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# Multi-stage development of the southern Tibet detachment system near Khula Kangri. New data from Gonto La

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## Abstract

Field observations from Gonto La (southern Tibet), a pass through the high Himalaya, reveal a continuous, planar, ~10°N-dipping detachment horizon (the Gonto La detachment). The detachment juxtaposes Tethyan dark slates over a footwall of extensive leucogranite of the Khula Kangri pluton, intruded into an injection complex layer regarded as an early Southern Tibet Detachment System (STDS) horizon. The leucogranite emplacement is protracted, and overlaps the STDS development. It is observed to intrude the earlier horizon of the STDS, which is deformed, partially cut by the pluton, and, in the southern part, rotated to a present south dip. Evidence for large scale folding and plutonism is also found east of Khula Kangri at Lhozag–La Kang, where the earlier STDS horizon is inferred. Here it excises the entire Palaeozoic Tethyan sedimentary sequence and is similarly folded. The Gonto La detachment, which cuts the Middle–Upper Miocene Khula Kangri pluton is, in turn, cut by the more steeply N-dipping Dzong Chu fault, demonstrating later N–S extension in this area. We interpret known outliers of Tethyan sequences in Bhutan as klippen, underlain by an early STDS horizon, which provide a more regional illustration of early extension on the STDS. In the Khula Kangri area, early extension was followed by plutonism and local relative uplift, and further N–S extension.

## 1. Introduction

The Southern Tibet Detachment System (STDS) is a series of north-dipping, low-angle detachments, found along the north flank of the high Himalaya. It was first identified by Burg (1983), and was described in detail by Burchfiel et al. (1992). The detachment system juxtaposes Tethyan sedimentary rocks against crystalline rock of the footwall; the High Himalayan Crystalline series (HHC). Typically, the detachment system has a footwall containing several hundred metres of mylonitic rock with injections of leucogranite (Burg, 1983; Burchfiel et al., 1992). In the Everest area, movement on the principal detachment is shown to have occurred between approximately 22 Ma and 19 Ma (Hodges et al., 1992). These data, taken together with an age of movement on the Main Central Thrust (MCT) constrained to ~20.9 Ma at one locality (Hubbard and Harrison, 1988), reflect

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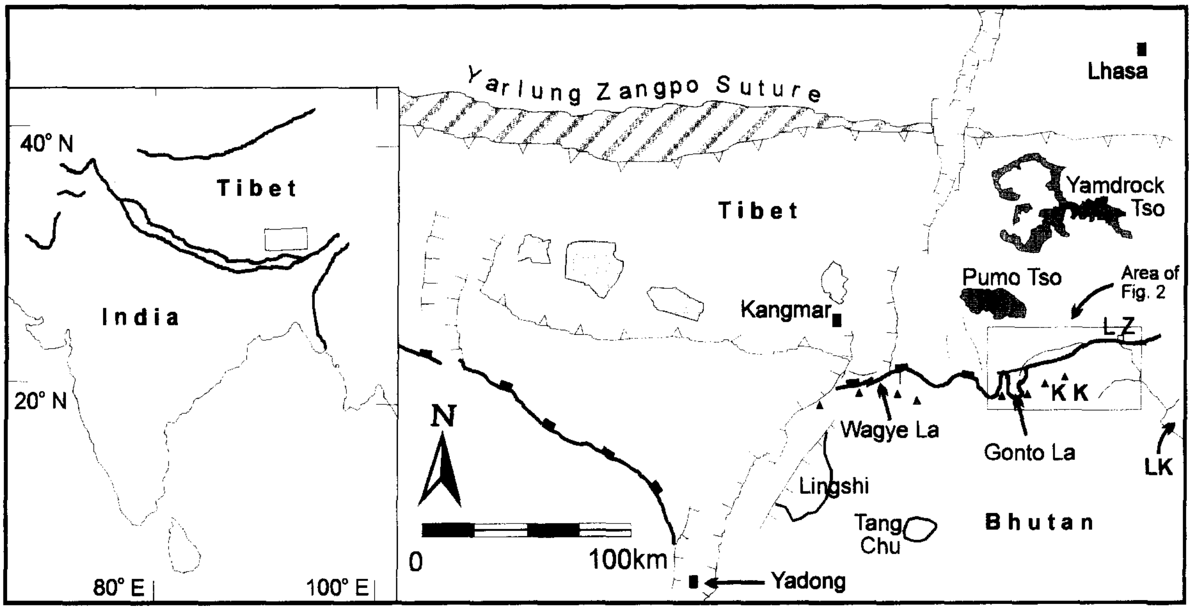


Fig. 1. Map showing main geological features of Southern Tibet. Stripes: Zangpo suture ophiolites and sediments of Xigaze Group; light grey: leucogranites of Lhagoi–Kangri belt; dark grey: lakes; lines with single barbs: Quaternary normal faults; lines with triangular barbs: thrusts; heavy lines with boxes: approximate trace of STDS; *KK* = Khula Kangri massif; *LZ* = Lhozag; *LK* = La Kang. Inset shows regional location of map area (box) in which thick black lines are major tectonic discontinuities. Modified after Burg et al. (1984).

a local simultaneity of N–S extension in the upper Himalaya with shortening at structurally deeper levels, (e.g., Burg et al., 1984; Burchfiel and Royden, 1985). Evidence from the western Himalaya (Herren, 1987; Searle et al., 1988) suggests that this extension developed along much of the orogen (Burchfiel et al., 1992). The term STDS is used here to mean the system which has allowed upper level extension of the Himalaya, including both the brittle detachment fault(s) (detachment sensu stricto; Davis et al., 1980) and any earlier related mylonitic horizons which accommodated ductile extensional deformation.

The Khula Kangri massif is part of the high Himalaya, situated north of the Bhutan frontier (Fig. 1). It is ~100 km south of the Yarlung–Zangpo suture and ~100 km east of the major (~70 km) plan view offset of the high peaks of the Himalayan chain termed the 'Yadong cross structure' (Burchfiel et al., 1992). The Yadong cross structure is marked by the Chomolhari–Masang Kang range, which bounds part of the N–S-trending Yadong-Gulu rift system developed in response to the Miocene to Recent E–W extension of southern Tibet (Armijo et al., 1986). The Khula Kangri massif is thought to consist mostly of the Khula Kangri leucogranite pluton (appendix A) and gneisses of the HHC (Pêcher et al., 1994), as is typical of the high Himalaya (Gansser, 1964; Le Fort, 1973). Less typical is the belt of Mesozoic Tethyan sedimentary rocks (structurally above the HHC and leucogranite) which dip south on the southern side of the massif (Dietrich and Gansser, 1981; Burchfiel et al., 1992; Bureau of Geology and Mineral Resources of Xizang (Tibet) Autonomous Region, 1993; Pêcher et al., 1994). Based upon the observations of the previous workers, the overall structure of the massif is that of a regional antiform (Fig. 2). On the eastern side of the massif, between the town of Lhozag, to the north, and La Kang, in the south (Fig. 2), the relationship between Tethyan Sedimentary rocks and the HHC is complex and the sequence has been intruded out in several places by the Khula Kangri pluton (Burg et al., 1984; Burchfiel et al., 1992; Pêcher et al., 1994). Here, both our observations and those of Burchfiel et al. (1992) revealed no obvious major detachment structure. Between Lhozag–La Kang and Wagye La, 80 km to the west (Fig. 1), where the STDS is last recognised (Burchfiel et al., 1992; Edwards et al., 1994), the valley of Gonto La cuts deep into the high Himalaya (Fig. 2). We visited the Gonto La valley to address

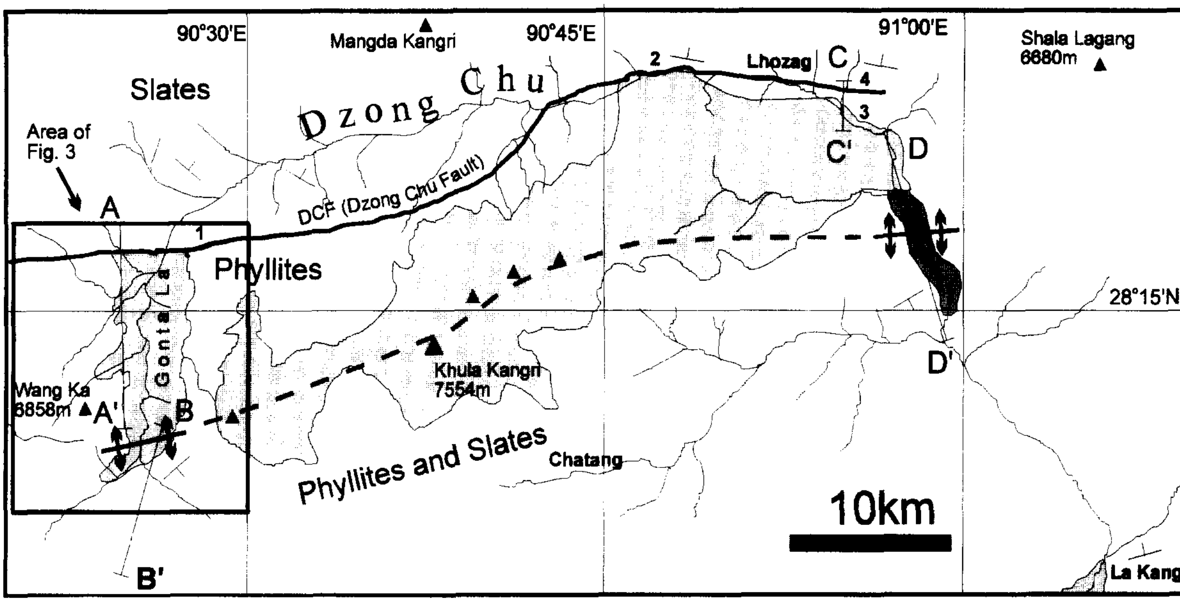


Fig. 2. Geologic summary map of Khula Kangri area (box in Fig. 1). Light grey: Khula Kangri leucogranite pluton; dark grey: structural window to High Himalayan crystalline series; black triangles: peaks over 6500 m; dashed black line: approximate trace of regional antiform; numbers: locations referred to in text. Tethyan sequences named in their approximate location. Cross-section locations are shown. Some high peaks are capped by slate and phyllite (not shown).

the problem presented by this change in nature of the STDS from west to east along the Tibet–Bhutan Himalaya. We were able to recognise the STDS in the Gonto La valley but unlike localities to the west (e.g., Burchfiel et al., 1992), we see evidence here for complex multi-stage development of the STDS. Coupled with further investigation of the STDS between Lhozag and La Kang and a re-evaluation of other sparse data pertaining to the area, we present the general hypothesis that there were two distinct periods of broadly N–S extension involving the STDS in the Khula Kangri area (both Gonto La and Lhozag–La Kang) separated by a period of folding, major plutonism and sufficient relative uplift to renew local N–S extension, at least near Gonto La.

## 2. Gonto La

### *2.1. Geological observations*

Gonto La is a 5450-m-high pass through the high Himalaya between Tibet and Bhutan, located southwest of Khula Kangri and north of Kanga Punzum (7500 m). The main glacial valley leading north from Gonto La crosses the ENE-trending line of the high Himalayan chain, where it cuts a ~13-km-long N–S trough deep (>2 km) into the local topography. This valley we term the Gonto La valley.

The Gonto La detachment outcrops all along the central and northern parts of the Gonto La valley on both the west and east valley walls. It is a planar, low-angle, gently north-dipping (~10°) normal fault. The hanging wall contains a unit of marbles and an overlying unit of phyllites. The footwall comprises leucogranite in the north and a gneissic sequence below a mylonitic leucogranite injection complex in the south (Figs. 3 and 4). The detachment was visited at locations 1 and 2 (Fig. 3). The Gonto La detachment is seen to extend from the points visited to the central portions of the Gonto La valley (Fig. 5), rising gradually in outcrop height to the south. From south of where last seen, the detachment projects to the upper levels of Kanga Punzum (Fig. 4); the Bhutan frontier. From the Dzong Chu valley, the Gonto La detachment rises up to the main Khula Kangri peaks east of the Gonto La valley and, to the west, up to the three peaks of Wang Ka. Interpolation of Thematic Mapper (TM) and topographic satellite imagery with the field observations shows the low-angle, north-dipping Gonto La detachment continuing for some

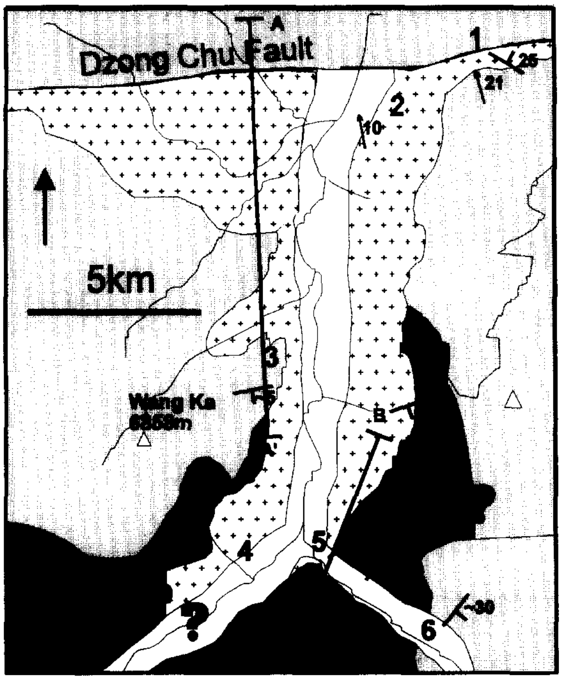


Fig. 3. Geologic map of Gonto La valley (box in Fig. 2). Crosses: leucogranite; light grey: Tethyan Mesozoic marble and phyllite; dark grey: injection complex; medium grey: gneiss; white: Quaternary cover. Numbers are locations referred to in text. Strike and dip symbols refer to foliation, arrows are lineation measurements (remote measurements are given as approximate dips). Question marks indicate specific uncertainty. *A–A′* and *B–B′* are cross-section lines.

distance to both the east and west of Gonto La valley. In addition, west of Wang Ka, we have identified gently-dipping planar surfaces that are interpreted to be the westward continuation of the Gonto La detachment by remote observation from the SE part of Nieru Valley, east of Wagye La.

The hanging wall of the Gonto La detachment is made up of a series of gently north-dipping marbles and overlying phyllites (Fig. 4). The phyllites may be Triassic or Jurassic in age based upon correlation along the Dzong Chu valley to the Lhozag area (Fig. 2) where *Danubites* sp. have been found in local slates (Bureau of Geology and Mineral Resources of Xizang (Tibet) Autonomous Region, 1993). The marbles are light to dark grey and, close to the granite, contain a number of inclusions of leucogranite a few to tens of centimetres in diameter. The marble shows intense, colour-laminated structural foliation, and shows inhomogeneous, pervasive deformation, with seemingly chaotic folding of the main foliation around the inclusions. The overall foliation is broadly parallel with foliation in the leucogranite in the footwall. The marble horizon tapers northward from >100 m thickness at location 3 (Fig. 3) to entire removal at location 1 (Fig. 3). The phyllites are mostly black and reach upper greenschist facies near their contact with the marble horizon. Some contain prominent porphyroblasts of andalusite, cordierite and/or chloritoid. The phyllite extends to above present erosion level, and therefore must have >400 m of structural thickness. The foliation broadly parallels the detachment below.

The footwall of the Gonto La detachment contains both a main intrusive leucogranite body (part of the Khula Kangri pluton), and a gneissic sequence overlain by a leucogranite injection-bearing high-strain horizon (which we term the injection complex). The detachment footwall consists mostly of leucogranite in the central portions, and exclusively of leucogranite in the northern portions (Figs. 2 and 3). In the southern portion, the gneissic sequence and the injection complex lie structurally above, and are in intrusive contact with the leucogranite (Fig. 6). Here, the margin of the pluton cuts, at a low angle, both the foliation of the gneissic sequence and the leucogran-

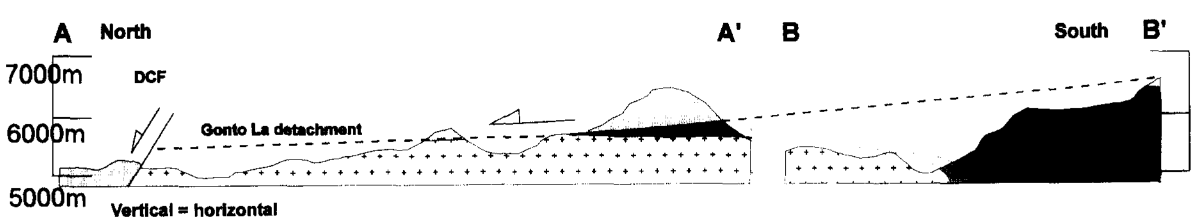


Fig. 4. Cross-section *A–A′* and *B–B′* along Gonto La valley (located on Fig. 3). Section *A–A′* is along western side of Gonto La valley, projected on to east facing line. Gap in section indicates join of two sections. Lines on south wall represent foliation within injection complex. Arrows show relative displacement sense of fault hanging walls. Small unshaded area in south is snow line on north shoulder of Kanga Punzum. Shading as for Fig. 3.

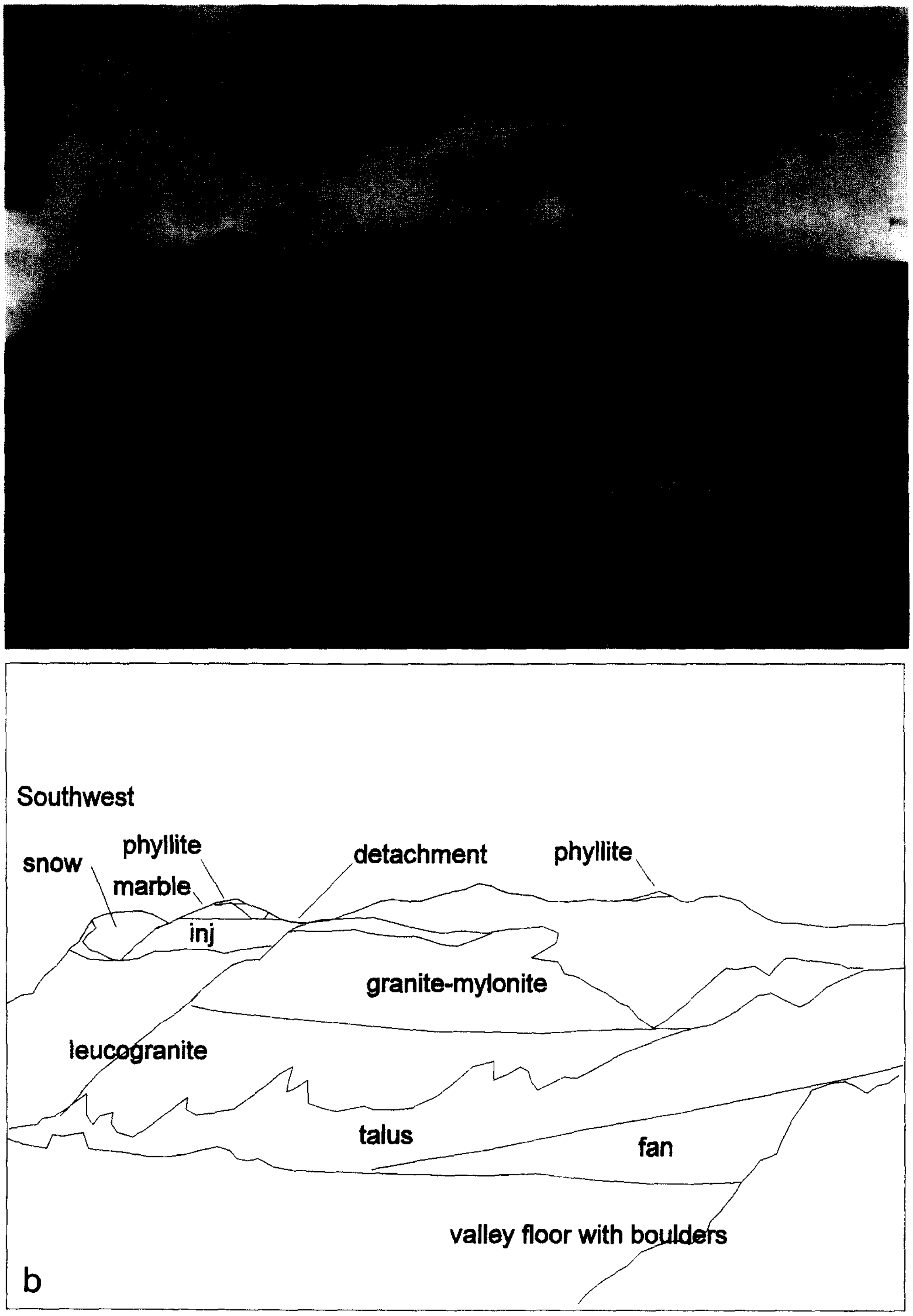


Fig. 5. Photo and line drawing looking west-southwest from location 1 (Fig. 3) at the north end of Gonto La valley. Gonta La detachment is continuous line running across hillside, dipping approximately 10°N. Upper 300 m up to detachment is granite–mylonite. Jagged cliffs in foreground are leucogranite of Khula Kangri pluton. Light and dark horizontal bands on peaks above detachment are gently north-dipping sequences of marble and phyllite, respectively (described in text). Note thin outcrop of gently south-dipping injection complex (*inj*) at location 3 (Fig. 3), which illustrates gradual excision by both Gonto La detachment above, and intrusive granite margin below. Towards south, injection complex layer systematically increases in both thickness and angle of dip (see description in text). DCF outcrops to right, outside field of view.

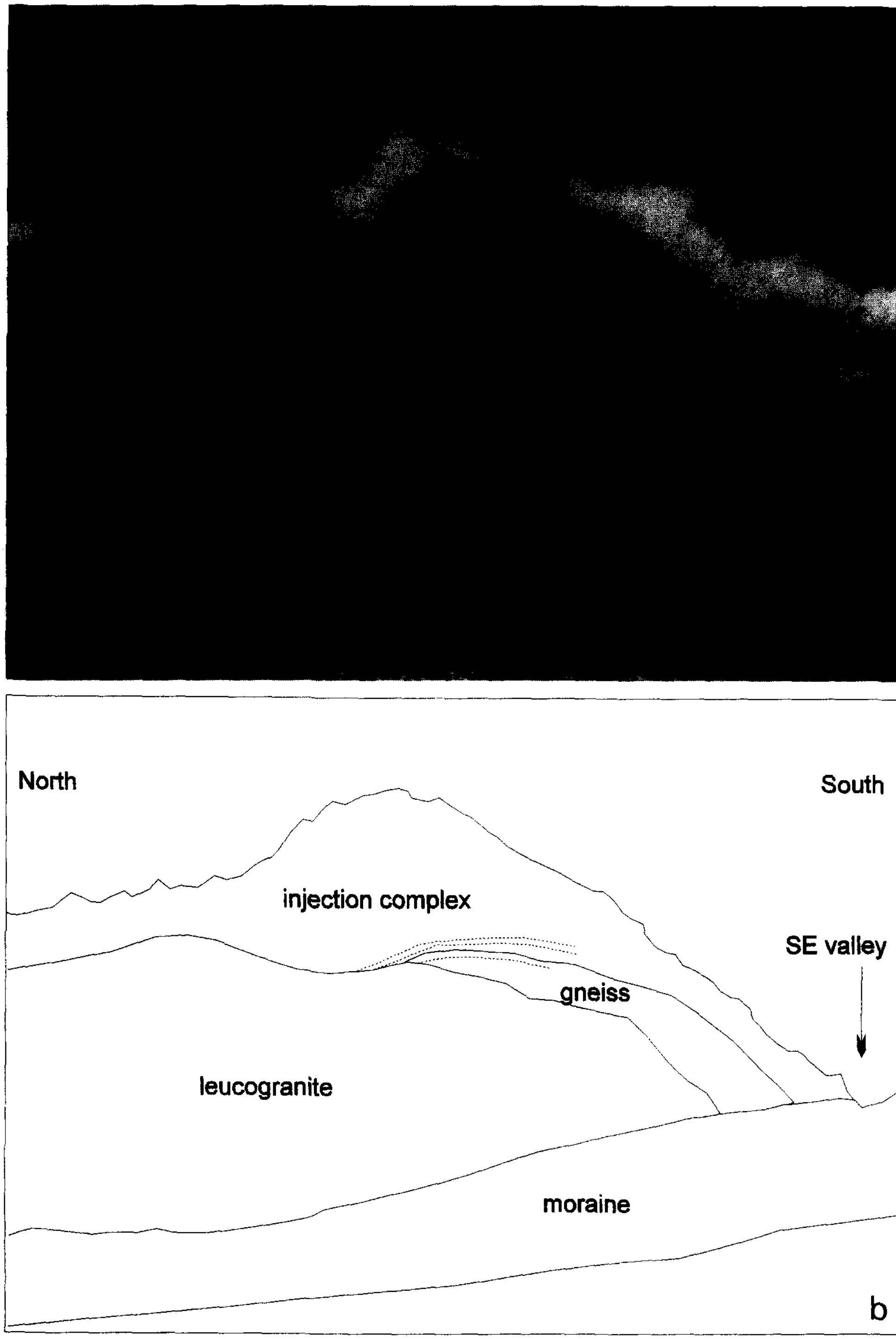


Fig. 6. Photo and line drawing from location 4 (Fig. 3) ~200 m above valley floor on southwest corner of main Gonto La valley looking across to entrance to SE valley (location 5, Fig. 3). View shows intrusive southern contact of leucogranite of Khula Kangri pluton truncating the gneiss and, to left, cutting leucogranite sills which define macroscopic foliation. The leucogranite is unfoliated at this contact. This cross-cutting relationship requires that the granite post-dates development of the mylonite of the injection complex (see text). Mesozoic (?) phyllites, structurally above the injection complex, outcrop up the SE valley, out of view. The Gonto La detachment projects from where it last outcrops in the north (left) to above present erosion level. Apparent antiformal shape of foliation (dashed lines on line drawing) is distortion due to perspective.

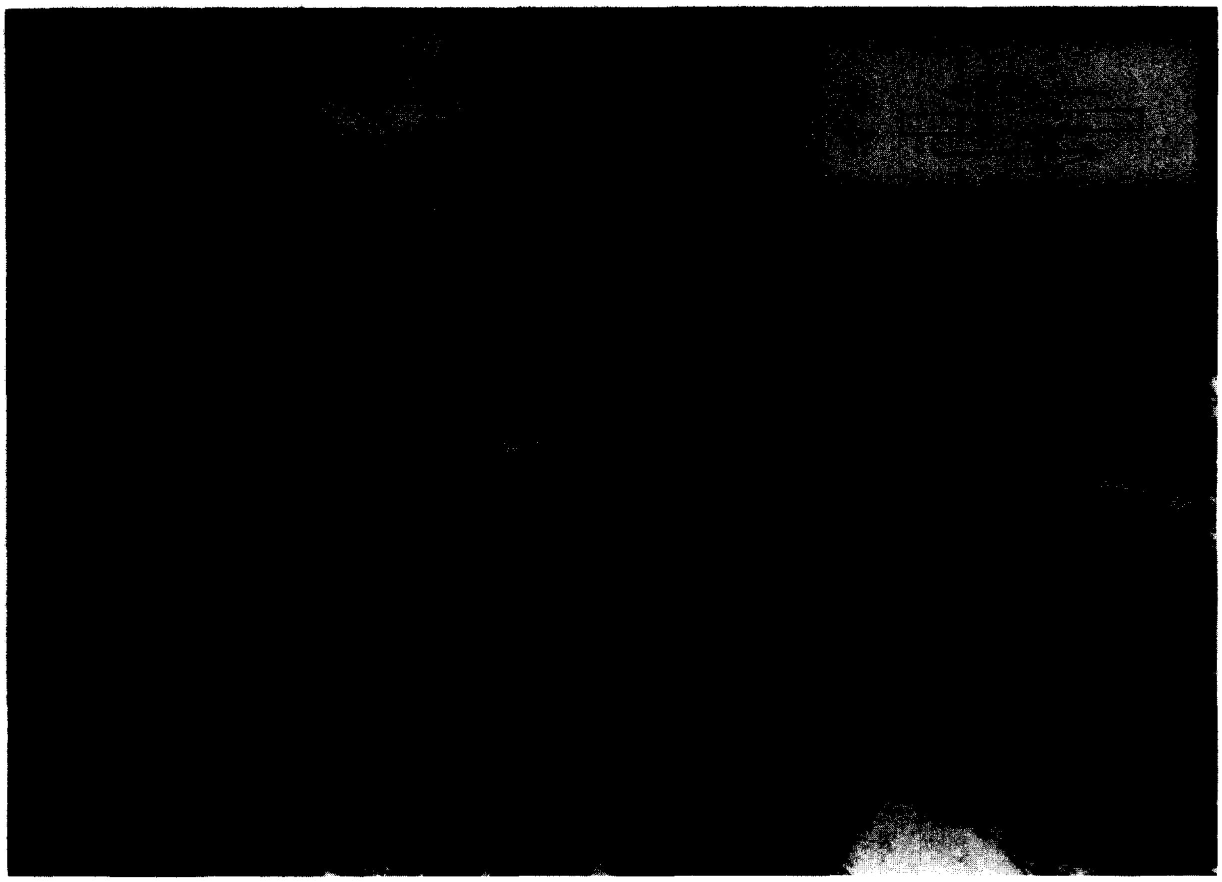

Fig. 7. Photomicrograph of mylonitic horizon of leucogranite (Appendix 1) from location 2 (Fig. 3) in northern Gonto La valley illustrating typical sense of shear indicators observed. Section is cut perpendicular to foliation, parallel to lineation (350°); crossed polars. Base of image is ~4.0 mm. North is to left, south to right. Polycrystalline quartz and feldspar ribbon aggregates define S-surfaces. In lower centre, asymmetry of inclusion tails of feldspar grain and mica fish show sinistral sense of shear (top-to-north).

ite sills that define the macroscopic foliation of the injection complex. The profile of the foliation of both the gneiss and the injection complex, like that of the pluton margin, forms a gentle curve. It dips ~40° to the south in the southern portions of the Gonto La valley and systematically becomes more shallowly dipping towards the central part of the valley, where the mylonitic injection complex is nearly flat-lying (Fig. 3). This approximates the southern part of an antiformal structure, which, in the N–S section of the Gonto La valley, may be thought of as half of an open fold. Any northern section of the antiformal structure would have been truncated by the ~10°N-dipping Gonto La detachment.

The leucogranite is predominantly medium-grained and contains quartz, feldspar, biotite, muscovite and tourmaline. In the northern parts of the valley (locations 1 and 2, Fig. 2) the uppermost part of the leucogranite pluton has a strong subsolidus foliation. The foliation dips ~10°N and contains a well-defined down-dip stretching lineation which is oriented 350 ± 5°. This is consistent with a stretching lineation of ~25° towards 350° measured near Summit 6301 between Gonto La and Khula Kangri by Pêcher et al. (1994). The foliation displays shear bands and a mesoscopic and microscopic S–C fabric (Fig. 7) which demonstrate top-to-north sense of shear (e.g., Berthé et al., 1979; Simpson and Schmid, 1983; Passchier and Simpson, 1986). This defines a horizon of granite–mylonite which extends down for ~300 m from where the pluton is cut by the planar detachment contact with the marble and phyllite above. Shear strain increases vertically upwards towards the detachment. The remaining parts of the

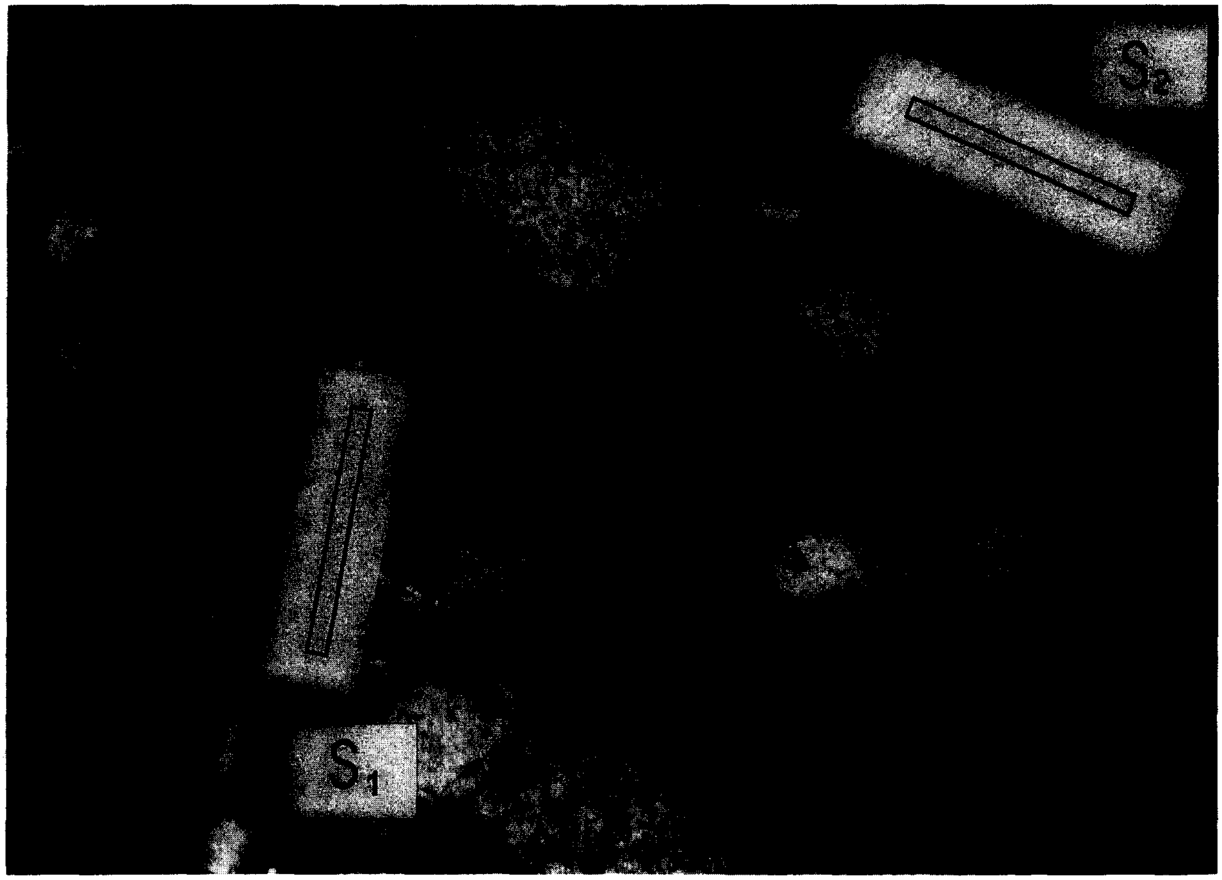


Fig. 8. Photomicrograph of biotite–sillimanite gneiss (Appendix B) near intrusive contact in southern Gonto La valley (location 5, Fig. 3). Base of image is ~4.0 mm. $S_1$ (in garnet grain) shows a foliation at a high angle to $S_2$, the gneissic foliation. Crossed polars.

leucogranite pluton within Gonto La are unfoliated although mineralogically the same as the foliated portions.

The rocks of the gneissic sequence consist of both schists and gneisses of quartzofeldspathic and mafic composition. There is a continuous macroscopic foliation throughout the sequence, which changes from gently- to more steeply-dipping towards the south. Near the pluton margin, the gneisses show hornfels effect. This includes: (1) sillimanite overgrowing biotite; and (2) recovery of quartz grains in areas of high strain where garnet foliation is at a high angle to the main foliation (Fig. 8 and appendix B). Within the gneiss there are a number of centimetre to metre wide quartz and quartz–muscovite–tourmaline veins filling steeply south- to southeast-dipping tension gash zones. The gneissic foliation is observed to bend into the tension gashes before being truncated on vein margins. The shear sense of fracture opening is top-to-south (normal sense) and is indicated by the bending of the foliation and en-echelon veins. The amount of extensional strain accumulated is minor (<1%). The fractures may be either: (1) antithetic Riedel shears; or (2) the result of pluton emplacement and/or antiformal folding. If they are antithetic Riedel shears, they require top-to-north displacement on the host shear zone, which is most likely the injection complex, or the Gonto La detachment, above.

Above the gneissic sequence is a high-strain horizon infested with leucogranite injection sills and dykes; the injection complex (Fig. 6). The foliation of the injection complex (high-strain horizon) has a shallower foliation dip than, and cuts, the foliation of the gneissic sequence below. Where the contact projects across the SE valley onto the back wall at the head of the main valley (Fig. 3), the gneissic sequence attains its maximum thickness of ~200 m. From here, the injection complex continues for >700 m to the limit of exposure (the snow line). Approximately 4 km up the SE valley from the gneiss contact, the injection complex passes to a structurally overlying phyllite sequence and, based upon the dip where last measured, we estimate the injection complex to be ~1000 m thick. If the gneiss forms a xenolithic lens within the injection complex, the original injection complex thickness may be greater. Typical STDS injection complex thicknesses are <1000 m (Burchfiel et al., 1992). Within the injection complex, leucogranite sills injected parallel with the foliation range in width from a few centimetres to several tens of metres and are foliated. Thinner sills are observed to be both isoclinally folded and show boudin structures. Some of the sills are asymmetrically folded and the apparent vergence suggests a top-to-north (in present orientation, thrust) sense of shear. The high-strain horizon in which the leucogranite sills occur is a mylonite augen gneiss with a well-defined S–C fabric. The mylonite contains ubiquitous augen and boudins of feldspar and quartz (1–5 mm in diameter) forming pale, mm horizons within thicker, intensely black, biotite-rich layers. The appearance is notably different from both the gneisses and the granite–mylonite. Within the mylonitic augen gneiss, the presence of abundant centimetre to metre thick lensoidal leucogranite layers, results in conspicuous light and dark bands which characterise the injection complex. Within the injection complex, directly below the detachment at location 3 (Fig. 3), multiple, steep, north-dipping normal faults of a few metres offset are prominent. These are thought to be the macroscopic equivalent of narrow shear-bands, developed in response to the relative northward motion of the hanging wall of the Gonto La detachment.

At the northern end of the Gonto La valley (location 1, Fig. 2), the leucogranite and, consequently, the Gonto La detachment, are truncated by an E–W-striking normal fault, dipping 22°N. This fault downthrows Mesozoic dark slates in the hanging wall against the leucogranite footwall. Here, a siliceous cataclasite about 2 m thick has developed above the unfoliated granite. Within the slate, there are numerous minor extensional structures (low- and high-angle, N-dipping faults, kink and shear bands). The unfoliated nature of the leucogranite footwall discriminates this fault from a bend in the Gonto La detachment. Additionally, there is evidence a few hundred metres north of this location for a steeper DCF splay in the form of groundbreak features and float colour changes. Movement on the DCF is later than final movement on the Gonto La detachment.

At location 6 (Fig. 3), remote observations show the injection complex overlain by a phyllite whose foliation is ~SE-dipping and parallel with the foliation of the injection complex below. Based upon phyllite samples in float, some contain cordierite porphyroblasts. From previous reports (Gansser, 1983; Bureau of Geology and Mineral Resources of Xizang (Tibet) Autonomous Region, 1993; Pêcher et al., 1994) this is part of the large belt of Mesozoic Tethyan sedimentary rocks which lie south of Khula Kangri, defining part of the broad antiformal culmination (here the southern limb) which mantles the Khula Kangri massif. TM imagery is consistent with this and shows the phyllite contact as a sharp colour contrast in the valley wall which continues along the south side of the massif to the south-dipping slates and phyllites near La Kang (Burchfiel et al., 1992). If the north-dipping, planar Gonto La detachment does continue up to Kanga Punzum [composed predominantly of HHC (Gansser, 1983)] then these phyllites must be part of the present footwall. It is possible, however, that the Gonto La detachment suddenly bends and dips south, hence forming the phyllite/injection complex contact.

### 2.2. Interpretation

The presence of a detachment footwall containing an injection complex made up of a thick sequence of boudined, isoclinally folded, mylonitic augen gneiss with asymmetrically folded leucogranite sills fits the summary STDS appearance given by Burchfiel et al. (1992). What is different here is that the foliation of the injection complex is south-dipping. We suggest that the thick sequence of the injection complex is the horizon, originally north-dipping, on which strain was localised during earlier ductile N–S extension in this area. Rotated to north-dipping, the apparent thrust sense structural indicators give a normal sense of shear. This would then be consistent with the overall N–S extensional mechanism which led to the

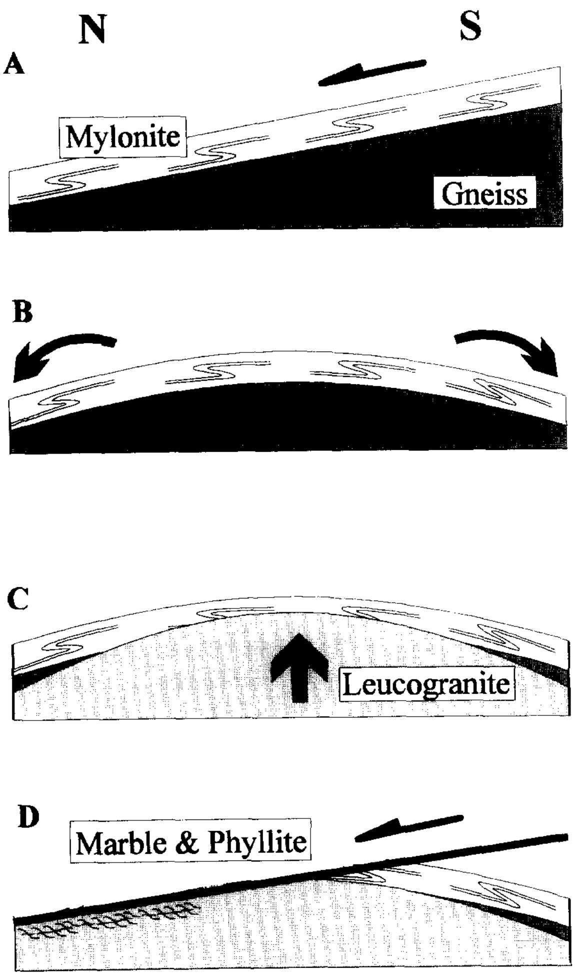


Fig. 9. Schematic illustration of interpreted history of Gonto La area. (A) Early N–S extension develops thick mylonitic injection complex horizon; a ductile, normal sense shear zone above gneiss (asymmetric fold symbols are general represention of sense of shear indicators found). (B) Folding or other mechanism causes rotation of southern part of mylonitic horizon to south-dipping (possibly associated with leucogranite intrusion, see discussion in text). (C) Emplacement of Khula Kangri pluton truncates foliation of gneiss and injection complex. (D) Later N–S extension causes further normal faulting (the observed Gonto La detachment) juxtaposing Mesozoic slate over leucogranite, gneisses, and injection complex. The implied hiatus in N–S extension is not required; displacement may have transferred to structurally higher level before pluton emplacement.

north-dipping Gonto La detachment. Accordingly, we propose the following series of events:

(1) The thick mylonite augen gneiss of the injection complex layer was formed before the final intrusion of the leucogranite (Fig. 9A), from N–S extension on a north-dipping horizon. This would have excised any Palaeozoic of the Tethyan sequence at Gonto La.

(2) The observed south-dipping foliation has been rotated to its present position by antiformal folding (Fig. 9B), which could be related to the emplacement of the leucogranite (Fig. 9C). During or after emplacement, the Gonto La detachment formed (Fig. 9D) and was active at least while the pluton cooled through solidus temperatures causing the granite–mylonite, the non-coaxially deformed marble horizon, the shear bands, and the steep normal faults.

## 3. The Dzong Chu Fault

The Dzong Chu Fault (DCF, Burchfiel et al., 1992) is named for the Dzong Chu (or Kuru Chu) valley, along which it outcrops (Fig. 2). It is a north side down normal fault which dips moderately to steeply to the north. It was first recognised by Burg (1983) who regarded it part of the STDS (Burg's 'Faille Normale Nord Himalayenne'). Although for much of its length along the Dzong Chu valley, the DCF forms the contact between the Mesozoic sedimentary rocks and the Khula Kangri pluton, Tethyan sequences also make up part of the footwall, and thus it is not a detachment of the STDS sensu classico. The DCF is observed in outcrop at, amongst others, locations 1, 2 and 4 (Fig. 2). Location 1 is the 22°N-dipping normal fault which truncates the Gonto La detachment. It is interpreted to be a shallowly-dipping splay. At location 2, leucogranite, injected into gneiss, outcropping on the northern side of the Dzong Chu, forms the footwall of an approximately 50°N-dipping fault plane which has brown Mesozoic slates as the hanging wall. At location 4, about 600 m north of where an intrusive contact of the Khula Kangri leucogranite outcrops at location 3 (Fig. 2 and appendix A), the DCF juxtaposes light Mesozoic slate upon dark Mesozoic slate. The fault plane dips 50–70°N and the fault forms a steep gully, or notch, on each side of the main, north-trending local valley. We find it of interest that at location 2, the hanging wall slates show no evidence of metamorphism from, or intrusion by offshoots of, the leucogranite, while the leucogranite intrusive contact at location 3 has a planar surface similar to location 2 yet is clearly not a fault plane; there is no evidence of any surface (brittle or ductile deformation horizon) within granite, or near it, within the metasedimentary aureole, which could have accommodated significant offset. The planar and steeply-dipping leucogranite intrusive contact at location 3 (Fig. 2), may be the result of a pre-existing planar fault surface delimiting the local emplacement horizon of the pluton. A splay of the Dzong Chu fault, which outcrops ~600 m to the north, would provide such a surface. This may be required based upon geobarometric data obtained by Guillot et al. (1995a) from unspecified localities in this general area ranging between 290 ± 40 MPa and 440 ± 60 MPa, which may imply several kilometres of throw. Additionally, this may mean there is some extensional strain not yet recognised within the aureole.

The fault contacts at locations 4 and 2 are obvious on the TM image of this region, and truncation of the black slate is also visible on the image on the east side of the foot of the Gonto La valley, immediately opposite location 1. The fault is identifiable all along the Dzong Chu valley forming a belt in places up to 10 km wide that consists of both a main, continuous structure, and a number of apparently less-continuous splays. The fault can also be traced to near Wagye La, at the SE end of Nieru Valley, where a similar fault has been recognised, including conspicuous ground-break features indicative of an active fault (Edwards et al., 1994), and to SW Nieru where we have observed it to be cut by the Yadong–Gulu rift system faults. Offset on the DCF is not known but, from correlation of the two slates juxtaposed at location 4 to where they outcrop in more-continuous sequence, net throw is estimated to be a minimum of several hundreds of metres, and previous field mapping (Burg, 1983) and the geobarometric data of Guillot et al. (1995a) suggest several kilometres.

Because the DCF cuts all other sets of structures in the area, it is interpreted to be very late, after latest movement on the Gonto La detachment and possibly coeval with minor, steep E–W-trending normal faults which are observed from Lhozag to La Kang.

## 4. Lhozag–La Kang

### 4.1. Geology

In an attempt to unravel the structurally complex nature of the STDS reported by Burchfiel et al. (1992) from their traverse between Lhozag and La Kang, and to try and correlate with the STDS seen at Gonto La, we visited this section (Fig. 2).

In the northern part of the section (Fig. 10, *C–C'*) the Khula Kangri pluton is found in intrusive contact with north-dipping Mesozoic black shale, 600 m south of the DCF. The intrusive contact outcrops discontinuously over 5–7 km south from where the contact is first observed south of the DCF. The discontinuous nature of the outcrop is largely due to a series of steep (40–70°) normal faults dipping both north and south. These offset the contact from a few to several tens of metres. Beyond ~10 km south from where our traverse begins (Fig. 10), leucogranite abruptly gives way to high-grade metamorphic rocks. These consist of a series of quartzofeldspathic, notably mica-poor schists and gneisses of upper amphibolite facies, with mafic-rich horizons, containing very pale quartz and feldspar augen structures. Following Burchfiel et al.

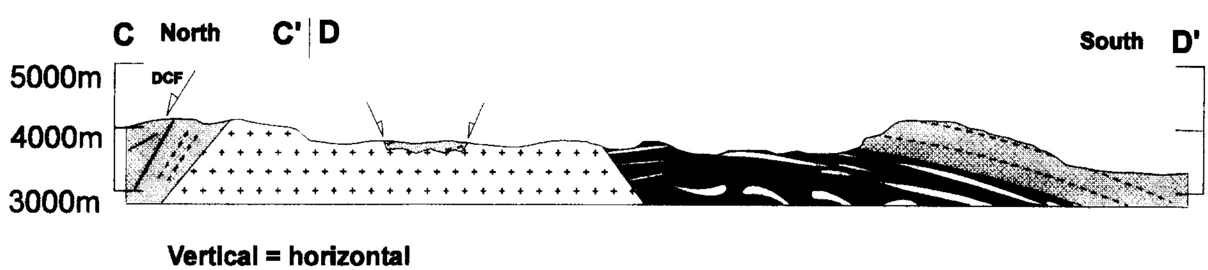


Fig. 10. Cross-section *C–C'* and *D–D'* from Lhozag to the Chatang valley confluence point, ~15 km north of La Kang (located on Fig. 2), shows antiformal culmination with HHC exposed in central portions. Light grey: Mesozoic slate (ornament indicates foliation); crosses: leucogranite; dark grey: general HHC (ornament showing schematic augen represents quartzofeldspathic augen gneiss and marbles; lens-shaped ornament is injection complex above). Injection complex is thought to be the location for the extensional horizon on which the Palaeozoic is excised.

(1992), we regard these as part of the HHC, and regard their exposure in the core of the broad antiform of Mesozoic Tethyan sequences as a structural window (Fig. 10, *D–D′*).

The southern contact between the main leucogranite pluton and the HHC was not reached due to the severity of topography. Burchfiel et al. (1992) show the contact to be a down-to-south normal fault. While there may have been down-to-south fault displacement here, the abruptness of the change, we hypothesise, is more likely due to a steep, southerly-dipping planar margin of the leucogranite, similar to the northern margin at location 3 (Fig. 2). The outcrop of gneissic rock represents the crest of a large antiform which spans the section from Lhozag to ~10 km north of La Kang. (Fig. 10). To the north, the schistosity of the Mesozoic slates and phyllites (and observed portions of the leucogranite contact) changes from gently to steeply north-dipping. To the south, the gneissic layering and overlying sedimentary sequences change dip from gently to steeply south-dipping.

To the south, lying structurally above the gneissic layer, is a series of leucogranite injections within a lower-grade amphibolite facies, mica-bearing schist sequence whose foliation is south-dipping. Structurally above this is a thick sequence of south dipping Mesozoic slates. Within the slates are multiple, steep (40° to 70°N) normal faults, similar to those found to the north. We were unable to determine if the contact between the slate and the leucogranite injection complex that is structurally above the HHC window is an old, now south-dipping detachment surface (sensu lato), due to inaccessibility of critical outcrops. Burchfiel et al. (1992) infer that the leucogranite injections below the phyllite and slate sequence have intruded out a major extensional horizon which pre-dates the development of the present antiform.

Our detailed field investigation was terminated here but Burchfiel et al. (1992, fig. 40) report synformal folding of the Mesozoic slate further to the south and, presumably, folding of the underlying, pre-existing detachment (as suggested on the cross section), which causes the sequence to become north-dipping in the area of La Kang. In this area, the north dipping Mesozoic slates lie upon the broad planar top of an injection complex above leucogranite. From detailed study in the area of La Kang, Burchfiel et al. (1992) suggest this to be a further outcrop of the extensional horizon inferred at the HHC structural window.

### 4.2. Interpretation

The present juxtaposition of Mesozoic sedimentary rocks on the HHC requires excision of the entire Palaeozoic section of the Tethyan sequence through some process and therefore we, as do Burchfiel et al. (1992), interpret the schist sequences to represent a horizon that is a part of the STDS that has enjoyed enough N–S extension to remove the Palaeozoic. The antiformal folding must, therefore, also fold the inferred earlier detachment. A south-dipping sequence of Mesozoic rock upon a gently folded detachment is very similar to what is observed in southern Gonto La and we consequently infer the early sequence of events seen at Gonto La to have occurred at Lhozag–La Kang, namely: (1) early N–S extension which generated a high-strain horizon and excised the Palaeozoic sequences; (2) folding of the horizon; and (3) later intrusion of the Khula Kangri leucogranite pluton which, as for Gonto La, intrudes out parts of the older detachment horizon. The plutonism may or may not be related to the folding.

## 5. The STDS in Bhutan

The ~70-km plan view offset in the high Himalayan crest between Nepal and Bhutan (Fig. 1), represented by the Yadong–Dogen rift, includes an associated offset of the STDS but not of the MCT/MBT (Nelson et al., 1995). Surface exposure of HHC per unit length of orogen is accordingly greater in Bhutan. There are, however, two outliers of Palaeozoic Tethyan sedimentary rock in Bhutan (Fig. 1), the Lingshi and Tang Chu areas (Gansser, 1983). These contain fossiliferous limestones, slates and quartz conglomerates which characterise passive margin sequences deposited in shallower water than the extensive Mesozoic black slates of the Khula Kangri area. At Tang Chu, trilobite- and brachiopod-bearing Devonian limestones lie <500 m above sillimanite gneisses intruded by leucogranite (Gansser, 1983, fig. 54). We infer that the low-grade Palaeozoic sedimentary rocks are juxtaposed upon higher-grade

HHC by a normal fault, and we offer the hypothesis that they represent Palaeozoic age, Tethyan klippen overlying an early horizon of the STDS. This is consistent with well-documented outcrop of the STDS along strike to the west (e.g., Everest, Dingye, Pali), where Palaeozoic Tethyan sedimentary sequences are also found in normal fault contact with the underlying HHC (Burg, 1983; Pêcher, 1991; Burchfiel et al., 1992; Guillot et al., 1993; Lombardo et al., 1993).

## 6. Discussion

### 6.1. Gonto La

The close relationship between leucogranite emplacement and extensional shear zones is well-displayed in the high Himalaya (e.g., Burg et al., 1984; Pêcher, 1991; Gapais et al., 1992), and complexities of shape due to syn-extensional laccolith injection (e.g., at Manaslu, Guillot et al., 1993) have been demonstrated in analogue modeling (Roman-Berdiel et al., 1995). We are unable, however, to constrain the specific mechanism that has operated at Gonto La. The rotation of the older extensional horizon at Gonto La may be due to isostatic rebound of the footwall of a low-angle fault (e.g., Davis, 1983; Wernicke and Axen, 1988; Block and Royden, 1990) as has been shown to occur in core complexes both with syn-extensional plutonism (e.g., Crittenden et al., 1980; Brun and Van Den Driessche, 1994; Lister and Baldwin, 1994) and without (e.g., Lister and Davis, 1989; Davis, 1994). Timing of any early plutonism is not constrained, and a core complex model can describe the history before final pluton emplacement insofar as a south dipping early horizon is predicted to accompany a northward directed hanging wall (e.g., Lister and Davis, 1989, fig. 20d, or Brun et al., 1994, fig. 4). The later stages of plutonism at Khula Kangri are well-constrained, however: The present southern margin cooled through solidus temperatures after motion on the early high-strain horizon at Gonto La had ceased. This is reflected by the absence of foliation in the pluton at the intrusive contact at location 5 (Fig. 3) and by the absence of evidence for non-coaxial flow in the adjacent gneiss. These field relationships therefore eliminate the following scenarios for Gonto La: (1) a core complex model for the overall history; (2) the possibility that the pluton acted as an obstacle around which the deformation horizon had to bend; and (3) any concept of 'ballooning' by the rising pluton, previously suggested by Edwards et al. (1995). This key field relationship does not, however, exclude syn-kinematic plutonism and folding in a contractional scenario (e.g., Hutton and Ingram, 1994). A contractional setting has been proposed for plutonism with synchronous thrusting and thickening of the MCT hanging wall Bhutan (Davidson et al., 1995; Hollister et al., 1995). The Khula Kangri pluton may therefore be emplaced in a large ramp anticline in the hanging wall of a south directed thrust. Any such period of shortening might suggest a hiatus in N–S extension in the area, but this is not required; extension may have been localised upon structurally higher levels (i.e. the Gonto La detachment) before or during pluton emplacement.

### 6.2. Lhozag–La Kang

N–S extension which post-dates the emplacement of the Khula Kangri pluton (and accompanied minor folding and relative uplift in the area) has been accommodated at Lhozag–La Kang, at least in part, by minor offset on a series of steeply-dipping normal faults. We did not recognise, however, a major low-angle normal fault equivalent to the Gonto La detachment. Burchfiel et al. (1992) proposed that the Khula Kangri pluton had a final period of emplacement in the area of Lhozag after the last movement on the local STDS horizon. Our observations at Gonto La support this hypothesis, insofar as the pluton intrudes the early, now-folded part of the inferred extensional horizon of the STDS both at Gonto La, and at Lhozag–La Kang. The question of whether there is a late detachment at Lhozag–La Kang remains. We identify three possibilities.

(1) No late detachment developed at Lhozag–La Kang, perhaps due to insufficient topographic gradient (the HHC outcrops at a lower elevation than in Gonto La valley, and surrounding present-day topography is generally lower). Post-plutonism, N–S extension (less than at Gonto La) was accommodated mostly by offset on the steep normal faults.

(2 and 3) A late detachment developed but was restricted to the slate sequences and is now above

present erosion level. It is not seen where it projects to the north as either (2) downthrow on the DCF has dropped it to below present erosion level, or (3) it has been cut out by later plutonism in the north part of the Lhozag–La Kang section (near the DCF). The last possibility requires a diachroneity in the late history of either general pluton emplacement or movement on the detachment.

We tend to favour the first suggestion (no late detachment at Lhozag–La Kang) as the hypothesis is consistent with the idea that the development of the STDS may be diachronous and show punctuated activity. It is also consistent with preliminary observations from the high country of Khula Kangri (Pêcher et al., 1994), where lineation trend seen within the leucogranite is identical to that observed at Gonto La and yet, singularly, no detachment was observed.

### 6.3. Regional relationships

Fig. 11 shows a cartoon which illustrates the main features we have discussed regarding the relationship of the STDS between Tibet and Bhutan. The Tethyan outliers in Bhutan are shown as klippen (see above), underlain by segments of an early detachment, and are broadly equated with the folded early STDS horizons of Gonto La and Lhozag–La Kang. For simplicity, this is shown as one structure, although the relationship could well be more complex. A later detachment (the Gonto La detachment) is shown truncating the folded, earlier detachment.

Assuming the development of a new topographic high to initiate movement on the younger detachment (Burchfiel and Royden, 1985), and assuming close association between plutonism and uplift (see England and Molnar, 1993, for a partial review) we suggest that, if the Khula Kangri pluton is a notably younger structure (appendix A), the Bhutan Himalaya represents a later topographic front. It is likely some structure exists beneath Khula Kangri (and Kanga Punzum) area to account for the plutonism and any relative uplift. Additionally, the folding of the earlier detachment in the Khula Kangri area may be similarly related to the relative uplift. The Kakhtang thrust in Bhutan, documented by Gansser (1983), is a major crustal feature which outcrops <20 km south of Kanga Punzum. This may be a structure on which late shortening has allowed relative uplift of the Khula Kangri–Kanga Punzum area, and which has provided a source for local leucogranite generation (e.g., Le Fort, 1982) and/or a pathway to bring the leucogranite up to emplacement lev-

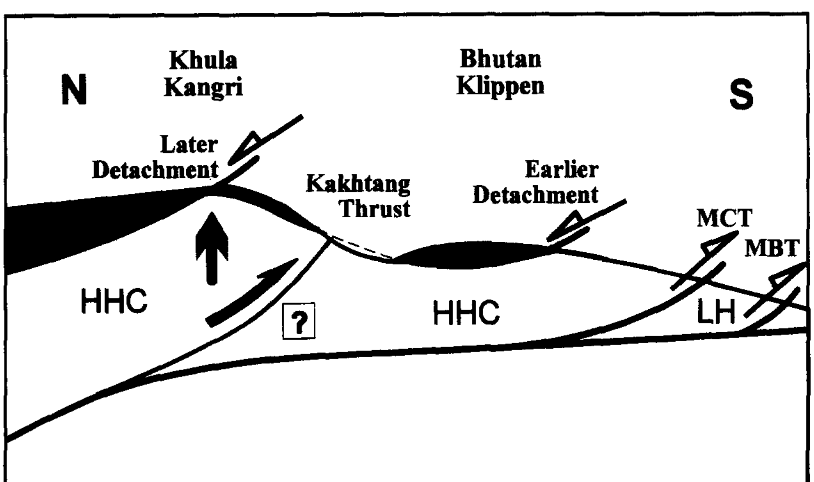


Fig. 11. Cartoon crustal section to show hypothesis of large scale relationship between early and late detachments in southern Tibet and Bhutan. Grey shade: Tethyan sedimentary sequences; *HHC* = High Himalayan Crystalline series; *LH* = Lesser Himalayan sequences; heavy lines: faults. Half-arrows show direction of relative offset of hanging wall. Large half arrow and full arrow represent general mechanism of rise of magma and uplift relative to lower Bhutan. Kakhtang thrust is suggestively added as one of the possibilities for a general magma pathway, relative uplift and folding of earlier STDS horizon(s) (see discussion in text). Footwall and hanging wall thicknesses are not intended to be accurate representations.

els (likely only if all magmatism is part of the same event, e.g., Deniel et al., 1987). Melt-present thrusting has been reported from central Bhutan (Hollister et al., 1995), and substantial migration of melt into the Khula Kangri area may have occurred by this mechanism. We note the Kakhtang thrust would then be out-of-sequence with, and cut, the older STDS horizon. Alternatively, but we think less likely, is a horse or steep frontal ramp at depth on the MCT/MBT sole, of enough magnitude to give a crustal-scale ramp anticline that provides local uplift (e.g., Nelson et al., 1995).

### 6.4. Estimates of strain

In Gonto La valley, based upon the absence of any part of the injection complex or leucogranite in the hanging wall, relative displacement on the Gonto La detachment fault is >15 km (assuming a net slip direction of 350°); the distance from the DCF to where phyllite is first seen in the footwall. If the Gonto La detachment occurs in the Kanga Punzum massif, and there represents the HHC/Tethyan sequence junction, fault displacement is >20 km. We cannot estimate horizontal extensional strain accommodated by the 300 m thick granite–mylonite horizon below the detachment (before development of brittle strain features), as cooling history for the Khula Kangri pluton is unconstrained. 20 km is less than the 35 km minimum relative displacement for the Chomolungma detachment at Mt. Everest determined by Burchfiel et al. (1992); however, the Gonto La detachment appears to be restricted to Mesozoic rocks. Very speculatively, assuming a Gonto La detachment angle of 10° and 20 km fault offset and a constant displacement vector, a vertical displacement of ~3.5 km is indicated. Added to an estimate of the excised Palaeozoic, based upon the section near Nyalam and Everest, of ~4 km (Burchfiel et al., 1992), or perhaps more (Lombardo et al., 1993), net throw is consistent with the Burchfiel et al. (1992) estimate of >5 km for the Chomolungma detachment. When added to the (unmeasured) amount of displacement represented by the exhumed HHC, net throw may approach the ~18 km calculated from Herren (1987) for the Zanskar Shear Zone.

At Lhozag–La Kang we estimate the net throw of the series of post-plutonism steep faults is <1 km. This is small relative to the estimates of strain at Gonto La. Assuming no late detachment or diachroneity in final plutonism, the difference in net throw could indicate: (1) a strain gradient, decreasing to the east, and/or (2) differential slip on the DCF.

### 6.5. Timing

Middle to late Miocene cooling ages have been determined for the Khula Kangri pluton (Debon et al., 1985; Maluski et al., 1988; Guillot et al., 1996; and appendix A). These are substantially younger than ages typically obtained for leucogranites in the central high Himalaya to date (see Burchfiel et al., 1992 for a review). The Gonto La detachment cuts the Khula Kangri pluton and we therefore infer that the Gonto La detachment was probably active during middle to late Miocene times. If so, this is the youngest age yet found for movement along a main detachment of the STDS.

A minimum age for cessation of extension along earlier detachment horizons south of the Khula Kangri antiformal trace is represented by the age of relative uplift of the Khula Kangri massif which accompanies folding of such horizons (this is assuming a given STDS horizon remains north-dipping whilst active). A probable middle to late Miocene age is indicated by the field relationships. We have suggested that the early STDS horizons may be more closely related to the STDS west of the Yadong cross structure than to the Gonto La detachment. This is also supported by plutonism at ~22 Ma cutting main detachments at Rongbuk (Hodges et al., 1992) and Manaslu (Harrison et al., 1995). We emphasise, however, that this is not required by our field observations, and that the hiatus in N–S extension observed at Gonto La may be minimal.

Field relationships near Annapurna in Nepal have been interpreted to suggest that approximately N–S extension on the local detachment gave way to E–W extension between ~17 and 14 Ma (Coleman and Hodges, 1995). It has consequently been suggested that this time period represents the onset of E–W extension for all of southern Tibet and the cessation of STDS activity in the form of N–S extension related to Himalayan topographic collapse (Coleman and Hodges, 1995; Searle, 1995). It is not clear to us if the onset of E–W extension is indeed coupled to the end of STDS activity, but the observation that the Gonto La detachment cuts the apparently middle to late Miocene Khula Kangri pluton is not consistent with the suggestion that all STDS movement ended between 17 and 14 Ma. More importantly, we have shown the complexity of STDS extension in this area, involving multi stage detachment development interrupted by folding. Additionally, previous workers have shown that the STDS: (1) may involve substantial wrench motion; (2) may locally consist of more than one structure; and (3) be laterally discontinuous (Pêcher, 1991; Burchfiel et al., 1992; Guillot et al., 1993; Lombardo et al., 1993; Hodges et al., 1994). We therefore stress that the southern Tibet detachment system is a complex system of detachment faults of varying periods of activity which cannot be regarded as one continuous, simple planar structure. Moreover, it is unlikely that a single portion of the STDS can give an unequivocal measure of such things as the change of the horizontal stress field in southern Tibet, in spite of suggestions to the contrary (Searle, 1995).

## 7. Conclusion

The valley of Gonto La provides the best observation to date of the STDS east of the Yadong Cross Structure offset of the high Himalaya. The Gonto La detachment is a planar, low-angle north-dipping, normal fault which juxtaposes Tethyan sequences over the middle to late Miocene Khula Kangri leucogranite pluton. The Khula Kangri leucogranite pluton has one of the youngest ages in the main belt of the HHC. Because the Gonto La detachment cuts the pluton, it represents very late N–S extension in this area. The N–S extension shows a strain history from leucogranite sub-magmatic fabric development in the main detachment footwall to truncation of the detachment by the steeper, brittle Dzong Chu fault. The Khula Kangri leucogranite cuts the S-dipping high-strain horizon in southern Gonto La valley after cessation of extension on this horizon. The overlying, also south-dipping Tethyan sequences are inferred be included in the footwall of the Gonto La detachment. The amount of HHC exhumed by the present Gonto La detachment pivots on whether our hypothesis that there are Tethyan sedimentary rocks in the footwall is correct (minor exhumation), or whether the detachment is tightly folded in southern Gonto La and the Tethyan rocks are in the hanging wall (major exhumation). The question of whether there can be a significant hiatus in N–S extension in this area is also central to this hypothesis. The S-dipping, high-strain horizon and Tethyan sequences at Gonto La are correlated to Lhozag–La Kang where rocks of the HHC are exposed below Mesozoic rocks, and the Palaeozoic is excised. Our observations indicate the STDS is a complex system of detachment horizons, and not a simple horizon with a restricted age of activity.

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## Appendix A. The Khula Kangri pluton

The Khula Kangri pluton is a phaneritic leucogranite. It outcrops in the Gonto La valley and at various localities around the Khula Kangri massif (Fig. 2). We interpret the massif to be underlain by a large leucogranite pluton with an areal extent of ~50 × 15 km. The pluton has been determined to have a depth of emplacement of about 12 km (Guillot et al., 1995a) similar to Himalayan leucogranites in Nepal (Guillot et al., 1995b).

The intrusive contact of the leucogranite at location 3 (Fig. 2) has an extremely steep metamorphic gradient; <70 m away from the contact, black slate shows no obvious effects of the intrusion. The metasediment at the intrusive contact is in (or near) amphibolite facies; a biotite–muscovite–garnet fine-grained schist with 50–60% injection material is seen within 5 m of the contact. The relatively thin aureole of this intrusive contact, compared with the regional size of the pluton, may be the result of either: (1) a later, local phase of leucogranite emplacement, or (2) unrecognised extensional shear across the margin.

K–Ar analyses: Debon et al. (1985) determined an isotopic cooling age for the Khula Kangri leucogranite of 13.3 ± 1.0 Ma based upon two muscovite samples. $^{40}Ar/^{39}Ar$ analyses: Maluski et al. (1988) obtained ages of 10.7 Ma and 11.4 Ma (biotite) and 10.9 and 10.8 Ma (muscovite) from two samples near Lhozag. Guillot et al. (submitted) report muscovite ages of 10.7–11.1 Ma and biotite ages of 11.6–13.0 Ma. The large contrast in $^{40}Ar/^{39}Ar$ cooling ages may be due to techniques of analytical and statistical error calculation (e.g., Harrison and Mahon, 1995). The range of ages probably is close to the crystallisation age. This is because sample locations (for those that are known) are near the intrusive pluton margin where the effects of rapid cooling are expected to cause prompt closure of micas to argon diffusion (McDougal and Harrison, 1988). Significant rapid cooling of the leucogranite may additionally have been through extensional unroofing along the Gonto La detachment (e.g., Pan and Kidd, 1992).

## Appendix B. Lithological and structural descriptions

### *B.1. Granite mylonite*

Mesoscopic fabric: Down dip stretching lineation is 5° towards 350 ± 5°. Shear bands dip 30 ± 5°N overprinting S–C fabric. Microscopic fabric: sections normal to foliation and parallel to lineation show S–C fabric. Top-to-north sense of shear is reflected by S–C fabric, by asymmetry of clasts defined by dynamically recrystallised tails, and by pressure shadows. Such is characteristic of a granite–mylonite (Berthé et al., 1979; Simpson and Schmid, 1983; Passchier and Simpson, 1986). Later shear bands are also apparent, and also demonstrate top to north sense of shear. Towards the top of the deformation horizon (metres from the marble layer) microstructures are composed of quartz laminae anastomosing around lesser-deformed augen of feldspar which suggests strain here is greater (e.g., Behrmann and Mainprice, 1987).

### *B.2. Gneiss*

Mesoscopic fabric: The foliation is defined by biotite- and/or hornblende-rich layers. Foliation dips range from 40° towards 150° at the pluton margin (location 5, Fig. 3) to 50° towards 120°, ~200 m up the SE Gonto La valley. There is an intermittently-developed biotite stretching lineation, plunging towards 170 ± 30°. The structurally lowermost portions of the sequence are in intrusive contact with the pluton. Microscopic fabric: Many examples of sillimanite replacing biotite. This is interpreted to be a hornfels effect from the intrusion. Closer to the pluton margin are equant, low-strain grains of quartz. Grains observed are only modestly elliptical and display a small size range. The quartz grains occur amongst common (<2 mm) garnets displaying bands of inclusions, typically non-parallel to the gneissic foliation (see Fig. 8), perhaps due to rotation from prolonged strain.

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