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Geology of the northern part of the Nanga Parbat massif, northern Pakistan, and its implications for Himalayan tectonics

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Abstract: The northern outcrop termination of Indian continental crust lies at the Nanga Parbat massif, from where this contribution presents new field data. The tectonic contact with the structurally overlying Kohistan island arc is concordant and ductile, is associated with interleaving of Nanga Parbat and Kohistan lithologies, and may be correlated with the Main Mantle thrust found elsewhere in the NW Himalayas. This ductile shear zone is locally overprinted by cataclastic faults associated with exhumation of the massif but overall, the northern outcrop termination of the massif is controlled by erosion through a gently, northward-plunging antiformal structure. This folds both the Main Mantle thrust and the underlying, concordant 'Layered Unit' of the Nanga Parbat basement. Thus there is no indication that the massif acted as a promontory to the Indian continent during collision nor that it is a structure entirely bound by neotectonic faults. Ductile shear fabrics associated with the 'Main Mantle thrust' are cross-cut by leucogranite sheets and pegmatites. These may represent the stockwork to a significant crustal-melt granite body described here in the northern massif. This Jutial granite shows many geochemical characteristics in common with similar bodies in the High Himalayas which are consistent with anatexis of the buried Indian continental basement rocks. However, the granite is enriched in heat producing elements (particularly Th: 22 ppm) and shows extremely high $^{87}Sr/^{86}Sr$ ratios (>0.88). The high concentrations of radiogenic Sr are also an attribute of a suite of hitherto enigmatic leucogranitic pegmatites that laces the Nanga Parbat massif, suggesting that these may represent a stockwork to a largely buried body of which the Jutial granite is a small exposure. The enrichment in heat-producing elements within the granite may reflect similarly high heat production in the source Indian continental crust requiring in turn a fundamental re-examination of the thermal evolution of this crust during Himalayan metamorphism and exhumation.

The Nanga Parbat massif occupies a pivotal position in the Himalayan collision belt (Fig. 1). It contains the northernmost outcrops of basement rocks belonging to the Indian continent exhumed from beneath a tectonic envelop of the Kohistan–Ladakh island arc at a late stage in the collision history. The massif lies at the NW physiographic termination of the Himalayan chain defined by the peak of Haramosh (7397 m) and Nanga Parbat (8125 m). Fission track studies (Zeitler 1985) have indicated that the topographic expression and exhumation of the massif are linked to young, rapid cooling of metamorphic rocks at recent rates locally exceeding 70 °C Ma^{-1}. Coward (1985) proposes that the overall structure is antiformal so that the Nanga Parbat massif occupies an erosional half-window around which the original India–Kohistan/Ladakh suture zone has been folded. He correlates the suture with the Main Mantle thrust (MMT) of Tahirkheli *et al.* (1979). The Main Mantle thrust was defined *c.* 200 km WSW of Nanga Parbat and named because serpentinites of the Kohistan arc have been carried in the hanging-wall onto the Indian continent.

The massif offers a number of linked problems which have significant bearing on Himalayan tectonic models. Since the early reconnaissance maps of the region (e.g. Tahirkheli *et al.* 1979) and follow-up studies of Coward and coworkers (e.g. Coward, 1985; Coward *et al.* 1986, 1988), work has concentrated on establishing the nature of tectonic contacts between rocks of the Indian continent within the Nanga Parbat massif and those of the adjacent Kohistan–Ladakh arc. Lawrence and others (Lawrence & Ghauri 1983; Madin *et al.* 1989; Chamberlain *et al.* 1989) consider the Nanga Parbat massif to be bounded by neotectonic lineaments, the Raikhot fault in the west and the Stak fault in the east. We find this nomenclature misleading for the following reasons. Detailed work along the western margin of the massif shows that the principal contact between Kohistan and India is a major, west-dipping ductile shear zone which operated under amphibolite facies conditions and shows apparent sinistral shear senses (Butler & Prior 1988). Similarly in the east, Treloar *et al.* (1991) show that the Kohistan (Ladakh) Nanga Parbat contact is a ductile shear zone. These observations support Coward's (1985; Coward *et al.* 1988) interpretation because once the antiformal structure of the massif has been unfolded the kinematics imply a general top-to-the-south transport of the island arc over the Indian continent. This transport direction is parallel not only to the regional thrusting axis in the Pakistan Himalayas (Coward *et al.* 1988) but also the plate convergence vector for India relative to Asia determined from magnetic anomaly patterns in the

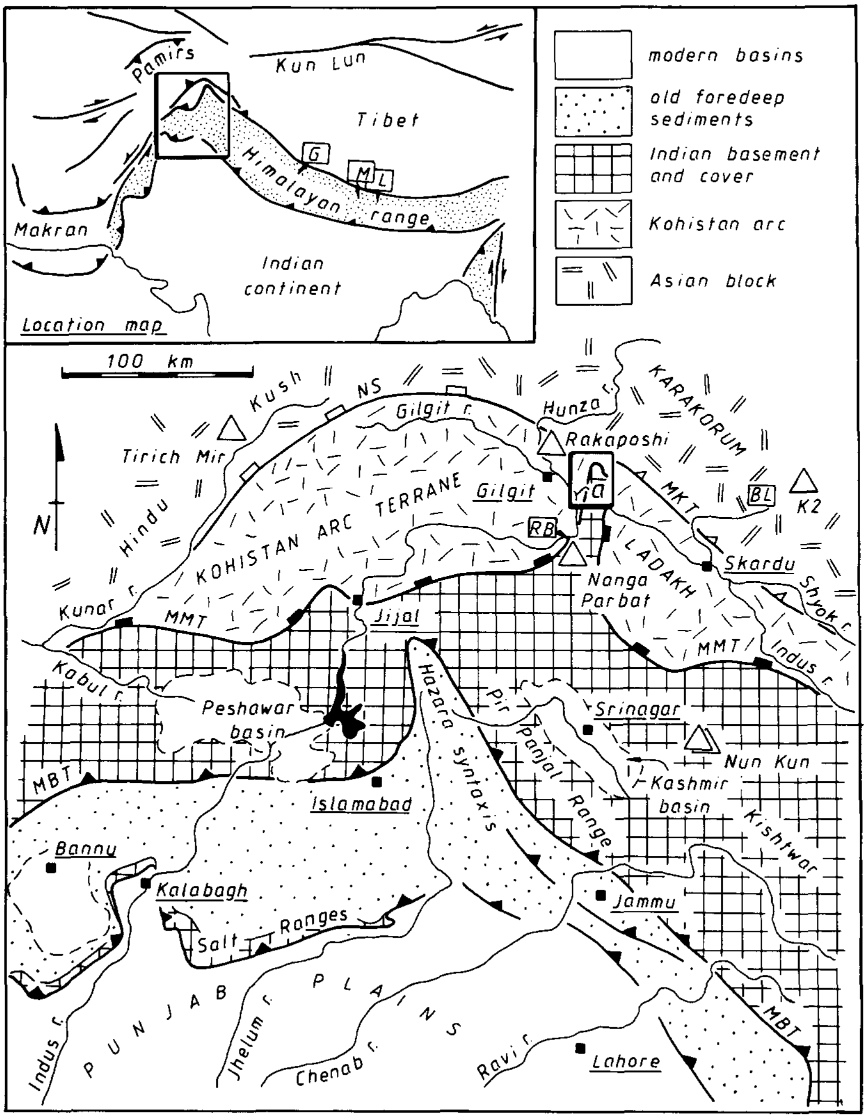


Fig. 1 Sketch map of the NW Himalayas showing the positions of major thrusts and sutures. MMT, Main Mantle thrust; NS, Northern suture (of Kohistan); MBT, Main Boundary thrust; RB, Raikhot bridge; BL, Baltoro leucogranites; a, location of Fig. 2. Inset: location map. G, Gangotri; M, Manaslu, L, Langtang.

Indian ocean (Patriat & Achane 1984). Nevertheless Butler & Prior (1988) note that the Main Mantle thrust at Nanga Parbat is not the original subduction zone since crustal structure is cut-out in the hanging-wall. Upper arc rocks have been emplaced directly onto the Indian continent with the omission of the forearc and lower arc. Here our usage of the term Main Mantle thrust is for the ductile contact between Kohistan and India which shows top-to-the-south shear sense, postdating magmatic activity in the Kohistan arc but which pre-dates leucogranitic magmatism emanating from the Indian continental basement (i.e. as used by Butler & Prior 1988). Uplift and exhumation of the massif along its western margin was accommodated initially by ductile shearing and then cataclastic faulting on NW-directed thrusts (the Liachar system) and N–S dextral strike-slip zones (the Shahbatot system of Butler *et al.* 1989).

Additional interest concerns the thermo-metamorphic evolution of the Nanga Parbat massif. Such work is important because the massif represents a unique sample of Indian continent basement, the northernmost in the Himalayan collision zone and as such may shed light onto the thermal consequences of crustal subduction. Chamberlain *et al.* (1989) present preliminary P–T paths for different parts of the Nanga Parbat massif and adjacent Kohistan arc which they suggest are indicative of a thermal and palaeobarometric discontinuity at the Main Mantle thrust with Kohistan overthrusting Nanga Parbat. Peak metamorphism in the footwall to the Main Mantle thrust may be represented geologically by the production of small volumes (at outcrop) of crustal melt leucogranites. Zeitler & Chamberlain (1991) present dates of overgrowths on zircons sampled from three leucogranite sheets. These range between 2.3 and 7 Ma for the rims of zircons with core ages of *c.* 1800 Ma, suggesting very recent anatexis of a Proterozoic basement complex. Clearly to interpret fully these results requires a consideration of granite petrogenesis within the massif, together with the relationships between various granite bodies, metamorphic fabrics and deformation in the host gneisses.

Despite the modern studies considerable uncertainty exists concerning the geological relationship between the internal structure of the massif, the Main Mantle thrust and other

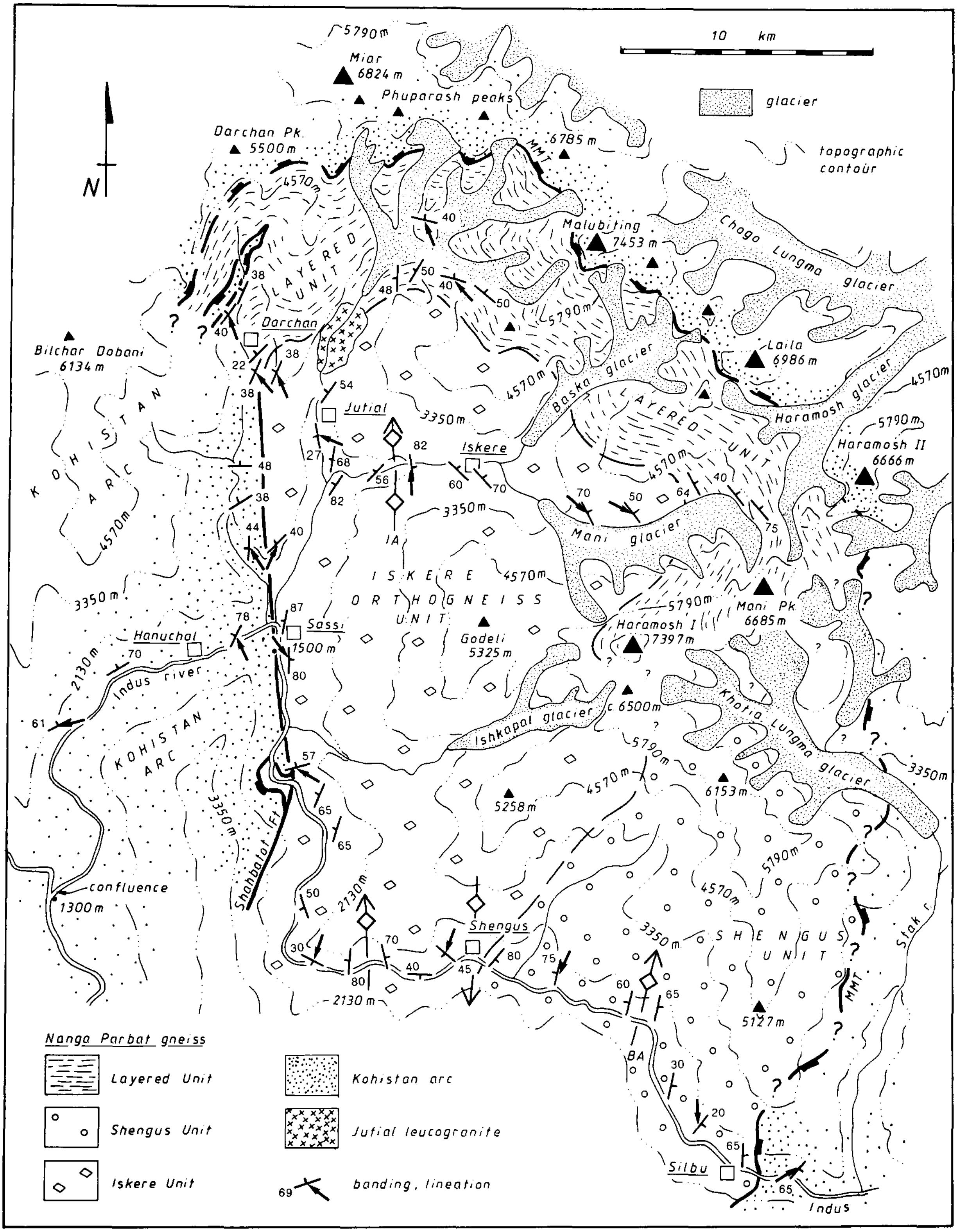
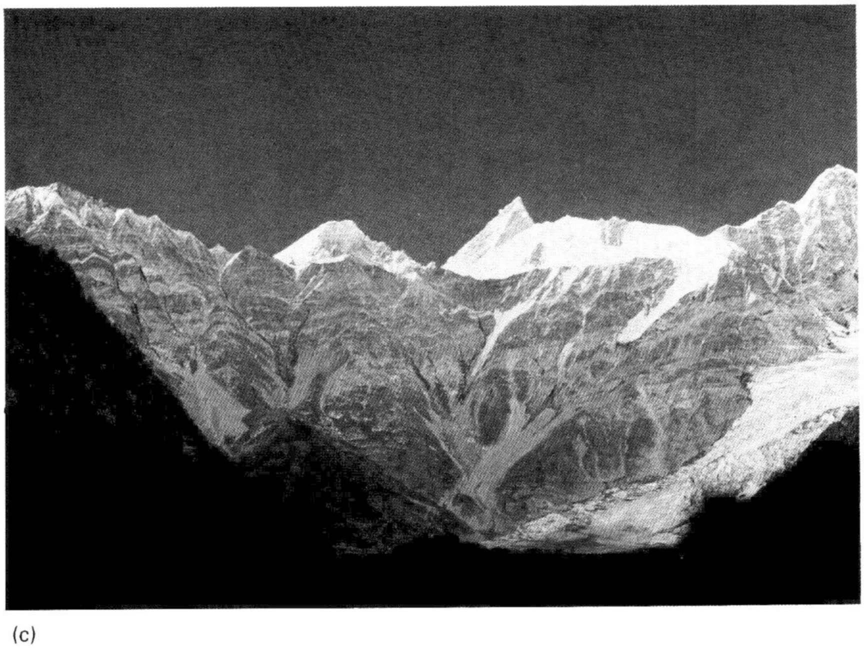


Fig. 2 Simplified map of the northern part of the Nanga Parbat massif (location on Fig. 1). Major antiforms are indicated; IA, Iskere antiform; BA, Bulache antiform. Foliation and stretching lineation orientations are indicated, those from the Indus gorge between Sassi and east of Silbu have been selected from Treloar *et al.* (1991). Topographic contours (three dots and dash ornamented lines) are constructed at the following intervals: 2130 m (7000 ft), 3350 m (11 000 ft), 4570 m (15 000 ft), 5790 m (19 000 ft) and 7010 m (23 000 ft), based on the Orthographic Sketch Map of the Karakoram, sheet 1, published by the Swiss Foundation for Alpine Research, Zurich (1990).

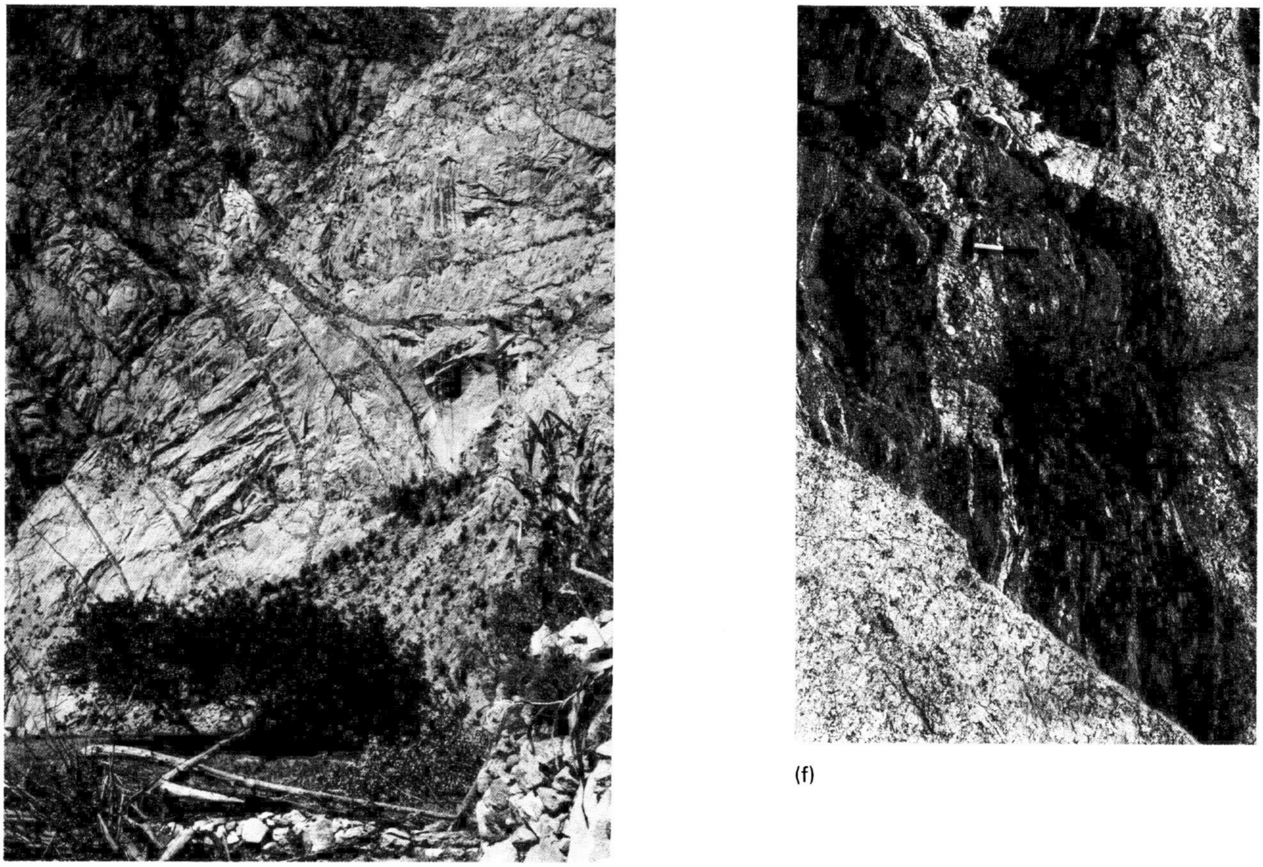
(a)

(b)

(d)



(c)



(e) (f)

Fig. 3 Field relationships in the northern part of the Nanga Parbat massif. (**a**) discordant amphibolite sheet cross-cutting banding in Shengus unit gneisses, Indus gorge west of Silbu. (**b**) view looking north into the Phuparash peaks (base of view *c.*3500 m, top *c.*6500 m). The 'MMT' is arrowed, with Kohistan rocks (green in the field) overlying well banded Layered Unit of the Nanga Parbat gneisses. (**c**) View eastwards onto the headwall of the Mani glacier. The hillside is *c.*2000 m high. Behind the sharp peak is Haramosh II (Kohistan arc material, *c.*2 km beyond the ridge). The peak to its left is thought to be composed of the Layered Unit of the Nanga Parbat gneisses. (**d**) Looking north onto the ridge just east of the mouth of the Darchan valley, with east-inclined cataclastic faults (part of the Shahbatot system) juxtaposing intact Kohistan arc material (with visibly cross-cutting 'confluence' granite sheets) against more highly shattered Nanga Parbat gneisses. Visible cliff height *c.*100 m, road for scale. (**e**) View looking north onto the hillsides above Iskere village (eastern limb of the Iskere antiform) with structure defined by folded amphibolite sheets (locally braching). The tree in the foreground is *c.*3 m high. (**f**) Detail of the margins of the Jutial granite showing discordant cross-cutting intrusional contacts against the banded gneisses of the Nanga Parbat massif. The hammer is 30 cm long.

major tectonic contacts further north. Particularly we wish to establish: whether the antiformal structure of the massif proposed by Coward (1985) closes to the north or terminates against the structures; if the Main Mantle thrust is folded around the antiformal structure; and whether there is evidence for neotectonic disruption of the structural relationships. Additionally we seek a larger leucogranite body which may yield information both on the origin of the leucogranitic pegmatites and sheets that lace the massif and on Himalayan crustal anatexis. This paper presents preliminary results from a series of short geological expeditions into the hills north of the Indus valley (Fig. 2) and some initial geochemical analyses bearing on granite petrogenesis on samples collected on these forays.

Lithotectonic units

The geology of the Nanga Parbat massif is described by Misch (1949), Wadia (1961), Butler & Prior (1988), Madin *et al.* (1989), Treloar *et al.* (1991) and others. It consists of an ancient orthogneiss complex (the Nanga Parbat gneiss of Misch 1949) which has been divided into the Shengus and Iskere gneisses by Madin *et al.* (1989). In the most widely studied and accessible Indus gorge transect (between Sassi and Silbu, Fig. 2) the suite consists of a migmatitic orthogneiss complex, which has yielded early Proterozoic U-Pb zircon ages (Zeitler *et al.* 1989), and a series of paragneisses which include intercalations of recognisably metasedimentary material (marbles, calcschists and pelites, the Shengus gneiss of Madin *et al.* 1989). Both units contain amphibolites which locally are discordant to banding (Fig. 3a). This suite has been extensively deformed by both Himalayan and, since the gneisses are Proterozoic in age, probably pre-Himalayan tectonics. Correlations with deformation histories in the Hazara area of the Pakistan Himalayas are discussed by Treloar *et al.* (1991). Deformation fabrics, including those along the Main Mantle thrust, are cross-cut by two-mica, tourmaline-bearing leucogranite sheets and pegmatites which are thought to represent late Himalayan crustal melts. Prior to this study the relationships between these leucogranite sheets and pegmatites and any parent granitic body were unknown.

The Kohistan arc consists of various types of metabasic material including large plutonic bodies (e.g. the Shuta gabbro of Madin *et al.* 1989) together with volcanic rocks and sediments exposed along its northern edge (Pudsey 1986). Near the confluence of the Indus and Gilgit rivers (Fig. 2) the metabasic rocks are cross-cut by a suite of biotite granite sheets and lamprophyres (Petterson & Windley 1985) which are deformed into the Main Mantle thrust in the Indus gorge. Thus these granitoids can be distinguished on structural grounds from the leucogranites within the massif.

At Sassi, in the Indus gorge (Fig. 2), the Main Mantle thrust is characterized by a zone, *c.* 500 m wide, of interleaved units derived from Kohistan and the Indian continent. The deformation fabric is subparallel to the boundaries between the main lithologies, presumed to indicate high tectonic strains. Included is a suite of supracrustal rocks, largely marbles with discordant amphibolite bodies (presumed pre-metamorphic minor intrusions), which Butler & Prior (1988) tentatively interpreted as Phanerozoic cover to the Indian continent. These rocks outcrop along the western margin of the massif as a thin veneer, representing about 100 m of stratigraphy.

Nature of the Kohistan–Nanga Parbat contact

North of Sassi, valleys lead up to the Phuparash peaks (Fig. 2). On the headwall of the Phuparash valley, at a minimum elevation of *c.* 4500 m but continuing to *c.* 6500 m, a major lithological contact was observed, separating green rocks from underlying dominantly red-coloured ones (Fig. 3b). This contact was not accessible. Nevertheless, observations of the float indicate that the upper unit (green) consisted of: (1) laminated quartz–chlorite–muscovite schists with layers of decussate acicular actinolite, commonly cemented by feroan calcite with epidote alterations (both pervasive and along fractures); (2) volcaniclastic sediments including bombs and lithic clasts (5–100 mm) in a green chlorite–quartz–white mica matrix; (3) carbonates, including siderite with calcite veins and layers; together with massive greenstones and phyllites. These units are typical of the upper art of the Kohistan arc, as described by Pudsey (1986). The underlying material was accessible. It consists of a strongly layered (100 m scale) unit consisting of alternations of ortho and paragneiss with abundant sheets of deformed granitoids, possibly original sills. This material is clearly part of the Indian continental basement. This 'Layered Unit' is distinct from both the Shengus and Iskere gneisses and has been recognized in several parts of the northern massif. It is characterized by strong layering, including both paragneiss and orthogneiss similar to the Shengus and Iskere units respectively but also includes thick amphibolites and marbles which have no affinities with Madin *et al.*'s (1989) subdivisions. Thus we show it as a distinct unit on Fig. 2. The contact is parallel to banding in the underlying Layered Unit and to foliation in the overlying green, presumably Kohistan, material. Thus it has the attributes of the Main Mantle thrust, as defined in the Indus gorge at Sassi (Butler & Prior 1988), albeit unconstrained by kinematic data. Abundant exposure around the upper Phuparash valley shows the contact to be gently folded, with an antiformal structure plunging generally northwards at *c.* 20°.

Further east, on the ridge between Malubiting and Laila peaks (Fig. 2), the contact is again visible, with the Layered Unit beneath. This contains a slice of amphibolites thought to be derived from the Kohistan arc which we presume to have been tectonically interleaved during shearing along the Main Mantle thrust. The easternmost outcrops visited were on the headwall of the Mani glacier (Fig. 2). The entire headwall consists of *c.* 2000 m vertical thickness of Layered Unit (Fig. 3c), consistently dipping east. We assume these outcrops to lie on the eastern lib of a major antiformal structure. We further suspect that the eastern edge of the Nanga Parbat massif lies only just east of the Mani glacier because the next peaks in this direction are composed of green rocks, presumably Kohistan (Ladakh) arc material (Fig. 3c). The next outcrop of the Main Mantle thrust we visited lies in the Indus gorge (Fig. 2) where it is vertical and concordant to adjacent tectonic banding (Treloar *et al.* 1991).

Returning to the NW margin of the massif, the Darchan valley also contains the ductile contact. Here a slice of Kohistan metabasites lies within the Layered Unit (Fig. 2). Further north, in the valley, slices of orthogneiss were discovered tectonically emplaced into lithologies of the upper part of the Kohistan arc. These slices are interpreted as interleavings of Nanga Parbat basement with Kohistan arc material formed during the early ductile shearing episode which juxtaposed to two units. As such they are analogous to the interleavings of lithologies along the Main Mantle thrust in the western (Butler & Prior 1988) and eastern (Treloar *et al.* 1991) parts of the Indus gorge.

Although a ductile shear zone can be traced down the Darchan valley, to link with the structures in the Indus gorge, it is unclear how the various Kohistan and Nanga Parbat lithologies link through. It seems likely that the shear zone in the Indus gorge west of Sassi (Fig. 2) contains a greater proportion of Kohistan-derived material than in the north. Despite these uncertainties the regional fold structure can be recognized. Along the ridge between the Darchan and Phuparash valleys the gneissic banding in the Nanga Parbat massif dips west. However, the apparently simple geometry is disrupted by late fault zones which display both dip-slip and strike-slip kinematics. As noted earlier, similar structures were documented by Butler *et al.* (1989) further south along the western margin of the massif. At the mouth of the Darchan valley (Fig. 2) their Shahbatot fault zone can be traced as a series of eastward-inclined faults, overprinting the generally steep ductile foliation (Fig. 3d). Further north however, late fault zones of demonstrably large displacements have not been found, although there are abundant small-offset cataclastic zones, as recognized by Madin *et al.* (1989).

Tectonic structures

Kinematics

As part of our study of regional structure, the orientations of minor structures were measured to aid investigations of the kinematics. Similar studies in the main Himalayan arc by Brunel (1985) established a radial pattern of overthrusting. Along the western margin of the Nanga Parbat massif a more complex pattern was recognized but successfully interpreted by relating minor structures to larger scale geometry (Butler *et al.* 1989). However this work concentrated on the high level, dominantly cataclastic structures associated with the later stages of development of the massif. The fabrics documented here are ductile, defined by amphibolite-facies mineral assemblages, and thus developed at significant depths in the crust. Figure 4 is a plot of stretching lineations associated with

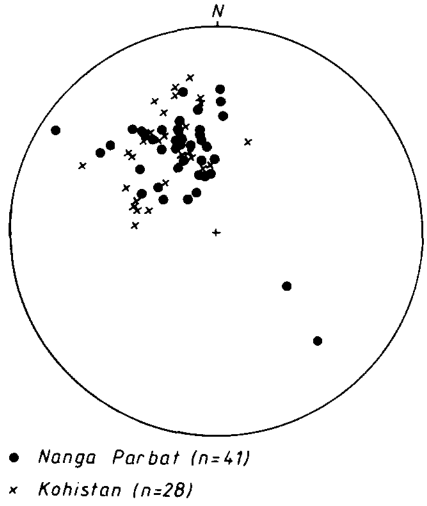


Fig. 4 Lower hemisphere, equal angle stereoplot of stretching lineations from the northern part of the Nanga Parbat massif.

ductile deformation fabrics measured in the northern part of the massif and surrounding Kohistan arc. They clearly cluster in the NW quadrant. If we assume that these linear structures results from a single episode of deformation and that the population has not been significantly reoriented by younger deformations an axis of tectonic transport may be defined as NW/NNW–SE/SSE. This is parallel to the thrusting direction in the Pakistan Himalayas (Coward *et al.* 1988) and to the direction of relative plate convergence between India and Asia for the past 30 Ma (Patriat & Achache 1984).

Although it is appealing to link small-scale structures directly to plate-scale kinematics there are fundamental difficulties. Some of these are discussed by Dewey *et al.* (1986), particularly the problem of strain partitioning in convergent zones. Nevertheless there is still an assumption that the small scale structures are representative of a larger strain field. In the Nanga Parbat district we have two specific problems with this assumption. First, we cannot be sure that the mineral stretching lineations were formed during Tertiary tectonism in outcrops away from the 'Main Mantle thrust'. We correlate foliation into the massif but this may well be foolhardy. There was certainly a period of fabric growth that pre-dates the basic dyke suite (e.g. Fig. 3a), probably a result of Proterozoic deformation. Second, the detailed studies of Treloar *et al.* (1991) along the Indus gorge established that some of the lineations in their area had been folded around antiformal structures. Consequently it may be unwise to use the linear structures within the massif to determine regional kinematics without first examining the consequence of folding.

Antiformal structures

The outcrop pattern of the 'Main Mantle thrust' is consistent with the antiform hypothesis for the massif. Not only is the Kohistan–Indian content contact antiformal but so too is the tectonic fabric (Fig. 5). Deeper within the massif, at Iskere (IA on Fig. 2) the antiform can be identified again, defined by folded amphibolite sheets (Fig. 3e). This may coincide with the Iskere antiform of Madin *et al.* (1989). Plausibly this is the same structure that folds the 'Main Mantle thrust' at Phuparash but regrettably the terrain prevents complete mapping. Nevertheless the youngest major folding within the massif can be related to folding of the 'Main Mantle thrust'. This is consistent with Coward's (1985) hypothesis of early emplacement of Kohistan onto the Indian continent followed by later buckling although the massif as a whole contains an array of en echelon antiforms. In the Indus gorge there are at least three major antiformal structures (Fig. 5). The largest closure is in the east and trends NNE (Treloar *et al.* 1991; BA on Fig. 2). This is not a simple continuation of the Iskere antiform but is a distinct structure, suggesting disharmonic folding along the massif. It is unclear how the composite antiformal structure of the massif controls the outcrop of the 'Main Mantle thrust' in the NE as this region is poorly known at present.

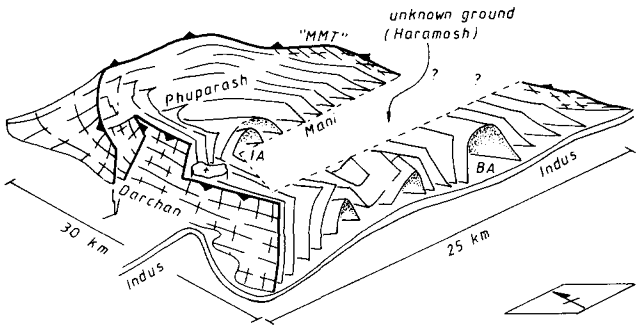


Fig. 5 Sketch block diagram illustrating the relationships between foliation within the Nanga Parbat massif and the Main Mantle thrust (MMT). The structures shown along the Indus valley are modified after Treloar *et al.* (1991, fig. 8a).

Folded lineations: some comments

The fold axes within the Nanga Parbat massif are oriented sub-parallel to the mean azimuth of stretching lineations. In many situations an assumption might be that folds and lineations have rotated into the direction of maximum finite elongation by intense simple shear strains (e.g. Lacassin & Mattauer 1985). To achieve perfect parallelism between stretching lineations and fold hinges during a single progressive deformation requires infinite strains and consequently the folds should be isoclinal. Such models are not appropriate here because the Nanga Parbat structure is tight but not isoclinal. If the fold developed by shortening perpendicular to the axial surface of the fold so that the shape modified from a simple buckle to a similar shape, pre-existing lineations would modify to high angles with respect to fold hinges. Such a pattern has been recognized at the western flank of the massif at Sassi (Butler *et al.* 1989) but has not been analysed geometrically. The regional orientation of stretching lineations within the massif is not explained by such a model. An exception to the general rule occurs when pre-existing stretching lineations are oriented parallel to the fold hinge. This may have been the case in the northern part of the massif but at present we can offer no convincing explanation for this apparent coincidence.

Leucogranite occurrences

A major geological problem of the Nanga Parbat region is the origin of the tourmaline-bearing leucogranites that form abundant veins and sheets throughout the northern region of the massif. Misch (1949) related them to a regional 'granitization' in which much of the basement complex was converted to granite during the Himalayan orogeny. These ideas have now been discredited, largely because the orthogneiss complex, which includes migmatites, has yielded Proterozoic ages (Zeitler *et al.* 1989). Field relationships show that migmatites developed early in the tectono-metamorphic evolution of the basement gneisses, are cross-cut by locally discordant amphibolite sheets, which are themselves cross-cut by the leucogranites. So the old granitoids and migmatites are unrelated to the leucogranite veins and pegmatites. At the northwest margin of the massif, the leucogranites cross-cut ductile deformation fabrics kinematically associated with the Main Mantle thrust (Butler & Prior 1988). Thus these intrusions are presumed by us to post-date peak metamorphism. The leucogranite veins may represent the stock-work above a larger leucogranite intrusion but prior to this study no such pluton had been found within the massif. However, a two-mica, tourmaline-bearing granite has been found that cross-cuts deformation fabrics in the surrounding Nanga Parbat basement. The Jutial leucogranite is a homogeneous body, at least 3 km in diameter, exposed on the eastern side of the Phuparash Valley (Fig. 2) and is significantly larger than other known leucogranites from the western Himalayas that form sills and sheets less than 10 m thick.

The granite is a coarse-grained body of approximately minimum-melt composition, made up of equal proportions of quartz, oligoclase and microperthite containing both euhredral biotite (5–10%) and muscovite (2–10%). Zircon and apatite are common accessory phases. Although largely undeformed, locally there is a weak preferred orientation of quartz grains, sutured grain boundaries, locally associated with chloritization and secondary muscovite growth. Tourmaline, where present, is generally skeletal in habit. Locally penetrative flow banding is defined by biotite-rich laminations.

At the margins of the granite, equigranular granitic sheets, 1–2 m thick, cross-cut deformation fabrics in the host gneisses (Fig. 3f). The sheets include a two-mica facies, similar in mineralogy to the main body of the Jutial granite, together with a muscovite-tourmaline facies that only rarely contains biotite or garnet crystals. Tourmaline in these sheets is euhedral, zoned schorlite and is believed to be magmatic in origin since it locally forms inclusions in garnet and, more rarely, defines a crude igneous layering. The distinction between muscovite + tourmaline and two-mica granites is observed in many of the Himalayan leucogranites and probably reflects varying activities of B and H_2O during crystallization (Scaillet *et al.* 1991).

The country rock includes pelitic (biotite–muscovite–quartz–plagioclase–alkali feldspar–apatite ± epidote) and basic (hornblende–biotite–quartz–plagioclase–titanite) lithologies. That the granite was injected into the country rock, rather than melted in situ, is indicated by clear cross-cutting field relationships. Abundant schlieren of paragneiss within the granite indicate that injection was largely passive and conformable though some re-orientation of xenoliths is observed.

Comparative geochemistry

Along the strike of the High Himalayas, discrete bodies of leucogranites of Miocene age (*c.* 20 Ma) are exposed, several of which have been studied in detail (see references from Gangotri, Langtang and Manaslu leucogranites, Table 1). These share a distinct geochemistry: a uniformly high silica content (>70% SiO_2), high alkalis (particularly K and Rb), depleted Ca, Sr and HFS elements such as Y and Zr and high initial $^{87}Sr/^{86}Sr$ ratios (>0.74) (Harris *et al.* 1986). All these characteristics can be related to fractional melting of a metasedimentary source (Scaillet *et al.* 1990; Harris & Inger 1992). A less common, but distinct leucogranite type has been identified in the Baltoro Plutonic Unit of the Karakorum (Crawford & Windley 1990). Although of similar age to the High Himalayan leucogranites, this suite differs in being associated with less evolved intrusions and in having high concentrations of Sr together with low Rb/Sr and Rb/Ba ratios (Table 1, Fig. 6). These characteristics, together with the lower initial $^{87}Sr/^{86}Sr$ ratios of the Baltoro leucogranite (<0.71) can be related to a source in the lower crust combined with fractional crystallization during ascent.

Eleven whole-rock samples of the Jutial leucogranite have been analysed for major and trace-element concentrations on the ARL (8420+) wavelength dispersive XRF at the Open University. These analyses show the Jutial leucogranite to be geochemically similar to the High Himalayan bodies, whilst it does not share geochemical characteristics with the Baltoro leucogranites (Fig. 6). Jutial is peraluminous, with a Rb/Sr ratio ranging between 2 and 8. This is consistent with vapour-absent melting of a metapelitic or metagreywacke source by incongruent melting of muscovite. A similar petrogenesis has been described by Harris & Inger (1992) for leucogranites from the Langtang district of the Nepalese Himalayas. High Rb concentrations coupled with low Nb and Y contents confirm a metasedimentary source for the Jutial leucogranite and are, reassuringly, consistent with magma genesis in a syn-collision environment (Pearce *et al.* 1984). Zirconium concentrations are low (47 ppm) indicating a magmatic temperature *c.* 700°C, assuming Zr saturation was reached and zircon inheritance is negligible (Watson & Harrison 1983). Interestingly, the Jutial suite differs from other Himalayan leucogranites in its high Th concentrations, exceeding 100 pm in some marginal sheets. The

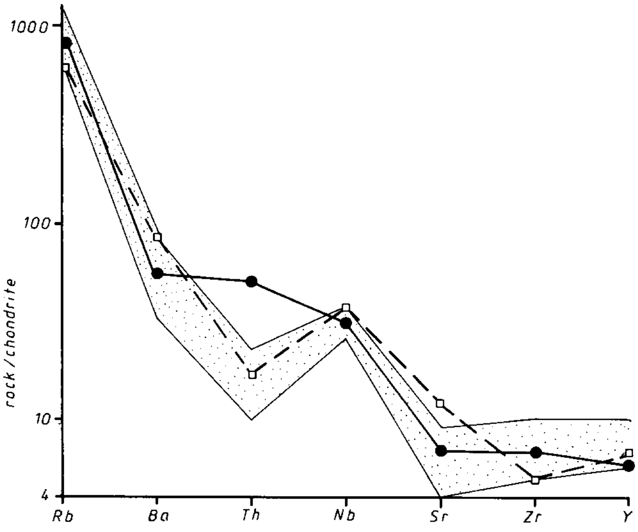


Fig. 6 Chondrite-normalized trace-element variation diagram for average concentrations observed in the Jutial granite (filled circles). The stippled area indicates the field of high Himalayan leucogranites and the dashed line that of the Baltoro leucogranite. For references see Table 1.

Table 1. *Average compositions of Himalayan leucogranites*

	Jutial	sd	Langtang[1]	Manaslu[2]	Gangotri[3]	Baltoro[4]
n	11		22	201	40	10
Wt%						
SiO_2	73.63	1.18	73.51	73.65	73.01	74.48
TiO_2	0.10	0.04	0.13	0.10	0.07	0.06
Al_2O_3	14.79	0.29	14.94	14.87	15.24	14.04
Fe_2O_3*	1.00	0.16	1.22	1.32	1.13	0.75
MnO	0.01	0.00	0.05	0.03	0.02	0.09
MgO	0.14	0.08	0.38	0.11	0.12	0.03
CaO	1.20	0.16	0.90	0.47	0.58	0.75
Na_2O	3.54	0.31	3.56	4.05	4.31	4.54
K_2O	5.16	0.55	4.81	4.56	4.56	4.20
P_2O_5	0.05	0.01	0.13	0.13	0.25	0.09
LOI	0.63	0.44	0.56	na	0.71	0.45
Total	100.26		100.19	99.29	99.65	99.48
ppm						
Rb	294	28	254	287	416	228
Ba	221	175	333	213	128	336
Sr	83	32	108	76	44	143
Th	22	10	9	6	4	7
Nb	11	2	10	na	13	13
Zr	47	13	66	43	35	33
Y	12	6	21	na	13	13
U	20	7	6	9	17	na

*All Fe calculated as Fe_2O_3.

[1] Inger (1991).

[2] Le Fort *et al.* (1987).

[3] Scaillet *et al.* (1990).

[4] Crawford & Windley (1990).

na, not analysed; sd, standard deviation.

average total heat production for this granite is correspondingly high (7.4 μWm^{-3}), double that of other analysed Himalayan granites. We expect this to reflect a similarly high heat production in the protolith gneisses.

$^{87}Sr/^{86}Sr$ ratios have been determined on seven widely dispersed whole-rock samples of the Jutial granite using the Finnigan MAT 261 mass spectrometer at the Open University (Table 2). These ratios are extremely high (>0.88), confirming the source as both metasedimentary and distinct from that of the Baltoro leucogranite suite discussed above. The remarkable uniformity of these ratios suggests that post-crystallization, fracture-controlled fluids have not contributed to the isotopic evolution. Isotopic equilibrium has not been reached within the Jutial pluton and whole-rock isotopic ratios neither define an isochron nor constrain the age of crystallization. This is a common attribute of Himalayan leucogranites. Although the source of the Jutial granite is characterized by higher concentrations of radiogenic Sr than are the protoliths of other High Himalayan granites (Fig. 7), metapelites with similar Sr isotopic ratios are known from south of the Main Central thrust in the Nepalese Himalayas (France-Lanord & Le Fort 1988). The absence of appropriate metasediments in the Kohistan arc adjacent to Nanga Parbat may explain why occurrences of tourmaline leucogranites are spatially restricted to within the massif and are absent in Kohistan.

Table 2. *Rb-Sr isotope data from the Jutial Granite*

Sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
J1A	276	56	15.54	0.8872 ± 1
J1B	316	69	13.16	0.8904 ± 1
J1C	310	76	11.72	0.8920 ± 1
J1E	253	61	11.91	0.8884 ± 1
J1F	289	74	11.22	0.8917 ± 1
J1G	270	106	7.32	0.8895 ± 1
J1I	288	58	14.26	0.8877 ± 1

The high $^{87}Sr/^{86}Sr$ ratios of the Jutial granite exceed whole-rock values measured from other Himalayan leucogranites with one exception: those derived from a suite of pegmatitic leucogranites collected from near Raikhot bridge, *c.*40 km south of our study area (Cliff *et al.* 1991). These pegmatites show syntectionic relationships to deformation fabrics associated with the Liachar thrust (Butler *et al.* 1989) which carries the Nanga Parbat massif, including the host gneisses and granites sheets, onto Quaternary river gravels. The sheets provide a broad spectrum of $^{87}Sr/^{86}Sr$ ratios, in excess of 0.90, in which isotopic equilibration was not reached even between adjacent phases. These attributes are ascribed to infiltration of radiogenic fluids under sub-solidus conditions, an explanation which we rejected above for the Jutial granite. Nevertheless we believe that the generally high $^{87}Sr/^{86}Sr$ ratios of the leucogranite sheets in the hanging-wall to the Liachar thrust near Raikhot and the main Jutial body, together with similarity of mineralogy and textures strongly suggests that the two suites are related. The sheets at Raikhot are probably derived from a source magma body locally exposed at Jutial. Zircon dating of the Raikhot sheets suggest an intrusion age of 2–8 Ma (Zeitler

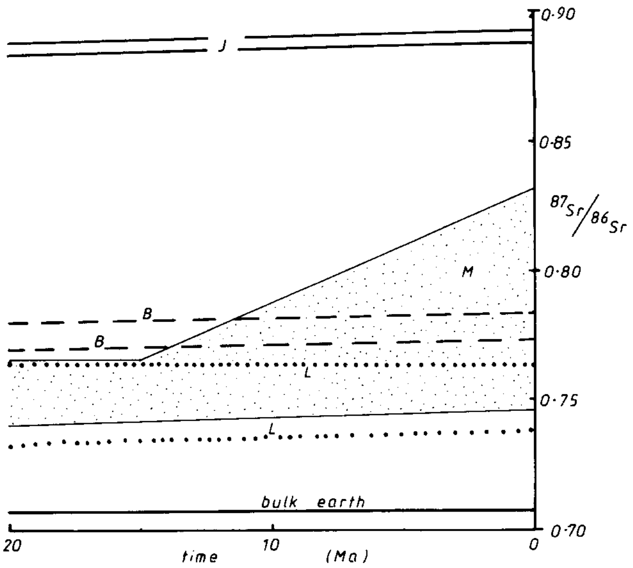


Fig. 7 Sr-isotope evolution diagram for high Himalayan leucogranites. J, Jutial; M (stippled area), Manaslu (Deniel *et al.* 1987); B (pecked), Bhutan (Dietrich & Gansser 1987); L (dotted), Langtang (Inger 1991). Bulk earth is shown for reference.

& Chamberlain 1991) and, if coeval with the Jutial intrusion, their emplacement marks the youngest known phase of crustal anatexis in the Himalayan chain. The upper intercept age of zircons from the Raikhot sheets led Zeitler & Chamberlain (1991) to suggest a source age of about 1850 Ma.

Discussion

A principal conclusion of this study is that the early ductile contact between the Kohistan island arc and the Indian continent ('MMT') can be traced onto the northern margin of the Nanga Parbat massif. Thus the northern outcrop termination of the massif is defined by erosion through the gently-plunging antiformal structure and not by truncation by neotectonic faults or by the northern suture of the Kohistan island arc, as proposed by Gansser (1980). The present structure of the Nanga Parbat massif is antiformal, defined not only by internal fabrics but also by the orientation of the enveloping Kohistan–India contact. This antiform is modified along the western margin of the massif by cataclastic faulting but early features are still recognizable. Ductile deformation occurred dominantly on a NW/NNW–SE/SSE axis.

These conclusions support the findings of early studies carried out by us further south in the massif (Butler & Prior 1988; Butler *et al.* 1989; Treloar *et al.* 1991). Critically they show that the northern margin of the Indian continent at Nanga Parbat is controlled at outcrop by a late fold structure. There is nothing which supports notions that the massif is related in any way to the pre-existing geometry of the Indian continental margin, either as a promontory (Wadia 1961) or as the edge of a west-facing embayment (Madin *et al.* 1989). It is likely that the Main Mantle thrust, the early ductile contact between Kohistan and India, links directly with the Indus Suture Zone to the east, as proposed by numerous authors so that, with respect to the India–Asia collision at least, Kohistan and Ladakh behaved a continuous terrane. Regrettably to demonstrate this fully requires tracing out the contact between Indian basement rocks and the palaeo-island arcs to the NE of Haramosh, in terrain not conducive to conventional mapping techniques.

Indian continental crust melted after the emplacement of Kohistan, generating the Jutial granite and its associated veins and pegmatites. The geochemical characteristics of the Jutial body and its possible association with the pegmatitic sheets in the hanging-wall to the Liachar thrust suggests vapour-absent melting of Early Proterozoic metasediments at 2–8 Ma, from a protolith of unusually high heat production. From calculations, Inger (1991) observes that heat production increases by a factor of *c.* 1.25 between source and melt during anatexis of Himalayan metasediments. Using this relationship, the protolith of the Jutial granite probably had a heat production of *c.* 6.0 $\mu W\ m^{-3}$. This compares with the value of 2.0 $\mu W\ m^{-3}$ used by Zeitler & Chamberlain (1991) for their thermal model of the Nanga Parbat massif. Their model requires decompression melting under water-undersaturated conditions of a source at initial depth of 30 km exhuming at an accelerating rate over the past 30 Ma, to a current value of 10 mm a^{-1}. They note that at such rapid rates of decompression, exhumed lithologies would spend insufficient time at temperatures in excess of the granite solidus for the observed protracted development of overgrowths on zircon in the source. Moreover, decompression melting of crustal lithologies will only generate small quantities of melt. If protoliths are exhumed from depths of 30 km and temperatures of 750 °C to 15 km, a melt fraction of *c.* 2% will result during adiabatic ascent, assuming conservation of entropy. It is unlikely that such a low melt fraction would leave its source. While concurring that melting occurred in water-undersaturated conditions, our new estimates of heat production may resolve some of these problems. Enhanced internal heat production in the protolith Nanga Parbat gneisses will greatly enhance the rate of melt production and therefore will contribute to a more plausible model for crustal anatexis. The search continues for the likely source lithologies within the massif to test these hypotheses.

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