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Deformation of leucogranites of the crystalline Main Central Sheet in southern Tibet (China)

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Abstract—Towards the top of the Main Central Sheet in southern Tibet (China) leucogranites intrude metamorphic rocks related to rocks of the Main Central Thrust in the Himalayas. Our study shows that the leucogranites suffered a northward shear deformation. The significance of this event is discussed in terms of gravity-driven décollement of the 10,000 m thick Tethyan sedimentary pile over its crystalline basement.

INTRODUCTION

The determination of shear sense within thrust sheets is fundamental to the understanding of orogenis. Considerable work has been carried out investigating ductile deformation and the resulting symmetry of fabrics within nappes and contact zones (e.g. Christie 1963, Escher *et al.* 1975, Marjoribanks 1976, Laurent & Etchecopar 1976, Brunel 1980, Coward & Kim 1981, Boullier & Quenardel 1981, Bouchez & Pecher 1981, Behrmann & Platt 1982). The purpose of this paper is to show that in the upper part of such structures, non-coaxial deformation criteria contrary to the regional sense of thrust sheets emplacement can be encountered. An example from southern Tibet is used. Our analysis of the fabric anomalies is based on the microtectonic description of leucogranites and crystallographic preferred orientations of plastically deformed quartz in the granites.

GEOLOGICAL SETTING

The Tethyan sedimentary sequence, essentially continuous from the Ordovician to Eocene (Mu *et al.* 1973), is underlain in southern Tibet (China) by the metamorphic basement of the Main Central Sheet. This crystalline nappe comprises pelitic metasediments, garnet–kyanite gneisses (±staurolite or sillimanite) marbles, quartzites, sillimanite–muscovite migmatites, some with garnet-bearing basic boudins, and augen granites gneisses which may be of Early Palaeozoic age, like similar series in Nepal (Pecher & Lefort 1977). This series has been recognized all along the 2000-km Himalayan Range (Gansser 1964) and is considered to be polymetamorphic (Gansser 1964, Fuchs 1981, Brunel 1983). During the summers of 1980 and 1981, six areas of the upper part of the Main Central Sheet between Lhoza (90°50′E = XT 125, Fig. 1) and Nyalam (86°E = XT B9 Fig. 1) were visited by Chinese and French geologists. Metamorphic rocks are intruded and hornfelsed by leucogranites with similar characteristics to those described in Nepal (Le Fort 1973, 1981) and in Bhutan (Dietrich & Gansser 1981). Plutons form lenticular sheets several metres thick dipping gently to the north (Fig. 2), or large aplo-pegmatitic networks of dykes, parallel to bedding or foliation in the highly deformed metamorphic country rocks (Fig. 3a). These granite sheets correspond to the Himalayan granites dated elsewhere as of Oligene to Miocene age (31–17 Ma, Krummenacher 1971, Chang *et al.* 1977, Vidal 1978, Xu *et al.* 1983).

The plutons studied have a relatively constant mineral composition of quartz (30–35%), weakly zoned An_{10-20} plagioclase (30–40%), perthitic K-feldspar, muscovite (5–10%) and partially chloritized biotite (5%). Accessory minerals (apatite, zircon and opaques) are rare. Tourmaline may be present (up to 15% in Lhoza). The rocks are generally of medium grain size. It has been proposed that they formed by anatexis immediately above the Main Central Thrust (M.C.T.) (Le Fort 1975,

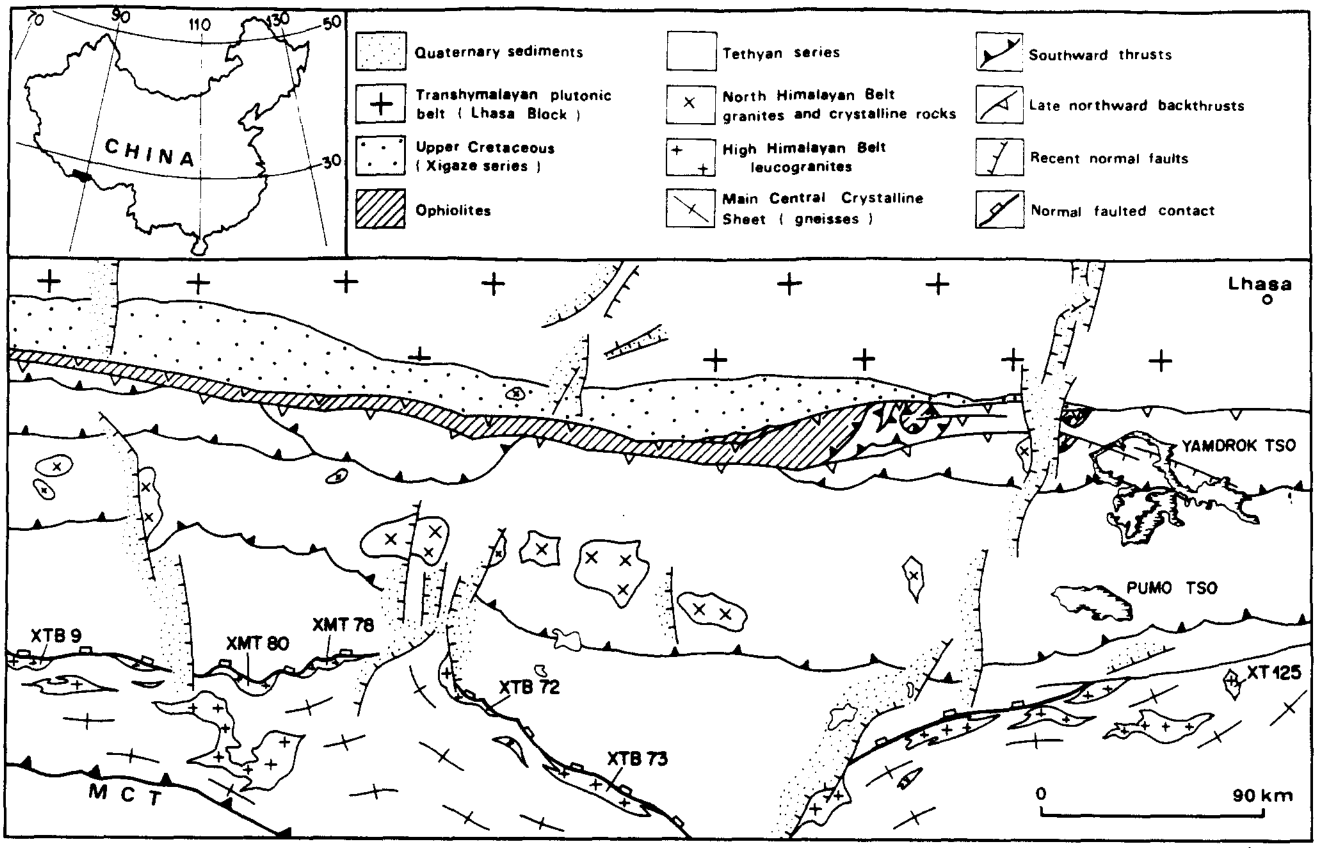

Fig. 1. Structural sketch map of southern Tibet and the location of the studied leucogranites.

Allègre & Ben Othman 1980, Dietrich & Gansser 1981, Vidal *et al.* 1982).

From Lhoza to Nyalam all the leucogranites observed are emplaced within a 2–3 km thick sequence of dark schists and/or of pyroxene–garnet marbles which belong to the so-called Sinian (of Late Precambrian age ? Yin & Kuo 1978). They are always restricted to the same lithological and structural position, a few hundred metres above the augen gneisses and the sillimanite gneisses of the Main Central Sheet and below the fossiliferous mid-Ordovician rock at the base of the Tethyan sequence.

Towards the bottom of the Sinian succession, the laccoliths and pegmatitic veins intrude anatectic sillimanite gneisses and diopside marbles (Lhoza), and are in metamorphic equilibrium with the surrounding rocks. Emplacement of the plutons was contemporaneous with the high temperature, intermediate to low pressure metamorphism (sillimanite + cordierite + garnet, Brunel 1983) and was associated with southward-directed reverse shear zones in which fibrolite is parallel to a N030°E stretching lineation.

In upper levels, the laccoliths do not intrude Tethyan sediments. Contact metamorphism in Lhoza produced large crystals of chiastolite cross cutting the foliation of the Sinian schists; elsewhere staurolite and chloritoid are common porphyroblasts. The contact between the Sinian rocks and the overlying Ordovician limestones (which possess a weak cleavage dipping more steeply northward than bedding) is clearly a northward-dipping fault which separates two zones with different structural and metamorphic histories. To the north, the Tethyan series have suffered a single and weak penetrative deformation (spaced fracture cleavage) whereas to the south, rocks underwent polyphase synmetamorphic deformation associated with the development of the M.C.T.

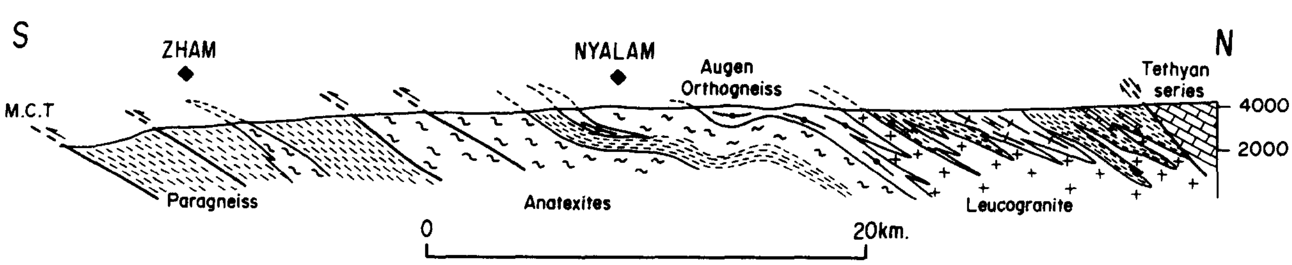

Fig. 2. Location of the studied leucogranites on a simplified section of the Main Central Crystalline Sheet (locality XTB 9 in Fig. 1).

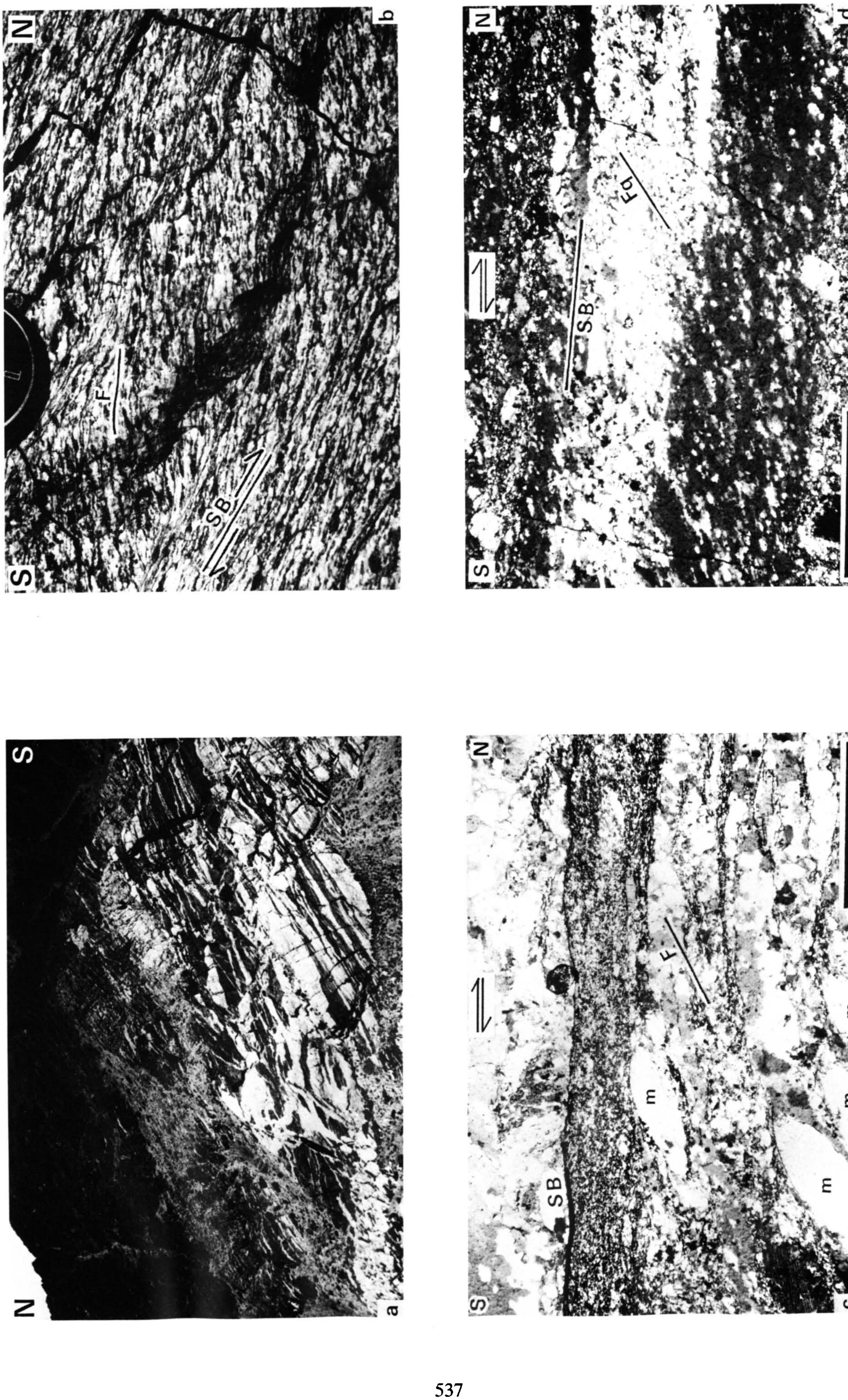

Fig. 3. (a) Typical leucogranite laccolith and veins intrusive into schists, calc-schists and marbles of the Sinian sequence at the top of the Main Central Crystalline Sheet (Plum Qü Valley, XTB 73). (b) Mesoscopic structure of the XTB 72 leucogranite showing foliation and shear plane relationships; *XZ* section of the rock. (c) Comminution of micas and K-feldspar grains within the shear bands. Note the juxtaposition of zones with continuous and discontinuous deformation mechanisms. F, foliation; SB, shear band; m, muscovite. XTB9 sample. Scale is 1 mm. (d) Polycrystalline quartz ribbons parallel to the shear bands. The grains define a shape fabric (F_q) oblique to the shear bands. XMT 80 sample. Scale is 0.4 mm.

MACROSCOPIC STRUCTURES

Towards the bottom of the Sinian sequence, the main cleavage of the surrounding rocks enters the plutons and passes into their foliation. Dykes here are isoclinally folded and the leucogranites themselves show a weak deformation, synkinematic with the southwards shearing of the M.C.T.

Towards the upper part of the Main Central Sheet the granites show a marked planar and linear fabric, two sets of planar structures being observed. A subhorizontal foliation plane (F) defined by the average flattening plane of the grains and preferred orientation of micas (Fig. 3b) is considered to represent the XY plane of the finite strain ellipsoid ($X \geqslant Y \geqslant Z$). Shear bands (S.B.) are regularly spaced (Fig. 3b) and generally dip gently northward at 15–30°. Shear bands and foliation intersect along the intermediate strain axis Y. The relationship between S.B. and F is the one which is classically observed in a shear deformation, the direction and sense of shearing being as indicated in Fig. 3(b) (Berthé *et al.* 1979, White *et al.* 1980, Burg *et al.* 1981).

A mineral lineation (L) (N020°E to N050°E according to the considered region) marked by a streaking of felsic and mafic minerals and by the long axes of quartz lenses and blebs of micas is developed within the F planes. This mineral stretching lineation is equated with the X axis of the finite strain ellipsoid.

Fibres and slickenside striations formed on the S.B. planes parallel the L direction within F planes, showing that the movement direction on shear planes is consistent with the direction of bulk flow.

The consistent asymmetry of non-coaxial deformation criteria (sigmoidal micas and polycrystalline aggregates, rotated porphyroclasts and pressure shadows) in the XZ plane (i.e. parallel to L and orthogonal to F) shows clearly that the planar and linear fabrics of all the studied leucogranite laccoliths denote a northward shearing event (Fig. 3b).

MICROSTRUCTURES

In thin-sections, microstructures associated with foliation development indicate plastic deformation (Figs. 3c & d). It is thought that foliation planes probably formed early in the history of progressive deformation, during ascent and emplacement of granites.

Comminution of the mica and feldspar grains (Fig. 3c) shows that shear bands are mainly due to a discontinuous deformation mechanism at a grain scale. These discontinuities are 50–100 μm wide and make an angle of 15–30° with the foliation. Textural relationships and retrogression of micas within shear bands clearly show that their development followed the appearance of the foliation during the progressive deformation history.

The foliation follows a sigmoidal trend across some shear bands, the pattern being comparable to that observed in continuous ductile shear zones by Ramsay & Graham (1970). It is thought that shear bands result from progressive deformation which leads to more heterogeneous strains at the grain scale. Quartz appears as elongated polycrystalline ribbons of fine grains (10–20 μm) parallel to the shear bands. In the XZ strain plane, these small grains define themselves a grain shape fabric (F_q) oblique to the shear bands. The angle between F_q and S.B. is smaller than that between $F \angle$ S.B. These obliquities also indicate a northward sense of shear (Fig. 3d) (e.g. Brunel 1980, 1983).

Micas are deformed, showing sigmoidal shapes. Their tips form elongate fine-grained aggregates scattered along shear planes (Fig. 3c). Feldspar porphyroclasts are truncated with cracks welded by quartz. Large fragments show little internal deformation. Pressure shadows around tourmaline and feldspar porphyroclasts are generally asymmetric. These microstructures clearly indicate that a northward shearing affected the magmatic mineralogical association and thus postdated the ascent of the granites.

LATTICE PREFERRED ORIENTATION OF QUARTZ

c-axis fabrics

Quartz **c**-axis fabrics have been measured in the XZ plane of strain using a universal stage. Measurements relate to rocks where polycrystalline ribbons of quartz (width ≃ 100 μm) are generally parallel to the foliation, F. Two types of diagram resulted from the analysis (Fig. 4). The first type (XTB 72, XMT 78, XTB 9) shows a pronounced scattering of **c**-axes within one or two girdles at a high angle to the mesoscopic shear direction (S.B.) with a maximum close to Y (about 8% of the measurements). The intersection of these girdles with the foliation at right angles to the lineation demonstrates that the fabric is genetically related to the present macroscopic structural elements. Following the prediction by computer modelling (Etchecopar 1977, Lister & Hobbs 1980) and as shown for natural shear zones in quartz-rich rocks (e.g. Bouchez 1977, Burg & Laurent 1978, Lister & Price 1978, Lister & Williams 1979) we interpret the asymmetry of the pattern as a criterion of non-coaxial deformation. The obliquity towards the north of the girdle which contains the maxima indicates a northward sense of shear. In the second type (XT 125, XTB 73, XMT 80) quartz **c**-axes tend to form incomplete girdles orthogonal to the shear bands and present a strong maximum (more than 10% of the measurements) around the Y axis of finite strain.

These diagrams relate to strongly deformed granite with a polycrystalline ribbon texture characterized by an oblique grain-shape fabric (F_q) and a small grain size (≃10 μm). Both the angle $F_q \angle$ S.B. and the obliquity between F_q and the girdle of **c**-axes are consistent with a northward sense of shear. Locally F_q has been seen to rotate towards S.B. which suggests inhomogeneous shear strain at the ribbon scale.

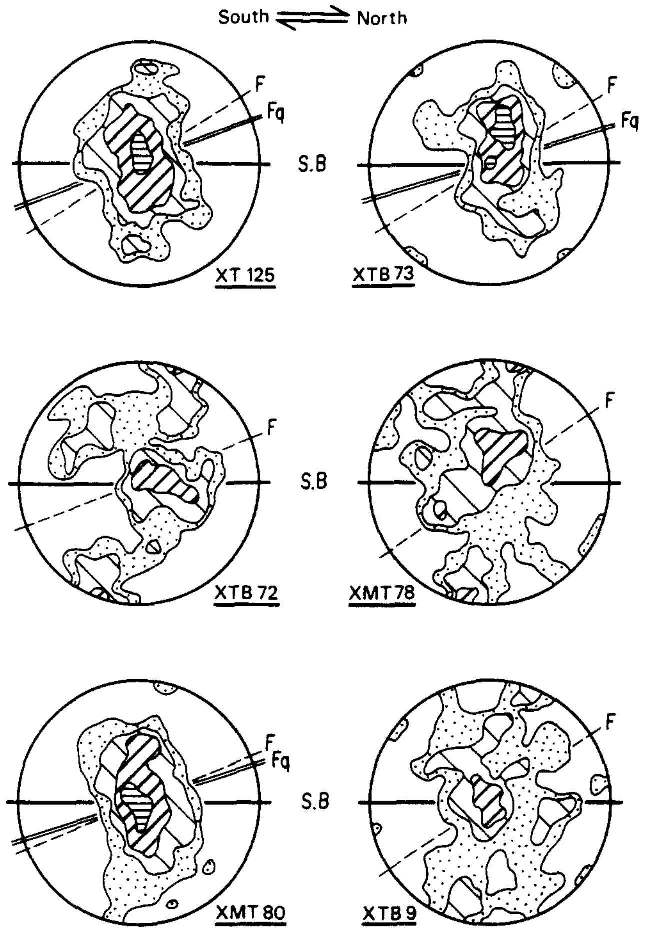

Fig. 4. Quartz c-axis fabrics. 240 measurements for each diagram. Contours at 1, 2, 4 and 10% per 1% area. F, foliation; SB, shear bands; F_q, plane containing the long axes of quartz grains. Schmidt net, lower hemisphere.

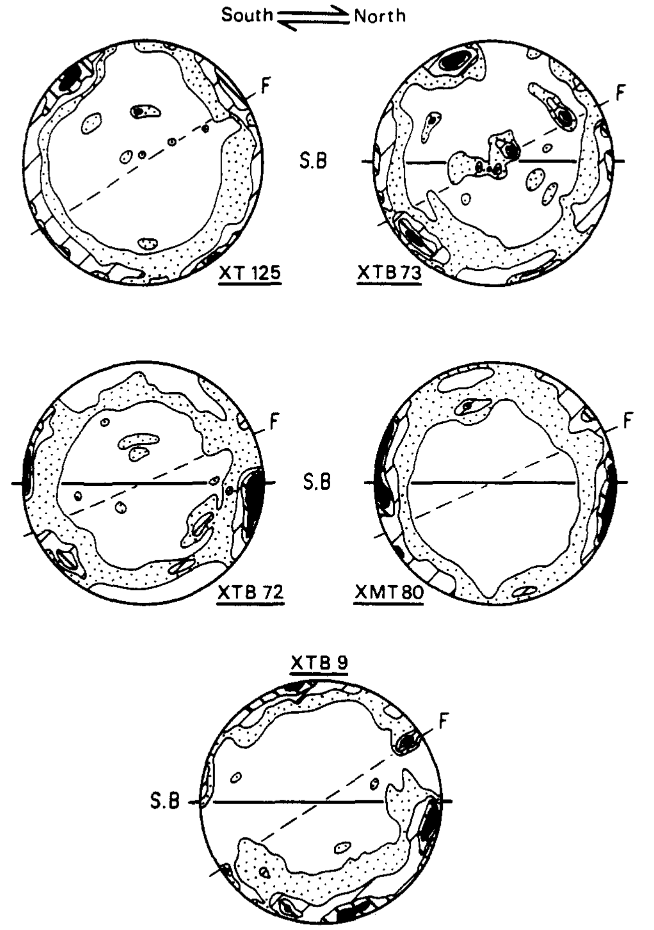

Fig. 5. Quartz a-axes fabrics. Contours at 1, 1.5, 2 and 2.5% per 1% area. X u.d. F, foliation; SB, shear bands.

a-axis fabrics

Preferred orientations of quartz **a**-axes have been measured by X-ray texture goniometry using the reflexion mode. Results (Fig. 5) outline a strong geometric dependence of the **c**-axis distribution on that of **a**-axes; **a**-axes being preferentially located in the *XZ* strain plane. This is consistent with the *Y* maximum preferred orientation of **c**-axes, although the two types of **c**-axis patterns inferred from the U-stage measurements are not distinguishable. A statistically dominant prismatic slip in an ⟨**a**⟩ direction is verified by the concentration of **a**-axes close to the mesoscopic shear direction (S.B.). **a**-axes patterns for samples XTB 72 and XMT 80 show that this maximum is close to the pole of the girdle containing the maximum concentration of **c**-axes. Assuming that the greatest concentration of **a**-axes marks the flow direction, this submaximum oblique to the foliation plane (*F* equated here to the *XY* plane of finite strain) clearly indicates rotational flow (Bouchez 1978), from south to north in the present case. The obliquity is not clear for samples XT 125, XTB 73 and XTB 9 and may be related to a lack of, or the poor development of, shear bands within the specimen used for texture goniometry analysis (Gapais & White 1982) which can be seen to have been homogeneously deformed at that scale.

Lattice preferred orientation of quartz suggests that the concentration of **c**-axes close to *Y* may increase with increasing amount of strain associated with shear bands as qualitatively estimated from their spacing. Prismatic glide in an ⟨**a**⟩ direction should be then as dominant deformation mechanism (White 1975). This is consistent with $T \leq 450°C$ and $P = 5$ kbars deformation conditions (Bhattacharyya & Pasayat 1968, Tullis *et al.* 1973, Bouchez & Pecher 1981).

DISCUSSION

The planar and linear fabric of the studied leucogranites indicates that, between 86°00′ and 90°50′E, relative movement of the hangingwall towards the north developed mylonitic gneisses up to hundreds of metres thick to the top of the Main Central Sheet. At first sight, a northward-shearing deformation younger than the Oligocene–Miocene leucogranites appears to be incongruous with the ubiquitous southward thrusting recognized along the Himalayas (Gansser 1964). This normal faulting in the high Himalayas, parallel and contemporaneous with thrusting in the Lesser Himalayas, can be represented by two-dimensional model in the vertical plane which contains the N–S movement direction (Fig. 6). Coordinate axes are selected with *X* and *Z* parallel and orthogonal respectively to the surface of the earth.

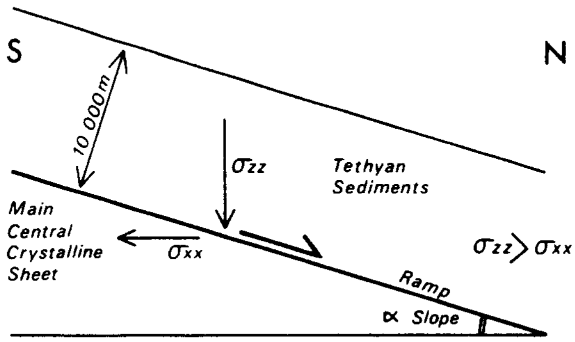

Fig. 6. Tentative explanation of the observed deformation. For details see text.

Assuming that the tectonic effect has only horizontal components and that the horizontal stress (σ_{xx}) and the vertical stress (σ_{zz}) are principal stresses, then the shear stress (τ) on a plane dipping at α is (Nadai 1950, vol. 1, p. 95);

$$|\tau| = 1/2(\sigma_{xx} - \sigma_{zz}) \sin 2\alpha, \quad (1)$$

and for sliding on the plane (Nadai 1950, vol. 2, p. 219).

$$|\tau| = |c + \sigma\mu|, \quad (2)$$

where σ is the normal stress on the plane, μ is the coefficient of internal solid (Coulomb type) friction and c is a positive material constant. From equation (1) it can be seen that normal faulting at the top of the Main Central Sheet implies that $\sigma_{zz} > \sigma_{xx}$ and that $|\tau| < 0$. Thrust faulting along the M.C.T. suggests that the horizontal stress exceeded the vertical stress, or $|\tau| > 0$. Such a stress field in a thrust sheet is of geological interest because it appears to be contrary to the stress field calculated for the upper part of the crust with a superposed uniaxial tectonic stress (Means 1976, pp. 115–117).

The value of the vertical stress can be estimated as

$$\sigma_{zz} = \int_0^z \rho(z) g \, dz. \quad (3)$$

In addition we also conclude that along the normal shear planes of the leucogranites

$$\sigma_{zz} \sin \alpha \geqslant \sigma_{xx} \cos \alpha, \quad (4)$$

and that along the M.C.T. planes

$$\sigma_{zz} \sin \alpha \leqslant \sigma_{xx} \cos \alpha. \quad (5)$$

These equations allow us to calculate two limiting conditions for the variation of σ_{xx} through the Main Central Sheet at the time when the studied deformation occurred.

Calculating σ_{zz} for an average $\rho \simeq 1.95$ for the Tibetan sediments and $\rho \simeq 2.7$ for the 5000 m thick Main Central Sheet, we get for 15–30° dipping shear planes:

$\sigma_{xx} < 0.530$ kbar if $\alpha = 15°$ $\quad \sigma_{xx} < 1.150$ kbar if $\alpha = 30°$
$\sigma_{xx} > 0.910$ kbar if $\alpha = 15°$ $\quad \sigma_{xx} > 1.970$ kbar if $\alpha = 30°$,

respectively at the top and at the bottom of the Main Central Sheet. The leucogranites could have been emplaced in a zone where $\sigma_{zz} > \sigma_{xx}$, thus allowing the gravity décollement of the upper series.

CONCLUSIONS

In Tibet (China) leucogranites restricted to the upper part of the Main Crystalline Sheet display a marked planar and linear fabric which resulted from progressive northward shear deformation. Deformation took place during ascent and emplacement of the granites; late evolution occurred after plutonism. The deformation history is related to northward normal faulting in the High-Himalayas, parallel and contemporaneous with compressive deformation on a regional scale and corresponding to a gravity-driven décollement of the 10,000 m thick Tethyan sedimentary pile from the crystalline basement. This gravitational effect is probably related to yield surfaces when high relief was formed and when the contact zone acquired a north-dipping slope related to a possible ramp of the M.C.T. (Fig. 6).

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