusting along the MCT and within the Higher Himalaya Crystalline.

(3) Leucogranites of the Higher Himalayan Crystalline (Le Fort, 1975) were emplaced contemporaneously with the high-temperature, intermediate- to low-pressure metamorphism (Brunel, 1983) and intruded contemporaneously with both southward- and northward-directed shear zones (Burg et al., 1984). The origin of leucogranites, the association with the inverted metamorphism in the Higher Himalayan Crystalline and their relationship to the thrusting and north-directed faulting events are not yet fully understood.

Quartz tectonites (quartz-rich deformed rocks) are widespread in the tectonic units of eastern Bhutan and derived from primary quartzitic beds in the Shumar group (Gansser, 1983) of the Lesser Himalaya and from magmatic/metamorphic veins in the Higher Himalayan Crystalline, which have been recrystallized and deformed during the thrusting event. This paper presents a synthesis of the evolution of the quartz microfabrics across the deformed rock-pile of the Higher Himalaya Crystalline in the Bhutan Hi-

malayas, correlating these with the associated geological framework. The study of the quartz microfabrics was carried out because it offers the possibility to compare different tectonic levels using commonly developed features and, thus, to record deformational changes. Because petrological control is also available, the detected microfabrics variations reflect the varying range of physical conditions (temperature, strain) during the deformation and correspond to the deformation mechanism and the strain path changes. Many experimental and field investigations have demonstrated that the quartz microfabric is a good kinematic and strain path indicator (Simpson and Schmid, 1983; Schmid and Casey, 1986; Mancktelow, 1987) and is also sensitive to the thermal environment during deformation (Boullier and Bouchez, 1978; Borradaile et al., 1982; Poirier, 1985). For recent reviews of applicability of crystallographic fabrics see Law (1990) and Schmid (1994).

A complete crystallographic fabric analysis with X-ray texture goniometry was performed on a range of quartz tectonites. After the description of the observed microfabrics we address the above mentioned problems and propose a tectonic model for the Bhutan Himalayas.

2. Regional setting

Quartzite samples for this study were collected along a north–south traverse across the Higher Himalaya Crystalline (HHC), Main Central Thrust (MCT) and Lesser Himalaya in central and eastern Bhutan. The first leg of the traverse — between Bjakar Dzong and Djüle La (Fig. 1) — was mainly across the strike of lithologic layering from elevations near 3000 to 4800 m within a higher (both structurally and topographically) portion of the Higher Himalaya Crystalline. The second part of our field work was in Eastern Bhutan. It consisted of mapping a road section between Bjakar Dzong and Tashigang over a length of ~270 km. This road section crosses the trace of the Main Central Thrust in two places (Fig. 1).

2.1. Tectonic framework

The crystalline rocks of the Higher Himalaya Crystalline assemblage (Fig. 1) are generally con-

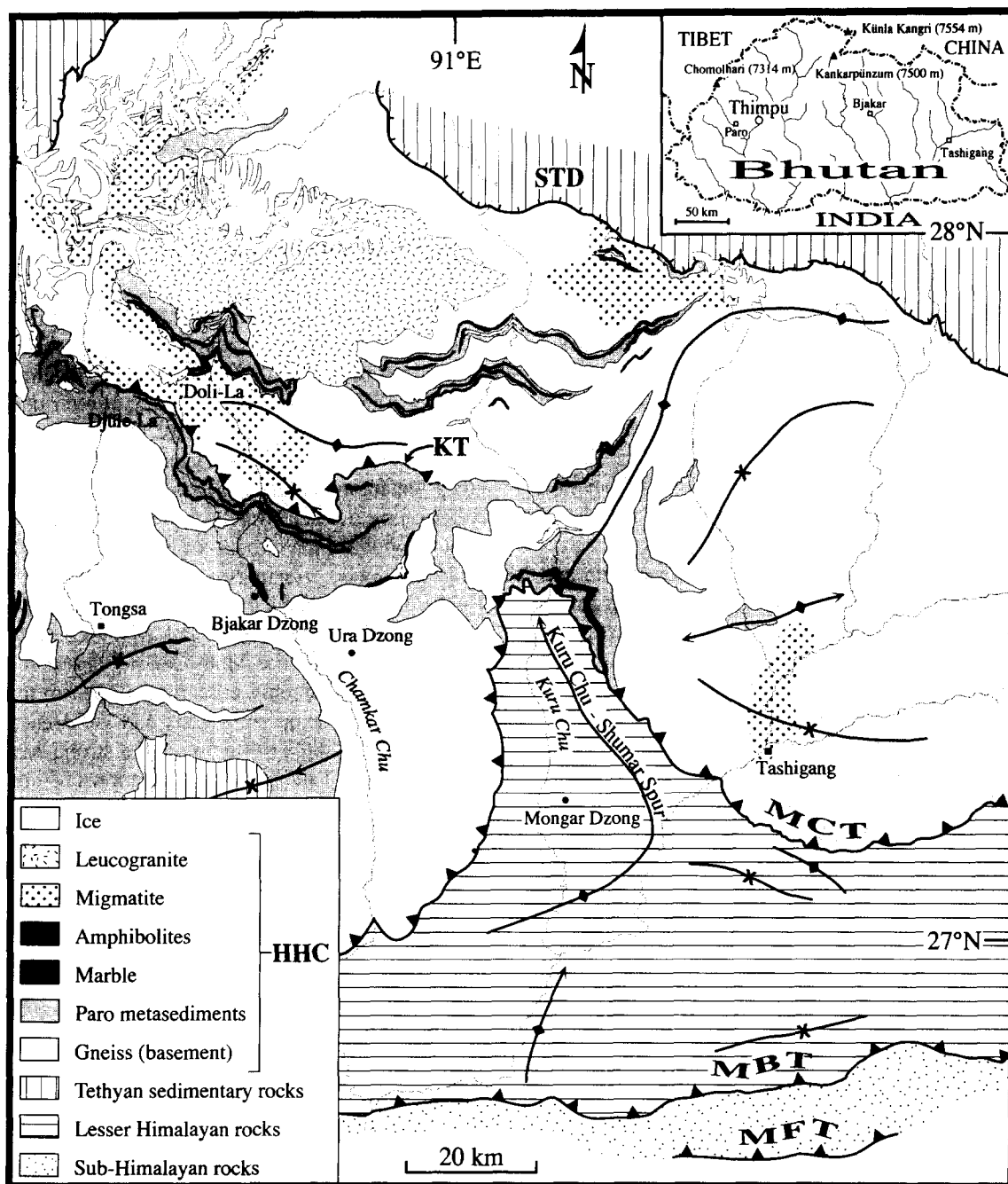


Fig. 1. Geological map of the central and eastern Bhutan Himalaya, indicating the main structural elements as discussed in the text. After Gansser (1983). *KT* = Kakhtang Thrust; *MBT* = Main Boundary Thrust; *MCT* = Main Central Thrust; *MFT* = Main Frontal Thrust; *STD* = South Tibetan Detachment.

sidered to represent a portion of the Indian Shield and its cover rocks. These rocks were emplaced by southward thrusting along the Main Central Thrust

(MCT) and Main Boundary Thrust (MBT) during the collision of the Indian subcontinent with Asia. The exposed gneiss and migmatite of the HHC in

Bhutan include the metamorphosed equivalents of the Paleozoic platform sedimentary sequence and the underlying Precambrian shield. Gansser (1983) assigned the rocks in the traverse area to two groups: (1) Paro metasediments comprised of pelitic schists, calc-silicate, marble, and (2) gneissic rocks. These metamorphic assemblages were intruded by Miocene age leucogranites. On average the main foliation in the HHC dips gently to the north. It is affected by long-wavelength, low-amplitude upright, E–W-trending folds. In the Djüle La area the main foliation is deformed into the form of a regional back fold: the Djüle La steep zone (Gansser, 1983) (Fig. 1). This deformation affects both the main foliation and the leucogranites. It develops a new, weak crenulation cleavage with a steep dip to the northeast. Where stretching lineations are present, they are oriented roughly north–south, parallel to the direction of convergence of India with Asia (Bouchez and Pêcher, 1981; Brunel, 1986). Macroscopic and microscopic high-temperature kinematic indicators show top-to-the-south sense of the tectonic transport. Rotated garnet porphyroblasts within the main foliation support the idea that the prograde kinematics involved top-to-the-south movement (e.g., Brunel, 1986; Davidson et al., 1995; Hollister et al., 1995).

In Bhutan, as in other parts of the Himalayas, the Lesser Himalaya is made up of a stack of thin thrust sheets. The lowermost thrust sheet of this stack ends against a steeply dipping E–W-trending thrust fault (the Main Boundary Thrust) which separates the Lesser Himalaya in the north from the Sub-Himalaya in the south (Gansser, 1964; Nautiyal et al., 1964). All the thrust sheets of the Lesser Himalaya of Bhutan are made up of Pre-Cambrian–Paleozoic rocks. The Shumar thrust sheet (Jangpangi, 1974) lies at the top of this pile of allochthonous rocks. The upper part of the Shumar group is made up of a layered sequence of quartzite, phyllite and marble, tectonically repeated several times.

The layers of the Shumar group, the MCT and the foliation of the overlying HHC have been affected by two groups of folds with axes at nearly right angles. The axial traces of one set of these folds run ENE–WSW, the axes plunging towards the northeast. The other set of folds is oriented transversally across the strike. These folds plunge to the northwest and the axial planes dip steeply to the east-northeast.

The most prominent structure of this group is the Kuru Chu–Shumar spur (Gansser, 1983), a broad asymmetric anticline. The interference between these two nearly orthogonal fold sets results in gentle dome and basin structures evident from the map pattern of lithologic units and metamorphic isograds (see geological map in Gansser, 1983).

2.2. Main Central Thrust Zone

The southern boundary of the Higher Himalaya Crystalline in Eastern Bhutan is defined by the Main Central Thrust (MCT) (Auden, 1935; Heim and Gansser, 1939; Gansser, 1964, 1983), also termed the Thimpu thrust (Ray et al., 1989). In Bhutan, nearly the entire length of the Main Central Thrust shows a steep metamorphic gradient from greenschist-facies rocks of the Lesser Himalaya structurally upwards to amphibolite-facies rocks of the overlying HHC (Gansser, 1983). As in Nepal (e.g., Brunel, 1986; Hubbard, 1989; Hubbard and Harrison, 1989), or Jammu and Kashmir (Jain and Manickavasagam, 1993) the area near the Main Central Thrust represents a zone, commonly exceeding 10 km in thickness, of highly deformed schists and gneisses with a gently north-dipping foliation and a strong, north-plunging mineral and stretching lineations. It is more appropriate, therefore, to describe the area in the vicinity of the MCT in terms of a wide thrust zone (referred to as ‘Main Central Thrust Zone’, MCTZ) rather than a discrete thrust plane. The main movement on the MCT (in terms of a boundary between rock units of the HHC and the Lesser Himalaya) occurred at about 15–20 Ma (e.g., Hubbard and Harrison, 1989). The whole history of the MCTZ, however, lasted much longer. Early phases of movement on the MCTZ, synchronous with prograde metamorphism in the Annapurna region are dated at 22.5 ± 0.1 Ma (Hodges et al., 1995), while low-temperature deformation in the MCTZ occurred as recently as ca. 7 Ma (Hubbard and Harrison, 1989; Hodges et al., 1995).

Our recent work and previous work (Swapp and Hollister, 1991) suggest that an additional major thrust fault zone, informally called Kakhtang thrust (Fig. 1), exists within the HHC, well above the MCT. This thrust is also indicated on the geological map of Gansser (1983) but without an interpretation. Its precise timing relative to that of the MCT is

not known, but many structural and metamorphic features observed across the MCT in Bhutan are similar to those across the Kakhtang thrust.

2.3. South Tibetan Detachment Zone

The top of the HHC is truncated by north-dipping low-angle faults and shear zones of the South Tibetan Detachment system (Burg et al., 1984; Brun et al., 1985; Herren, 1987; Kündig, 1988; Pêcher, 1991; Burchfiel et al., 1992). In some areas it has been shown that this deformation affected rocks structurally situated as far as 3000–4000 m beneath the brittle fault (e.g., Brun et al., 1985). During our field work we did not approach this zone of top-to-the-north movement. Recent geochronological data (e.g., Coleman, 1995; Hodges et al., 1995; Searle, 1995) suggest that both the Main Central Thrust and South Tibetan Detachment Zone (STDZ) were active simultaneously between 22 and 19 Ma.

2.4. Himalayan metamorphism

Within the Lesser Himalaya the structurally lowest pelitic rocks reached lower greenschist-facies conditions, structurally grading upward into upper greenschist-facies rocks (Gansser, 1983). The isograds parallel both the Main Boundary Thrust and the Main Central Thrust. The metamorphic rocks of the HHC in Bhutan (Fig. 2) range from lower to upper amphibolite facies, the highest-grade rocks being located to the north and in a structurally higher position. The isograds within the HHC begin with the lower amphibolite facies as indicated by the appearance of hornblende, staurolite, kyanite and garnet on a belt parallel to the MCT (Gansser, 1983). The highest-grade rocks reach sillimanite granulite facies, spacially associated with the sites of leucogranite intrusions (Swapp and Hollister, 1991). Structurally further upwards the metamorphic rocks grade progressively back into greenschist-facies rocks found at the base of the Tethyan sediments. Hence, the metamorphic sequence is inverted above the MCT but the right way up in the uppermost part of HHC (Gansser, 1983, fig. 125). The true inversion of metamorphic isograds, oriented sub-parallel to the MCT, can be nicely deduced in the Kuru Chu–Shumar spur which acts as a tectonic half-

window (Fig. 2). Similar structure is seen to the west of Bhutan in the Ranjit window of the Darjeeling–Sikkim Himalaya (Mohan et al., 1989, fig. 1).

However, our field observations show that this inversion of metamorphic sequences is, locally, repeated in Bhutan. Indeed, garnet + staurolite schist, the lowest-grade rocks in the HHC of Bhutan, are found about 40 km north of the MCT (in map view), structurally above higher-grade garnet + staurolite $\pm$ kyanite $\pm$ sillimanite schist. These lower-grade rocks are found in the footwall of the Kakhtang thrust, whose hangingwall is formed by migmatitic gneiss and garnet + sillimanite schist. Spiral inclusion trails in staurolite and garnet show that metamorphism was synchronous with high-temperature deformation in the footwall rocks (e.g., Davidson et al., 1995). Contrary to the MCT, the Kakhtang thrust cuts obliquely through the synkinematic isograds (Fig. 2), suggesting a different origin of the associated inverted metamorphic sequence.

Because of the substantial shear displacement and the indication for high-temperature decompression in the upper part of the HHC, Swapp and Hollister (1991) suggested that the migmatite may have formed at a deep level within the crust prior to thrusting along the Kakhtang thrust, and that melt in the lower crust led to the initiation of thrusting. The structural relation of the leucogranites to the host rocks (Davidson et al., 1995; Hollister et al., 1995) shows that the leucogranite magmas were injected along the thrust zone and probably helped to maintain a complicated thermal structure in the HHC during uplift and exhumation of the High Himalayas in Bhutan, including the inversion of isotherms. We can hypothesize that local inversions of isotherms were due to heat advection from the large Mönlakarchung–Pasalum intrusion (see also Swapp and Hollister, 1991 and Hollister et al., 1995). The complex and partially re-equilibrated metamorphic assemblages imply rapid exhumation followed by rapid cooling.

2.5. Leucogranites

Within and at the northern edge of the Higher Himalayan Crystalline, about a dozen intrusions of tourmaline bearing leucogranite occur. Systematically the distribution of leucogranites coincides with the highest metamorphic grades. The particu-

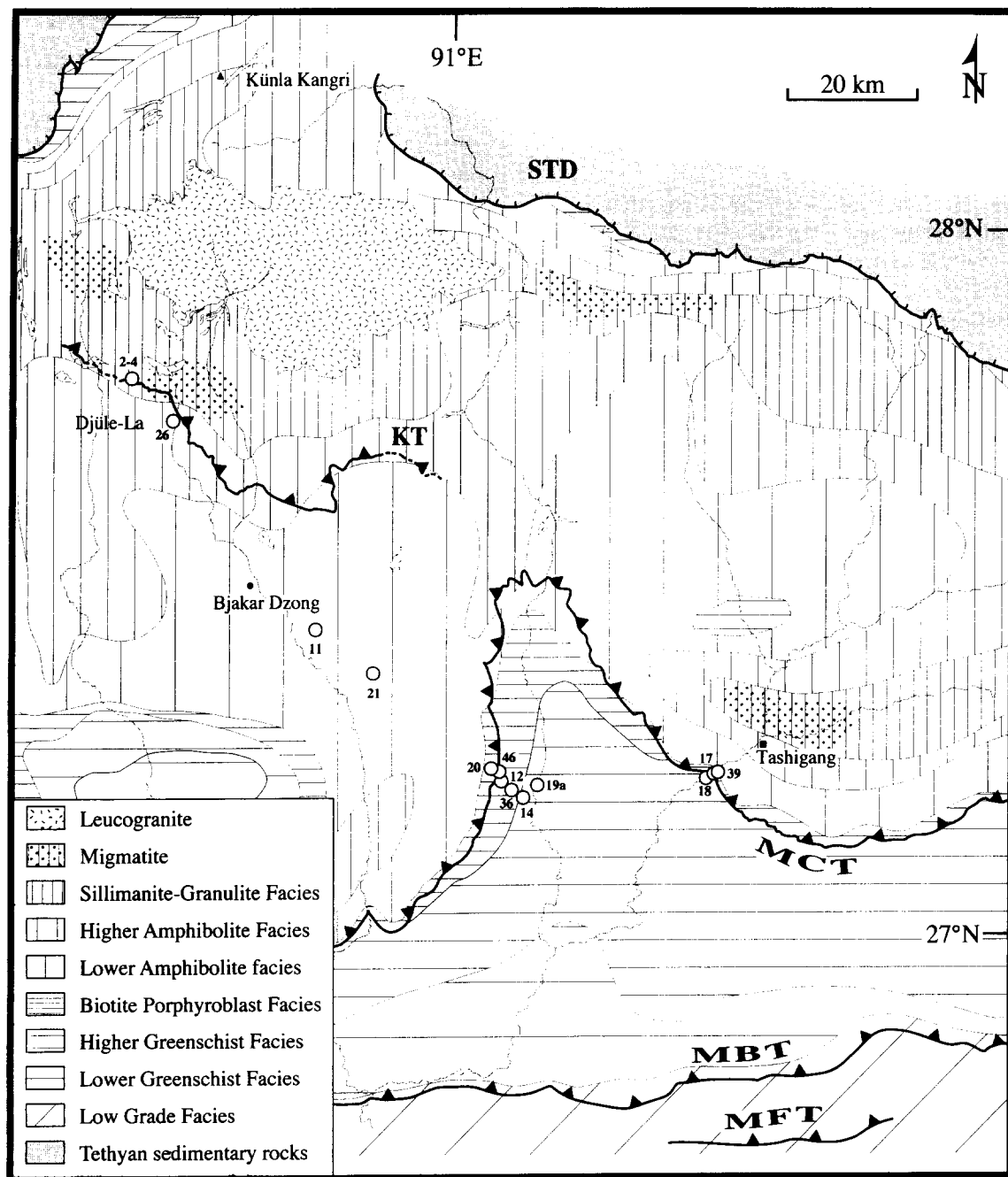


Fig. 2. Metamorphic map of the central and eastern Bhutan Himalaya as mapped by Gansser (1983). *KT* = Kakhtang Thrust; *MBT* = Main Boundary Thrust; *MCT* = Main Central Thrust; *MFT* = Main Frontal Thrust; *STD* = South Tibetan Detachment. Also shown are localities of studied quartzite samples.

lar isotopic and trace-element ratios of Himalayan leucogranites suggest that they are derived from upper-crustal melts (Le Fort et al., 1987). In the

Bhutan Himalaya, three main intrusions can be recognized: Chung La, Gophu La and Mönlakarchung-Pasalum (Dietrich and Gansser, 1981). The largest

leucogranite body is the Mönlakarchung–Pasalum intrusion (Dietrich and Gansser, 1981; Ferrara et al., 1985) with an areal exposure of ~ 800 km². The leucogranite intrusions in Bhutan are broadly concordant with the regional structures and the main foliation in the HHC (Gansser, 1983; Ferrara et al., 1991). Most leucogranite bodies are in contact with calc-silicate and marble zones. In the Chomolhari massif of western Bhutan, however, leucogranites also intrude the Cheka formation (Jangpangi, 1978) which is a metasedimentary cover unit of the Tethys Himalaya (Gansser, 1983).

In the Djüle La area — south of the Mönlakarchung–Pasalum intrusion — leucogranite dikes and sills ranging in size from a few centimetres to 1 km in thickness synkinematically intruded the HHC. Leucogranite dikes cross-cut a pre-existing foliation and are at the same time tightly folded with axial planes parallel to the same foliation (Figs. 3a and 3b). An axial planar magmatic to solid-state foliation is also present in some of the dikes. Leucogranite sills tend to have well developed magmatic to sub-magmatic foliations (Davidson et al., 1995). The small sills typically are asymmetrically boudinaged (Fig. 3c). The boudins interior exhibits mostly igneous fabrics and textures (Davidson et al., 1995) indicating that the sills and dikes were intruded and crystallized during top-to-the-south shearing.

Burg et al. (1984) made similar observations in leucogranites from the upper part of the HHC in southern Tibet between Lhoza and Nyalam. In this area, the main cleavage of the surrounding rocks enters the leucogranite plutons and passes into their foliation. Dikes are tightly folded and leucogranites display a marked planar and linear fabric which resulted from progressive *northward* shear deformation consistent with the South Tibetan Detachment zone kinematics. This deformation took place during ascent and emplacement of the leucogranites, just to the north of the Mönlakarchung–Pasalum intrusion (Burchfiel et al., 1992).

3. Quartz microfabrics

3.1. Methodology

In this paper, *microstructure* is used to describe the form and spatial relationship of grains, and *tex-*

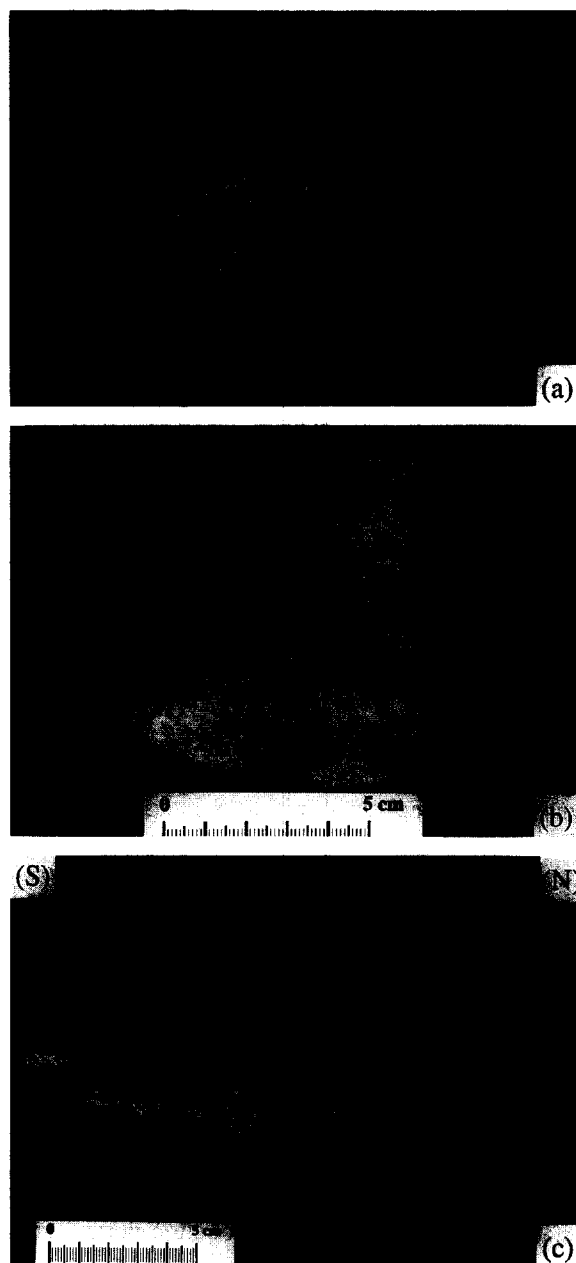


Fig. 3. Deformed leucogranite dikes and sills in the Djüle La injection complex. (a) Folded leucogranite dike in paragneiss from the HHC of Bhutan. The length of the specimen is ~ 50 cm. (b) Detail of sample shown on the previous photograph. Note the weak axial planar cleavage in the dike parallel to the foliation in the paragneiss. The scale bar is 5 cm. (c) Asymmetric boudin of leucogranite sill from the footwall of the Kakhtang thrust. North is to the right and top is up. The scale bar is 5 cm.

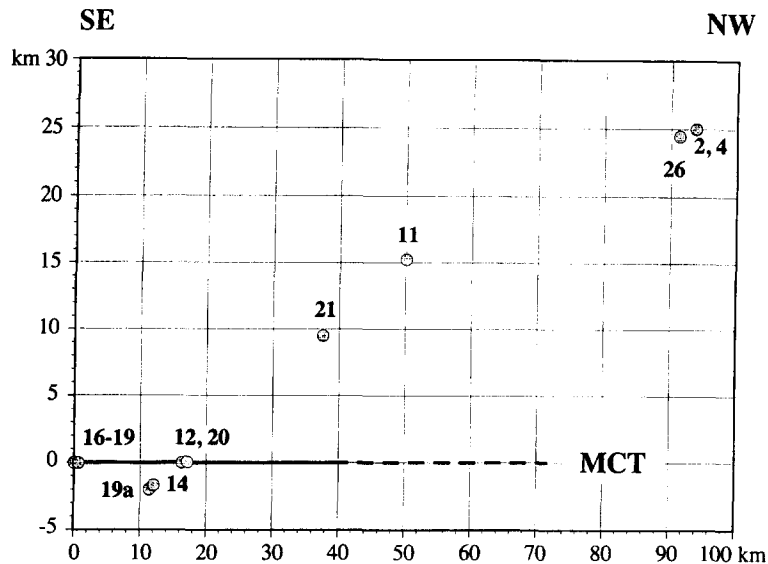


Fig. 4. Schematic SE–NW cross-section through the studied area, where the MCT is a horizontal reference plane to show the vertical distance of the quartzite samples from the MCT. The MCT is reconstructed after Gansser (1983, fig. 128).

ture is used as a synonym for the *crystallographic preferred orientation fabric* (e.g., Weiss and Wenk, 1985).

All the samples show grain-shape and crystallographic preferred orientations. Complete texture analysis was performed with a Scintag XDS 2000 X-ray texture goniometer. The data are presented in the form of pole figures calculated from the orientation distribution functions (e.g., Casey, 1981; Schmid et al., 1981). The regenerated pole figures are consistent with the measured ones. Data are plotted on upper-hemisphere, equal-area stereographic projections with the foliation aligned vertically E–W, and the lineation oriented E–W. Calculated pole figures are represented for *c*-axis, second-order prisms $a(11\bar{2}0)$ and first-order prisms $m(10\bar{1}0)$. All the samples have been oriented such that the view direction is constant, north to the right. The preferred orientation of sample axes (here foliation normal and lineation) in crystal coordinates is given by inverse pole figures. The inverse pole figures are calculated for sample directions parallel to the foliation plane normal (N–S) and parallel to the macroscopic lineation (E–W). These directions are chosen because — given the high strain — the foliation and lineation are subparallel to the imposed shear plane and movement direction, respectively. Because the studied quartz tectonites are coarse grained and impure,

several scans were made (2 or 4) and averaged in order to increase the statistics.

The texture patterns obtained from the fabric analyses from the Bhutan Himalaya, in combination with the microstructure, show a trend from south to north, i.e. from middle greenschist-facies to higher amphibolite conditions. The locations of samples are indicated on the metamorphic map (Fig. 2) and on the schematic cross-section where the horizontal plane is the MCT (Fig. 4).

3.2. Optical microstructure

The average grain size generally increases from the lowermost tectonic levels (ca. 100 μm) to the highest tectonic levels (1–2 mm) (Fig. 5). This trend is, however, not systematic. From bottom to top the grain size progressively increases to that of sample No. 21, located ~8 km above the MCT plane (Fig. 4). Structurally further upwards the grain size rapidly decreases to sizes comparable to those seen at the MCT, in order to increase again to the structurally highest location of sample No. 4. Pinning of the grain boundaries by phyllosilicates controls the grain size at the lower tectonic levels (e.g., Fig. 5a). With increasing grain-size, both for quartz and phyllosilicates, the necessary energy to overcome the pinning also increases. At the highest tectonic levels,

large mica crystals can be observed within the quartz grains and also at the grain boundaries.

Most of the observed samples have subequant grain shapes, i.e. the ellipticity of quartz grains in most of the samples is very low. In XZ thin sections, aspect ratios range from 1:1 to 3:1 (Fig. 5). Quartz grain aspect ratio is typically controlled by mica alignment. The best example is sample 19a which is the structurally lowest site relative to the MCT (Fig. 4). Here quartz grains possess length-width ratios of ca. 3:1 in the XZ section and display a preferred orientation of long axes. Abundant mica defines single grain domains, with quartz grains elongated parallel to the foliation defined by these micas. In other cases a weak preferred grain shape alignment of quartz grains defines a second foliation oblique to the macroscopic one. The angle between the two foliations varies between 20 and 40° and it is consistent with the top-to-the-south sense of shear. This angle between the dimensional fabrics is larger in samples showing exaggerated grain growth and often exceeds 45°.

Undulose extinction and poorly defined deformation bands are observed within the quartz grains from all locations. Sub-grains (average grain-size from 35 to 45 μm) are also present. Rare deformation lamellae appear to be sub-basal.

A deformed quartzite vein in a leucogranite dike (sample 4) is very different from the other samples. The microstructure is indicative of rapid grain boundary migration and exaggerated grain-growth. The average grain size is ca. 0.5–3 mm. Two important classes of sub-grain boundaries could be distinguished: prismatic $\{hki0\}$, having a boundary trace parallel to the c -axis and basal $\{0001\}$, having a trace perpendicular to the related grain c -axis (Fig. 7).

At relatively low metamorphic grades an equilibrium 'foam' microstructure (Schmid, 1994) formed by nearly equant dynamically recrystallized grains with well equilibrated grain boundaries. Dynamic recrystallization by subgrain rotation went to completion and helped in developing an end-orientation for easy slip (Schmid, 1994). Structurally higher, large grains with frequent curved boundaries suggest incipient grain-growth and dynamic recrystallisation by grain boundary migration. Grains several millimetres in size, interpenetrated in three dimensions and including numerous and well developed phyl-

losilicates indicate extensive grain-growth, and are observed only in two samples: 21 and 4 (Figs. 5f and 5i). Boundaries between grains with high-angular misorientations of the c -axis are strongly lobate whereas low-angle boundaries are much straighter (as observed also by Mancktelow, 1990).

3.3. Texture

The c -axes are mostly distributed along unequally populated crossed-girdles which may evolve into an inclined single girdle. In these cases a single elongated maximum in the center of the pole figure is developed. This feature is observed in the samples with the smallest grain size (11 and 19a in Fig. 6). The asymmetry of the stronger girdle in respect to the macroscopic foliation indicates top-to-the-south movement in all of the samples.

In sample 4, collected in the deformed leucogranite dike, c -axes cluster in two maxima near to the primitive circle: normal to the foliation and parallel to the lineation. The quartz grains having c -axis close to the lineation (X) have basal subgrain boundaries. The other grains have mostly prismatic subgrain boundaries. If interpreted in terms of coexisting (a)- and (c)-slip directions (e.g., Mainprice et al., 1986), both fabric components give a consistent sense of shear that conforms with top-to-the-south shearing.

The a -axes cluster in 3 maxima with a tendency to form a small circle around the macroscopic lineation (e.g., sample 14). In two cases (samples 17 and 18) the pattern of a -axis distribution has resemblance to a small circle around the foliation normal (Z). The dominant maximum is perpendicular to the more densely populated c -axis girdle. The a -axis asymmetry is consistent with that of the c -axis, and indicates top-to-the-south movement.

The inverse pole figures show more readily the following features: The foliation pole is seen to favour alignment with positive rhombs r or (102) and second-order prisms a . As a result of the scalar addition, however, the maximum is mostly located in the center of the inverse pole figure. The only substantial difference is observed in sample 4 which shows a tendency for a foliation normal to align with the basal plane. Inverse pole figures for the X direction (E–W section) show the tendency for the m (or some intermediate as a result of the scalar

addition) to align close to the macroscopic lineation. Again, the only difference is in sample 4 which shows the tendency of a , m and c to align parallel to the macroscopic lineation.

3.4. Previous authors

There are several previous studies of the quartz microfabrics in tectonites collected along profiles

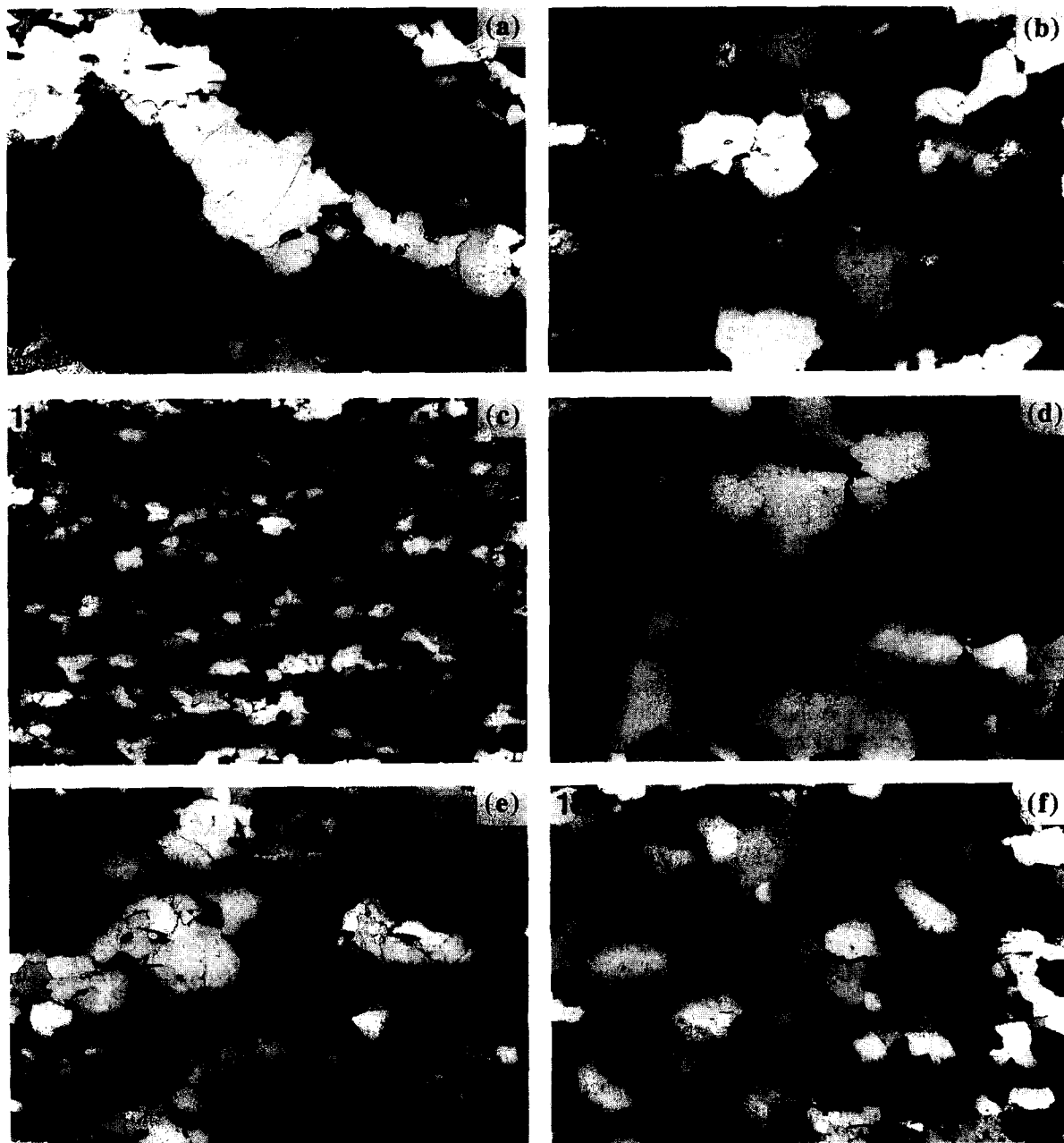


Fig. 5. Photomicrographs of samples discussed in this paper. (a) 4, (b) 2, (c) 11, (d) 21, (e) 12, (f) 18, (g) 17, (h) 14, (i) 19a. The photomicrographs were taken in plane-polarized light. The thin sections were cut parallel to the mineral stretching lineation and perpendicular to the foliation. Foliation orientation horizontal in all sections. The view direction is to the west. Width of field for all photomicrographs is 3 mm [the scale bar is given in (i)].

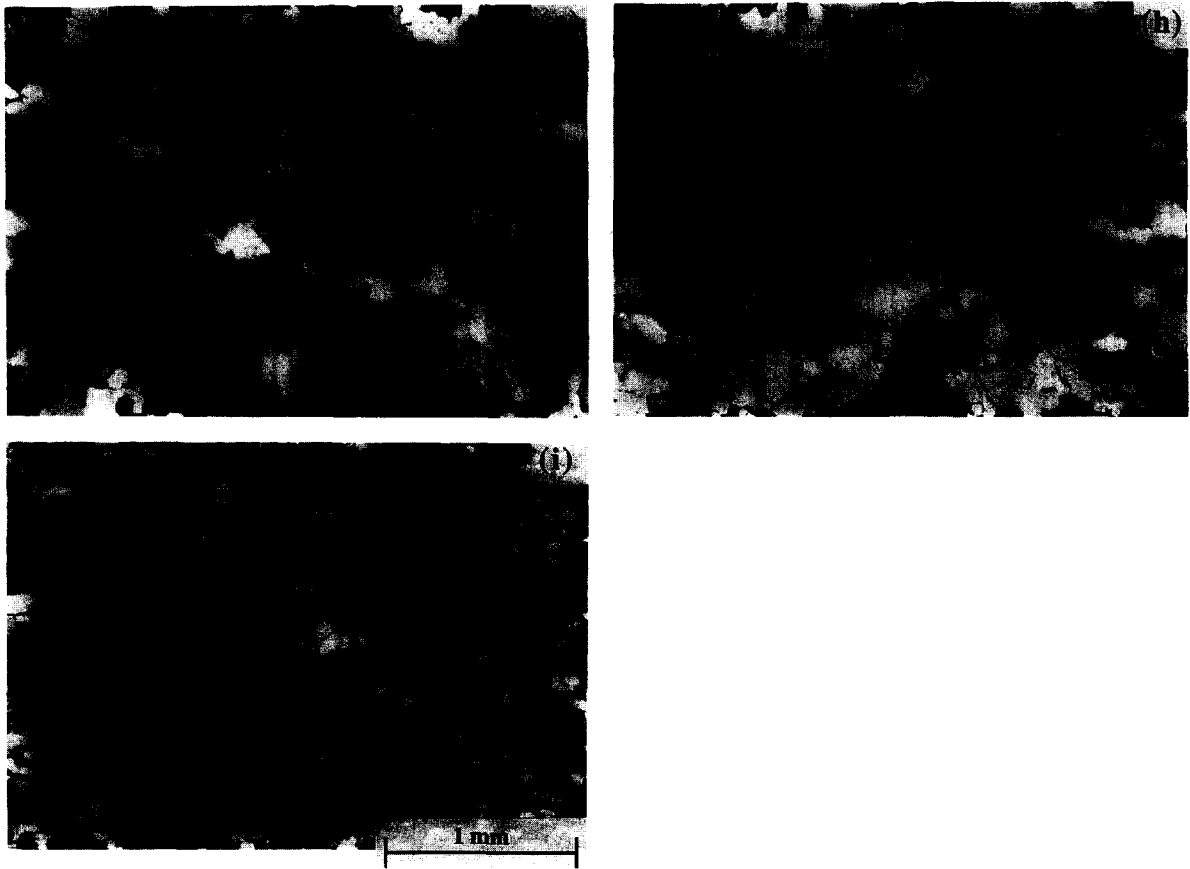


Fig. 5. Continued.

across the Main Central Thrust and HHC: Boullier and Bouchez (1978), Brunel (1980, 1983), Bouchez and Pêcher (1981), Burg et al. (1984), Greco (1989). From the base of the pile in Lesser Himalaya (in western and central Nepal) up to the top of the HHC, Bouchez and Pêcher (1981) observed a microstructural zonation that has been largely confirmed by later authors (Brunel, 1983; Greco, 1989). According to Bouchez and Pêcher (1981) and Greco (1989), in the upper tectonic levels, where a high degree of recrystallization is recognized, the strain is accommodated by prismatic or rhomb slip systems. This correlates with a decrease in the activity of basal slip (Bouchez and Pêcher, 1981), inferred also from the stereograms of Greco (1989), which predominates at the lower temperatures found in Lesser Himalaya. In the studies of quartz microfabrics from profiles across the Main Central Thrust zone in western and central Nepal (Brunel, 1980, 1983), the textural vari-

ations are interpreted to result from changes of temperature conditions in time: rhomb and prismatic slip are related to earlier deformation whereas basal slip is active during later, cooler stages of deformation.

4. Summary of microfabrics

4.1. Regional fabric transition

Throughout the Lesser and Higher Himalaya the quartz microstructures and associated measured textures (*c*, *a* and *m* axes) show a zonal distribution which is strongly correlated with the distribution of the syntectonic paleoisotherms. The textural patterns show a trend from north to south, i.e. from higher amphibolite- to middle greenschist-facies conditions. This trend suggests a temperature dependence of the quartz microfabrics consistent with numerical simulations by Jessell and Lister (1990).

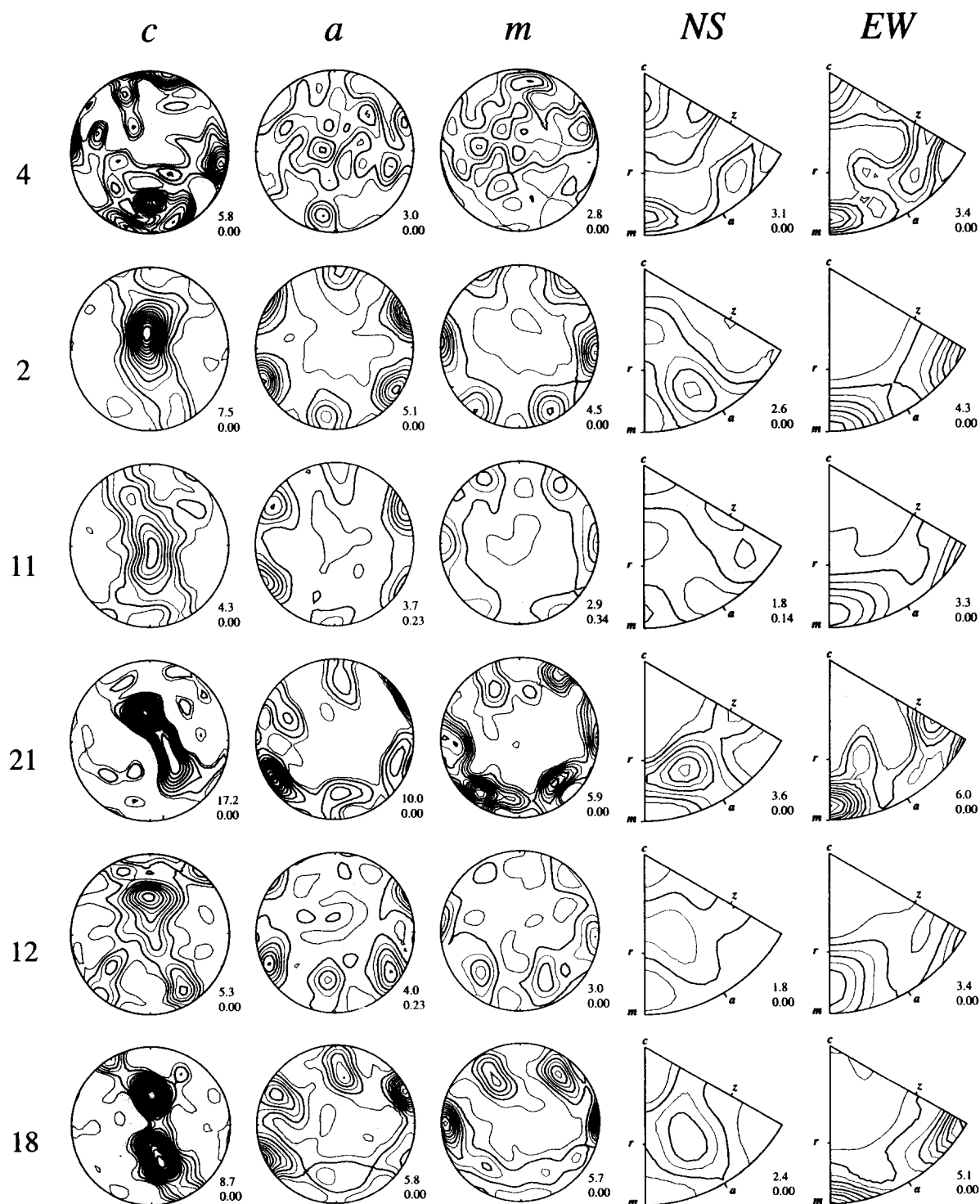


Fig. 6. Quartz X-ray textures. Pole figures of the regenerated *c*-axis (*c*), second-order prisms (*a*) and first-order prisms (*m*). In general the sample reference frame is such that the foliation normal is N–S and the lineation E–W. All the samples have been oriented such that the view direction is the same—to the west. Where the rotational component of deformation is known the movement sense is top-to-the south. Equal area upper hemisphere plot, contoured at 0.5, 1, 1.5, 2, ... times uniform, except for sample 21 contoured at 0.5, 1, 2, 3, ... stippled below 1. Inverse pole figures for sample directions are shown in columns NS and EW. A crystal projection with the *c*-axis in the centre was chosen, and the position of the *r*, *z* and *a*-directions are indicated. (NS) inverse pole figure for the foliation plane normal; (EW) inverse pole figure for the macroscopic lineation direction.

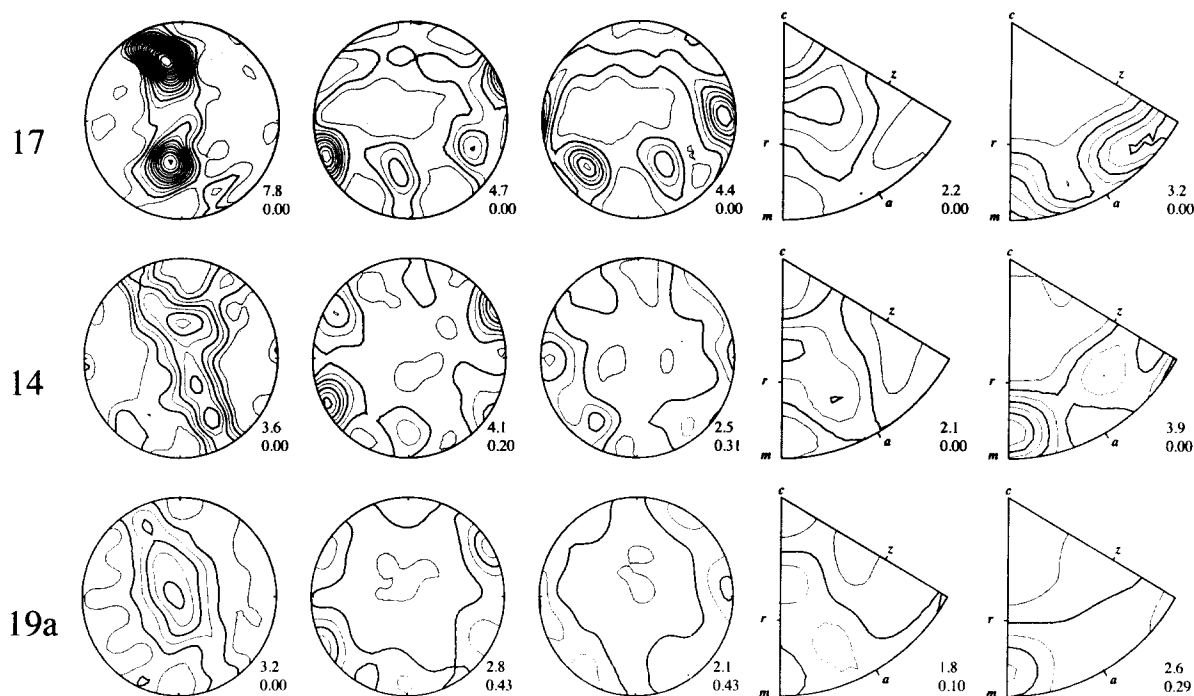


Fig. 6. Continued.

As suggested by several authors (e.g., Law et al., 1984; Law, 1987) the existence of different textural domains could have formed within a thrust sheet during a single tectonic event and as the result of a gradient in metamorphic conditions. Moderate to strong shear deformation, nearly homogeneously distributed across the MCTZ and the HHC, developed thanks to the high ductility expected under upper greenschist- to amphibolite-facies metamorphic conditions. Cooler environments prevailing in the Lesser Himalaya enhanced the ductility differences between different lithologies at the base of the tectonic pile, promoting strain partitioning (Bouchez and Pêcher, 1981; Greco, 1989). At high stress and/or high strain rate, narrow and cold shear zones probably developed within the Lesser Himalaya at a time when the overlying HHC pile was no longer plastically deforming.

In our working area the intensity of crystallographic preferred orientation does not increase, nor is there a marked fabric transition towards the MCT as is expected for high-strain zones (e.g., Law et al., 1984, 1986; Schmid and Casey, 1986; Law, 1987). The overprinted and incompletely recovered

substructures (undulose extinction, subgrains, deformational lamellae) indicate that minor stress pulses post-dated the thermal peak in most of the investigated area. The preservation of high-temperature textures (samples from granulite-facies rocks and leucogranites) and dynamic recrystallization, which have not been tempered or overprinted by lower temperature deformation, however indicate quenched microfabrics. This in turn suggests rapid exhumation of the HHC in the Bhutan Himalaya.

4.2. Active slip systems

Most of the quartzite samples from the Bhutan Himalaya show maxima at the division point of the *c*-axis cross-girdles and to lesser extent maxima at the center of the *c*-axis stereogram. These positions are classically interpreted as representing dominant $\langle a \rangle$ -slip on rhombohedron and prism respectively. According to experiments and numerical modeling this is typical for low to moderate temperature conditions (Christie et al., 1964; White, 1975; Bouchez, 1978). Maxima close to the primitive (basal slip) of the *c*-axis stereogram are observed in sample 4



Fig. 7. Basal {0001} subgrain boundaries in quartzite from a deformed leucogranite dike (sample 4). The photomicrograph was taken in plane-polarized light. The thin sections was cut parallel to mineral stretching lineation and perpendicular to foliation. The foliation is horizontal. The scale bar is 100 μm .

only. In the deformed leucogranite dikes and sills of Djüle La the plastic deformation of quartz is accommodated by prism $\langle c \rangle$ -slip. The presence of optically visible basal {0001} subgrain boundaries and strong concentration of c -axis parallel to the inferred shearing direction (close to the stretching lineation) are considered characteristic of $\langle c \rangle$ slip (Fig. 7). Slip in the $\langle c \rangle$ direction occurs at high temperature (650–750°C) and moderate hydrostatic pressure (350–400 MPa) under geological conditions of strain rate and deviatoric stress (Lister and Dornsiepen, 1982; Mainprice et al., 1986). When associated with igneous intrusions such as granites (Blumenfeld et al., 1986; Gapais and Barbarin, 1986; Mainprice et al., 1986; Blumenfeld and Bouchez, 1988) prism $\langle c \rangle$ -slip may indicate plastic deformation at temperatures near the granite solidus (see discussion by Paterson et al., 1989). A recent experimental study (Scaillet et al., 1995) shows, indeed, that the temperatures in the source regions of the Himalayan leucogranites were above 700°C (probably 750–770°C).

Quartz textures have been measured in a structurally higher position in deformed quartz tectonites in the leucogranites in the southern Tibet between Lhoza and Nyalam (Burg et al., 1984). The inferred dominant deformation mechanism is again prismatic glide in the $\langle a \rangle$ direction. This is interpreted by

these authors as consistent with greenschist-facies conditions during deformation.

Simple patterns are not found among the Himalayan quartzites, and no clear-cut rules can be found between the microstructural (and thermal) zonation and the textures. However the 'rhomb' and, to a lesser extent the 'prismatic' sub-maxima, tend to strengthen the higher-temperature conditions (MCTZ, HHC and STDZ). This correlates with a weakening of the 'basal' sub-maxima which in turn are well represented in the lower temperatures (Lesser Himalaya) (Brunel, 1980, 1983; Bouchez and Pêcher, 1981; Greco, 1989). The pole figures indicate the active slip planes and directions of the last ductile increment of the deformation. Owing to the number of variables potentially controlling crystallographic preferred orientation — like combinations of different mechanisms such as slip and recrystallization (see discussions by Law, 1990; Wenk and Christie, 1991) — it is difficult to interpret the measured textures in terms of dominant slip systems and directions. We therefore choose to remain with a qualitative description of the observed crystallographic fabrics, emphasizing the detected textural and microstructural trends.

4.3. Strain path

The asymmetric texture of *c*-axis and *a*-axis suggests a moderately rotational strain regime (Schmid and Casey, 1986, fig. 14). The stronger *c*-axis girdle is oblique to the foliation and the strongest *a*-axis maximum is perpendicular to that girdle. If interpreted in terms of coaxial deformation, the main features of the pole figures for the *c*-axis and *a*-axis suggest plane strain to weakly constrictional finite strain (Schmid and Casey, 1986, fig. 15). One can observe vestiges of the crossed girdles of *c*-axis and small circles of *a*-axis around the macroscopic lineation (*X*). These textural characteristics, and the ones from central and western Himalaya (Brunel, 1980, 1983; Bouchez and Pêcher, 1981; Greco, 1989) suggest the coexistence of pure shear and simple shear components: i.e., differential shortening components normal and parallel to a broad zone including MCTZ, HHC and STDZ.

4.4. Ductile deformation and inverted metamorphism

The moderate to strong crystallographic preferred orientation and strong dynamic recrystallization are found in every analyzed sample, indicating that the described deformation is pervasively distributed throughout the HHC. Therefore, the term 'Tibetan slab' for the HHC is misleading as it is a wide zone of heterogeneous shear. Also, the mapped MCT in eastern Bhutan is interpreted as a protolith boundary, and not as a fabric boundary. From this it follows that there is only one zone of inverted metamorphism across the MCTZ; not one above (in the HHC) and one below the MCT (in the Lesser Himalaya). This zone of condensed isograds (MCTZ) shows an inverted metamorphic sequence. This inverted metamorphic sequence could, therefore, be explained by deformation and stretching of earlier formed peak metamorphic isograds corresponding to a normal thermal gradient. The presently inverted metamorphic sequence is, therefore, formed by material points that reached peak temperatures at different times and places, not corresponding to their present day structural position (Jamieson et al., 1995). The inverted metamorphic sequence is a consequence of pervasive ductile shearing in

the MCTZ and is not due to an inverted thermal gradient.

The situation at the Kakhtang thrust is, however, different in that the inverted metamorphic sequence is interpreted to be at least locally caused by inverted isotherms. The increase in peak temperatures structurally upwards is directly linked to the synkinematic intrusion of leucogranites. The site of these intrusions is systematically linked to areas of the highest metamorphic grade and the isograds cut obliquely across the structural trend (Figs. 1 and 2). This, together with the documented change in microfabric (sample 4) and new thermobarometric data (Hollister et al., 1995) suggests a locally inverted thermal gradient during thrusting as was also documented elsewhere (Davidson et al., 1992). Local inversion of isotherms near the Kakhtang thrust is interpreted to be due to heat advection by the leucogranite intrusions (Hollister et al., 1995).

5. Discussion

5.1. Ductile extrusion of the HHC in the Bhutan Himalayas

Recently obtained geochronological data (e.g., Macfarlane et al., 1992; Hodges et al., 1993, 1995; Coleman, 1995; Searle, 1995) suggest that both MCTZ and STDZ were active simultaneously between 22 and 19 Ma. Normal shearing-faulting between the HHC and Tethys Himalaya is shown to be contemporaneous with compressive deformation on a regional scale (Burg et al., 1984), movements along MCTZ and the STDZ both being directed perpendicular to the strike of the orogen. The most reliable date of 18.1 Ma for the Manaslu granite (Deniel et al., 1987) implies that the melting was roughly synchronous with the MCTZ and STDZ. Guillot et al. (1994) suggest that the crystallization age of the Manaslu intrusion is at least 22–23 Ma and that the rapid cooling of the aureole occurred several million years after crystallization, between 19 and 16 Ma. These ages are not necessarily the same for Bhutan because the movements on the STDZ have been shown to be diachronous along strike (e.g., Guillot et al., 1994). Indeed, the Kula Kangri intrusion — north of the Mönlakarchung–Pasalum intrusion — has provided cooling ages of 10.7 to 11.4 Ma, based

on concordant muscovite and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages (Maluski et al., 1988). Biotites and muscovites from the leucogranites in western Bhutan yielded Rb–Sr ages between 11 and 12 Ma (Gansser, 1983). The cooling ages for Gophu La leucogranite intrusion (Ferrara et al., 1991) are 14.7 ± 0.2 Ma to 15.0 ± 0.3 Ma for muscovite and 14.0 ± 0.2 Ma to 15.1 ± 0.2 Ma for biotite.

Bounded below by north-dipping, south-directed shear zones (MCTZ) and above by north dipping normal faults (STDZ), the central Himalaya has the shape of an orogenic wedge. Platt (1993) has proposed several possible extensional geometries in orogenic wedges. The HHC can be best approximated by a model whereby a thrust is formed above a rigid underthrusting plate (e.g., Lesser Himalaya), with a rigid buttress (e.g., Tibet–Tethyan Himalaya) at the rear. The STDZ simply forms a hinterland-dipping backstop which does not form as a consequence of large scale crustal thinning of an overthickened orogenic wedge. South-directed extrusion of HHC rather than north–south extension is responsible for the normal fault geometry at the STDZ (Burchfiel et al., 1992). As noted by Searle (1995) the Himalaya has been under compressional stresses since 50 Ma and there was never any net crustal extension during that period. The model of an extruding wedge has been already proposed for the central Himalayas in order to explain the simultaneous operation of southward thrusting along MCT and normal fault extension on the STD (Burchfiel and Royden, 1985; Kündig, 1988, 1989; Burchfiel et al., 1992; Hodges et al., 1993).

As has been shown previously, the MCTZ represents a broad zone of ductile deformation with top-to-the-south thrusting. The highest-grade rocks in the central Himalaya are found in units emplaced southward over lower-grade units, overlain by other lower-grade units relatively displaced northward on top. This is exactly the geometry which would result from nappes being expelled from an active subduction zone (Wheeler, 1991). These observations, together with our field data from the Bhutan Himalaya, lead us to hypothesize that the extruding wedge of HHC did not act as a rigid block but was deformed pervasively during its extrusion. We propose that ductile extrusion of the HHC and part of Lesser Himalaya between the STDZ at the top and

the MCTZ at the bottom is largely responsible for the observed metamorphic sequence (Fig. 8), local inversions such as along the Kakhtang thrust being caused by synkinematic leucogranite intrusions.

Ductile extrusion in the central Himalayas is interpreted to be related to the leucogranite intrusions. Leucogranite dikes and sills at Djüle La intruded the HHC syntectonically during top-to-the-south shearing. This deformation was synchronous with isothermal decompression (Davidson et al., 1995; Hollister et al., 1995). The top-to-the-south shearing was penetrative before, during, and after the intrusion of leucogranites. The evidences consist of: (1) the well developed fabric being cut by leucogranites who immediately became deformed and part of that same fabric; (2) the synkinematic high-*T* metamorphic reactions (Davidson et al., 1995); and (3) similar kinematics indicated by the textures studied all across the profile through the HHC. Penetrative deformation occurred at high temperatures everywhere and no retrograde metamorphic minerals have been found. Instead, sillimanite and biotite grow in strain shadows (Swapp and Hollister, 1991).

The field relationships between country rocks and the major leucogranite intrusions at the highest tectonic levels in the HHC were not observed on our expedition. It is, however, assumed that the leucogranite dikes and sills of Djüle La are roughly the same age as the Mönlakarchung–Pasalum intrusion. This implies that the large leucogranite intrusions were also emplaced during (or near the end) of penetrative deformation within the HHC of Bhutan Himalaya.

Apart from complications near the Kakhtang thrust distributed heterogeneous simple shear in the MCTZ has simply deformed the metamorphic isograds which largely acted as passive markers. This lead to an inverted metamorphic sequence by a mechanism analogous to the *card pack* mechanism of formation of similar folds (Ramsay, 1967, pp. 430–436) (Fig. 9). As a consequence of the inclined shear planes, and heterogeneous displacement along them, the deformed metamorphic isograds result in an inverted metamorphic sequence in the overturned limb formed by thrust shearing, and a right way up metamorphic sequence in the normal limb overprinted by normal faulting. Whether the metamorphic isograds are actually inverted in cross-section depends on the amount of displacement (compare subfigures 9a and

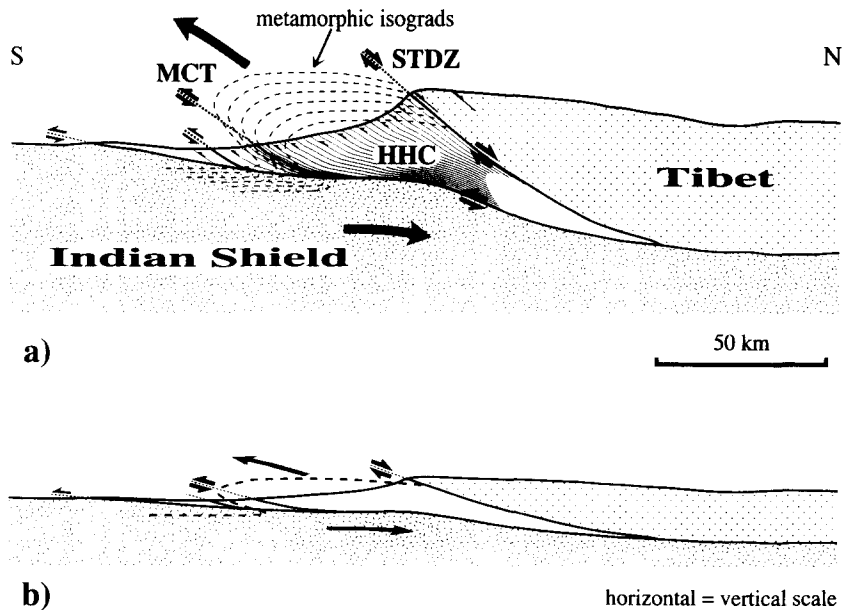


Fig. 8. Schematic cross-section of the Himalayas displaying implied relations between the Main Central Thrust zone and South Tibetan Detachment zone. A shallow crustal wedge is tectonically extruded to the south relative to India and Tibet. Extrusion is accommodated by shearing within the MCT zone at the bottom and by normal faulting in the STD zone at the top, a boundary that acts as a hinterland dipping normal fault. The wedge is pervasively ductily deformed, although the deformation is more concentrated on the boundaries of the wedge. The penetrative deformation, and maximal finite displacement in its core, result in passive folding of metamorphic isograds. Effects of shear heating and heat advection due to the leucogranite intrusions are not taken into account. The non-parallel walls formed by the MCT and STD are instrumental for inducing channel flow within the HHC. (a) Vertical scale ca. 2.5 times exaggerated. (b) Verical and horizontal scale are the same.

9b). However, even moderate shearing (Fig. 9a) will lead to a map pattern which may erroneously be interpreted in terms of inverted isograds. Actual inversion of the metamorphic sequence in the vicinity of the MCTZ (Fig. 9b) is inferred from the isograd map pattern found around the half-window in the Kuru Chu–Shumar spur and around the Ranjit window (Gansser, 1983, fig. 125). The characteristics of such an inverted metamorphic sequences are the parallelism (in map view) of structures and isograds and the non-contemporaneity of peak metamorphism and deformation. The deformation itself is not synchronous everywhere but propagates towards the foreland. A similar model, whereby the ductile shear displacement along pervasive shear planes caused metamorphic inversion, was proposed by Jain and Manickavasagam (1993) for the Higher Himalayan crystalline in Jammu and Kashmir. Their model, however, considers only top-to-the-south shearing.

Burg et al. (1984), Brun et al. (1985), Kündig (1989), and Burchfiel et al. (1992) have shown that

the deformation along STDZ is not restricted to a single fault plane but is distributed in the footwall for up to 3–4 km. Both Burg et al. (1984) and Burchfiel et al. (1992) noticed an overprint of top-to-the-north shearing over an older top-to-the-south thrusting in the Künla Kangri area, just north of the Bhutan border. The heat brought by the Mönlakarchung–Pasalum leucogranite intrusion probably helped the inversion of flow kinematics.

A model of tectonic extrusion in terms of a superposition of pure shear on simple shear was proposed for the Helvetic Nappes of Switzerland (Dietrich and Casey, 1989). The authors observed a vertical metamorphic gradient based on illite crystallinity values. This gradient is inverted in the lower limb and it is the right way up in the upper limb. A similar model was proposed for the HHC by Searle et al. (1988) and Searle and Rex (1989): a postmetamorphic recumbent folding and telescoping of isograds lead to the inverted metamorphic field gradient. This model is, however, not directly applicable on the HHC of

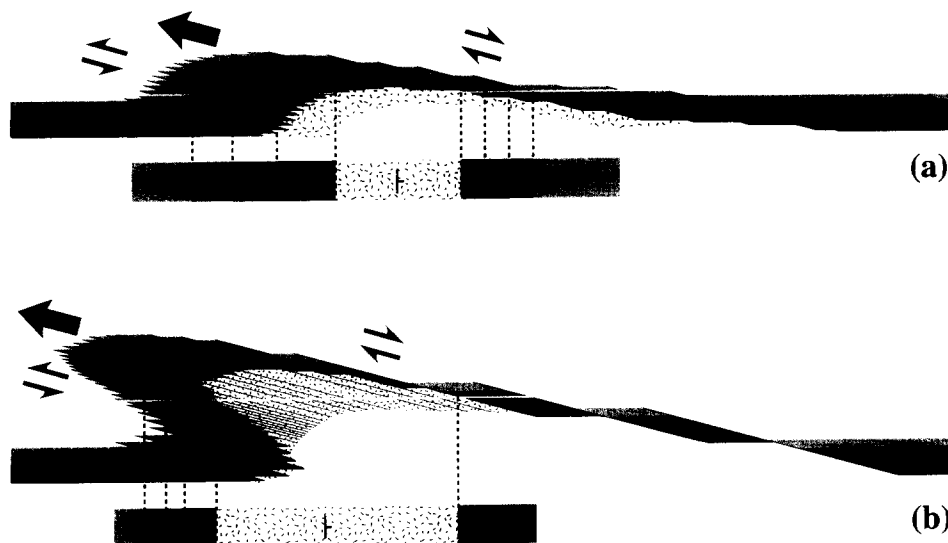


Fig. 9. Geometric representation of ductile extrusion of an orogenic wedge along pervasive shear planes. Schematic crust has four metamorphic zones and a magmatic intrusion, white horizontal line is the erosional surface. The inversion of a metamorphic sequence is the result of movements along pervasive inclined shear planes. (a) Moderate extrusion causes an inverted metamorphic sequence in the map view although in the cross-section the isograds are still right way up. (b) Large amount of extrusion leads to the inverted metamorphic sequence in the map view and to the inverted metamorphic isograds in the cross-section. Below both diagrams (a) and (b) is a strip of corresponding map pattern of metamorphic zones. In both cases, in the area of the normal faulting the isograds remain right way up. The distribution of the isograds on the map view is the result of dip of the shear planes, displacement along them and topographic level. The situation depicted in subfigure (b) is taken here as representative for the geological situation in the Bhutan Himalaya.

the Bhutan Himalaya. Buckle folding on such a scale would involve the entire lithosphere. Furthermore, the low strain rate of such deformation would allow the metamorphic isograds to re-equilibrate. Indications for such a process, field and geophysical, are lacking.

The combination of active underthrusting (heterogeneous simple shear) and the gravitational effect (pure shear) were proposed to be the driving forces of the southward extrusion of wedge shaped central Himalayas. Burg et al. (1984) suggest that the mechanism for simultaneous operation of the MCT and the STD was the gravity-driven décollement of the 10 000 m thick Tethyan sedimentary pile due to the presence of high topographic relief. Recent physical modeling (Chemenda et al., 1995) has shown that syn-collisional exhumation of previously subducted (underthrust) crustal material can occur due to the failure of the subducting slab (along the MCT in our case). Erosional unloading causes the buoyant upper crust to be exhumed (at a rate comparable to the subduction rate) producing a normal sense movement

along the upper surface of the slab (STDZ). This model, however, regards the exhumed crustal slice as a rigid slab constrained by well defined thrust and normal faults.

5.2. Channel flow model

The process of extrusive flow suggested here can be approximated quantitatively by channel flow models that have been used to describe subduction zone processes (e.g., England and Holland, 1979; Shreve and Cloos, 1986; Mancktelow, 1995). Such model characterizes a thrust system as a viscous material-filled channel lying between two rigid sheets that deform the viscous material between them through induced shear and pressure gradients within the channel. The exact result depends on the geometry of the channel, but the simplest qualitative characteristic of these models is that the velocity field is a hybrid between two end-members (e.g., Turcotte and Schubert, 1982; Mancktelow, 1995, fig. 2): (1) induced shear (applied at the boundaries) which pro-

duces a uniform vorticity (simple shear) across the channel; and (2) induced pressure gradients produce a ‘pipe-flow’ effect with highest velocities in the center of the channel and opposite vorticity at the top and bottom of the channel. The predicted kinematic histories for the two end-members are markedly different. In the HHC the main history of the system apparently records a hybrid process with a major influence of the pipe-flow effect. In particular, the reverse shear sense at the top of the channel is exactly the flow-pattern inferred across the top of the HHC along the South Tibetan Detachment system whereas south-direct ductile thrusting dominates at the base of the HHC belt. It is this extrusion process that we suggest was the dominant mechanism in the HHC of Bhutan. In these channel flow models (e.g., Shreve and Cloos, 1986; Mancktelow, 1995) the transition from uniform simple shear to ‘extrusive flow’ is highly sensitive to viscosity and to lateral pressure gradients.

In a parallel-sided channel, the driving force for reverse flow at the top of the channel — the buoyancy of subducted material — is compensated by lithostatic pressure. In situations where the channel walls are non-parallel the (nonlithostatic) pressure gradient might cause high rates of buoyant return flow of the channel fill provided that the viscosity is low enough (Mancktelow, 1995). Recent geophysical data (e.g., Makovsky and Klempner, 1995; Mechie et al., 1995; Nelson et al., 1995) suggest that the HHC (as constrained by STD and MCT) has, indeed, a geometry of a channel with downward converging walls.

Turcotte and Schubert (1982), p. 234, eq. 6-17, give the following equation for the mean velocity of flow in a parallel-sided channel:

$$\bar{v} = -\frac{h^2}{12\mu} \frac{dp}{dx} + \frac{v_0}{2} \quad (1)$$

where $\bar{v}$ is the mean velocity, h is the thickness of the channel, μ is the viscosity of the fluid, dp/dx is the pressure gradient and v_0 is the velocity of one side of the channel. Taking $h = 1000$ m, $\bar{v} = 20$ mm/y, $dp/dx = 2$ MPa/km and $v_0 = 0$, Eq. (1) gives a value of 10^{17} Pa s. Turcotte and Schubert (1982), p. 339, eq. 7-250, give Eq. (2) for the effective viscosity of a power-law material:

$$\mu_{\text{eff}} = \frac{1}{2C_1\sigma_0^{n-1}} \exp(E_a/RT) \quad (2)$$

where μ_{eff} is the effective viscosity, C_1 is the pre-exponential term of power-law creep, σ_0 is the stress, n is the exponent of power-law creep, E_a is the activation energy, R is the gas constant and T the absolute temperature. Eq. 6-8 of Turcotte and Schubert (1982) $d\tau/dy = dp/dx$ shows that the stress in the channel is of the order of 1 MPa. With this value for σ_0 and values for wet quartz of $\log_{10} C_1 = 3.2$ GPa $^{-n}$ s $^{-1}$, $n = 2.4$ and $E_a = 160$ kJ mol $^{-1}$, taken from Kirby (1985), the necessary temperature is 730°C.

Based on the evidence presented by both Burg et al. (1984) and Burchfiel et al. (1992) for a reversal in shear sense during the history of flow along the South Tibetan Detachment, it seems likely that the extrusive flow in the Himalayan system developed late in the history. Thus, given the sensitivity of the models to lateral pressure gradients and viscosity, this raises the question of which of these parameters induced the transition from simple uniform shear to extrusive flow. In a thrust system such as the Himalayan MCT, a lateral pressure gradient would develop due to building of topography during collisional tectonics. For example, along the present Himalayan front, there is 4–6 km of topographic relief over a horizontal distance of ~ 100 km which would produce a lateral pressure gradient of ~ 1 –2 MPa/km. Thus, during the history of mountain building in the Himalayan system a lateral pressure gradient was clearly developed and could have contributed to the extrusive flow. Similarly, major changes in viscosity also accompanied motion on the MCT. Swapp and Hollister (1991) presented evidence of early heating of the HHC followed by rapid high- T decompression. This early heating history may have been aided by strain heating (e.g., Pavlis, 1986; Molnar and England, 1990; or Peacock, 1991) or by heat advection due to the leucogranite intrusions into the HHC (e.g., Hollister et al., 1995). Irrespective of the source of the heat, the related temperature increase would result in a drop in viscosity within the ‘channel’ at the same time as the creation of orogenic topography produced a lateral pressure gradient within the channel. Furthermore, the localization of melt probably lubricated the roofing channel wall relaxing the assumption of non-slip boundary conditions of the channel material at the walls (e.g., Batchelor, 1967, p. 295). Reverse flow can, consequently, develop in the whole upper part of the channel (see Mancktelow,

1995, fig. 13) and assist rapid tectonic extrusion. We suggest that both these processes (pressure gradient and low viscosity) together led to the extrusive flow of the HHC.

6. Conclusions

The integration of field mapping and quartz microfabrics observations within the Bhutan Himalaya leads to the following conclusions:

(1) Asymmetry of *c*- and *a*-axis fabrics indicates top-to-the-south shearing from the Lesser Himalaya to the injection complex at the base of the Mönlakarchung–Pasalum intrusion. The finite strain ellipsoid inferred from the texture pattern is moderately constrictional throughout the study area. No substantial change in strain magnitude in the quartz tectonites is observed throughout the HHC of the Bhutan Himalayas.

(2) Notwithstanding minor differences, most of the samples from MCTZ and HHC of the Bhutan Himalaya show very similar crystallographic fabrics. Temperature differences did not lead to changes in the active slip systems except for the deformed leucogranite sills and dikes where $\langle c \rangle$ -slip was active. Microstructure is more sensitive to the varying temperature conditions of the deformation than the texture.

(3) Our kinematic interpretation involves a component of coaxial thinning across the channel and concomitant north–south stretching parallel to the thrusting direction.

(4) A tectonic model is proposed in order to explain the distribution of kinematic domains. This model involves ductile southward extrusion of the Higher Himalaya Crystalline of Bhutan. Due to the displacement distribution, governed by channel flow, the largest finite displacement is to be expected in the upper part of the ‘channel’. This zone is underlain by the highest-grade rocks and the belt of leucogranite intrusions.

(5) The inverted metamorphic sequence in the Bhutan Himalaya is largely explained to result from the deformation of the metamorphic isograds into a crustal-scale antiform by ductile shearing. Locally, associated with the Kakhtang thrust, the peak metamorphic isograds were inverted during deformation due to heat advection from a large leucogranite in-

trusion leading to the inversion of isotherms. Rapid exhumation, in both cases, is a necessary prerequisite for preserving deformed isograds. Quenched quartz microfabrics and thermobarometric data (Davidson et al., 1995) support such a model for rapid exhumation.

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