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A GEOLOGICAL PROFILE ACROSS THE BALTORO-KARAKORAM RANGE, N. PAKISTAN

M. P. SEARLE[1], A. J. REX[1], R. TIRRUL[2], B. F. WINDLEY[1], M. ST. ONGE[2] and P. HOFFMAN[2]

[1] Department of Geology, The University, Leicester LE1 7RH, UK.
[2] Geological Survey of Canada, 588 Booth Street, Ottawa, Ontario K1A OE4, Canada.

ABSTRACT

The Karakoram batholith along the Baltoro glacier transect separates a northern sedimentary domain with structural culminations of high-grade gneisses (K2 gneiss) from a southern high-grade metamorphic domain. The Baltoro plutonic units range in composition from biotite granodiorite to garnet bearing two mica leucogranite; they have no mafic dykes and no volcanic component. The Baltoro granite is interpreted as being crustally derived from partial melting of deeper level rocks equivalent to the high-grade metamorphics in the south. The relationships between metamorphism, crustal-scale ductile shearing, migmatisation and magmatism are discussed.

INTRODUCTION

Aspects of the geology and collision tectonics of the western Himalaya have recently been studied, largely on a reconnaisance basis in both Kohistan (Tahirkheli *et al.*, 1979; Coward *et al.*, 1982, 1986) and Ladakh (Honegger *et al.*, 1982; Searle, 1983, 1986). These studies have resulted in the interpretation of the geodynamic evolution of the rocks along the northern margin of the Indian plate and within the Tethyan suture zones to the north — both the southern, main Indus-Tsangpo suture zone (= Main Mantle Thrust zone in Pakistan) and the northern Shyok suture zone (Fig. 1). In general, the Shyok suture closed as a result of collision between the Karakoram plate and the Kohistan island arc-microplate during the late-Cretaceous (95–70M.a.). Closure of the Indus-Tsangpo suture zone (ITSZ) occurred during the mid-Tertiary (45–40 M.a.) and deformation spread southwards across the Tibetan-Tethys and High Himalayan zones during the Oligocene-Miocene (Searle, 1983). Continued convergence during

Pliocene-Recent times has resulted in a major N-directed backthrusting zone along the ITSZ as well as extensive breakback, and out-of-sequence thrusts (Searle, 1986). The Main Karakoram thrust (MKT) is one late-stage breakback thrust that bounds the northern side of the Shyok suture zone.

Little work has been done on the rocks north of the Shyok suture in the Karakoram Ranges since the classic studies of Desio (1964, 1979), Desio and Zanettin (1970), and Zanettin (1964). The Karakoram is one of the highest, most glaciated, and most inaccessible mountain ranges on Earth. Since the building of the Karakoram highway from Gilgit to Kashgar along the Hunza valley, a number of geological studies have been initiated along this transect (Prior, 1986; Debon *et al.,* 1986). This paper however reports preliminary findings from a reconnaissance survey of the Biafo glacier to the Latok peaks (1984) and from a 3½ month expedition to K2 and Masherbrum (1985) along the Baltoro, Godwin-Austin and Gasherbrum glacier systems and many subsidiary side glaciers branching off these access routes (Figs. 1 & 2).

The geology of the Baltoro-Muztagh Karakoram can be divided into three major structural domains: a northern sedimentary domain with culminations of high-grade metamorphic rocks, and a southern high-grade metamorphic domain, separated by the 12–15 km wide Karakoram batholith.

NORTHERN KARAKORAM DOMAIN

North of the Karakoram batholith, the Broad Peak and Gasherbrum Ranges are largely made of a sedimentary series ranging in age from Carboniferous to ? Cretaceous (Desio, 1964, 1979). These rocks are weakly metamorphosed along the Baltoro glacier, Crystal and Marble peaks to Concordia and are strongly deformed. The sedimentary sequence was not studied in detail due to extreme inaccessibility on the Pakistan side of the border, but more detailed studies have been made on the Chinese side along the Shaksgam valley (Auden, 1937; Desio, 1980).

Along the Baltoro glacier a well-cleaved Carboniferous black shale sequence is overlain by a thick late Palaeozoic-Mesozoic carbonate sequence comprising the Permo-Triassic Shaksgam Fm. and the Jurassic Aghil Fm., separated by a prominent multi-coloured, fluviatile conglomerate (Urdok Fm.). Overlying the Jurassic carbonates in the Broad Peak Range a series of green fissile shales and highly strained conglomerates (Khalkhal Fm.) are interbedded with crystal lithic tuffs and intruded by sub-volcanic porphyrys. On the SW face of Broad Peak and the west face of Gasherbrum IV, plagioclase-hornblende quartz-diorites intrude the Khalkhal Fm.

In general terms the sedimentary evolution of the Karakoram plate appears to conform to other well known southern Tethyan plate margins in the Middle East and Asia, showing a dominantly stable carbonate platform succes-

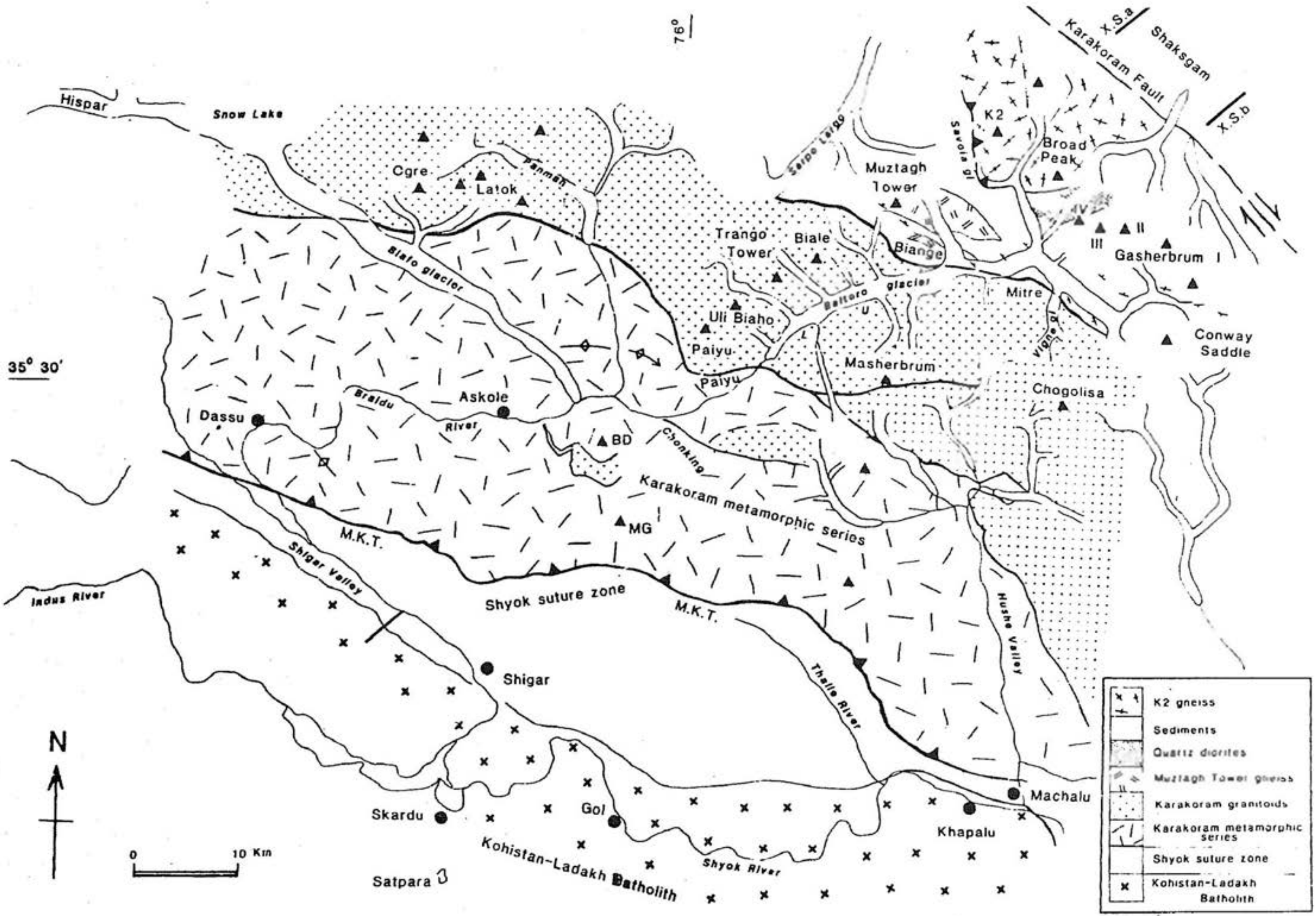

Fig. 1. Geological sketch map of the Baltoro-Muztagh Karakoram. MG = Mango Gusar; BD = Bakhor Das; M.K.T. = Main Karakoram Thrust.

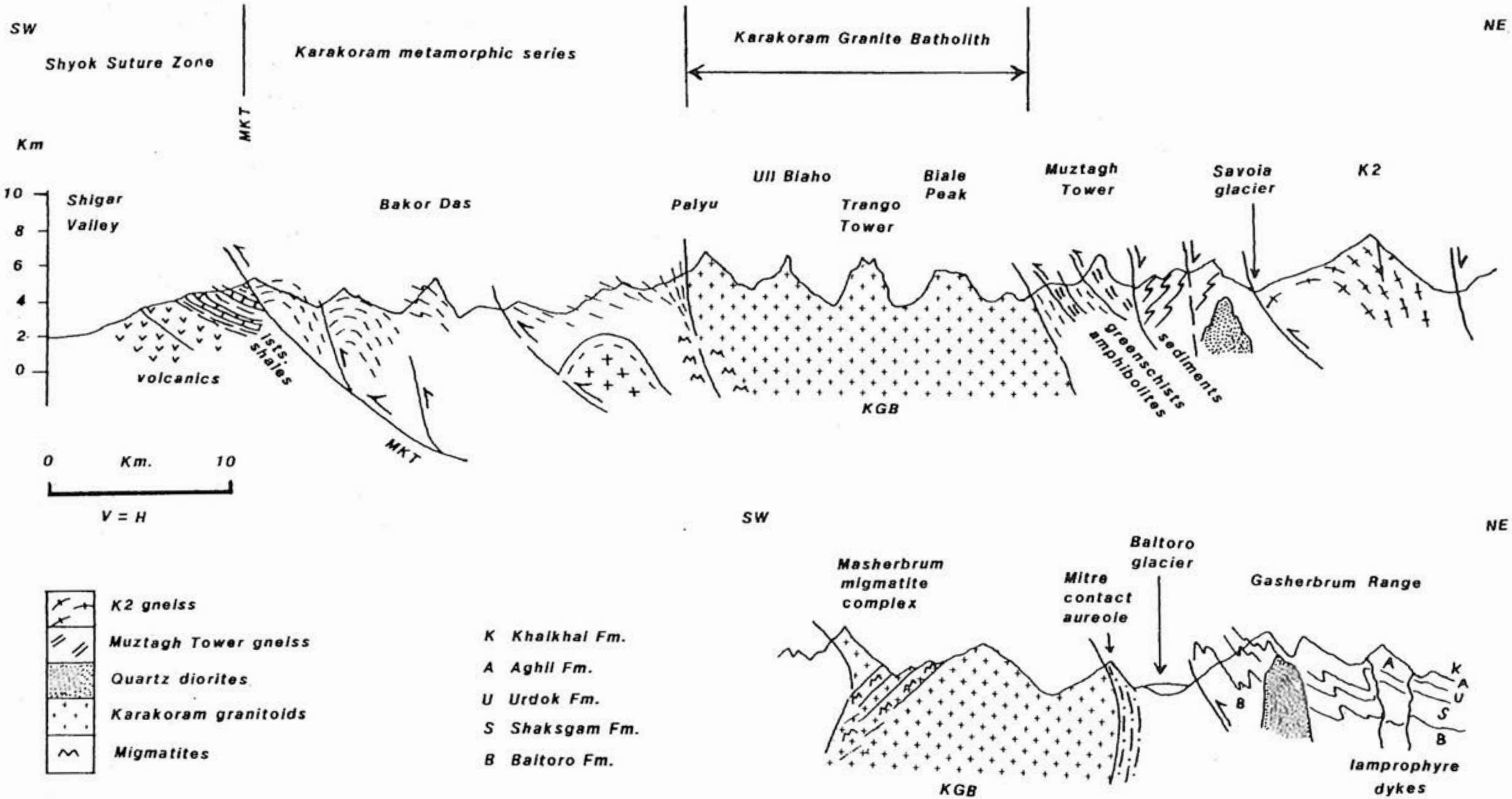

Fig. 2. Cross-sections of the Baltoro-Muztagh Karakoram; locations shown on Fig. 1. Stratigraphic formations after Desio (1964, 1979).

sion during the Mesozoic up until initial collision of the Karakoram plate with the Kohistan-Dras island arc to the south during the late Cretaceous (Pudsey *et al.,* 1986).

K2 GNEISS

Structural culminations of high-grade metamorphic rocks occur on K2 and the western side of Broad Peak (Desio and Zanettin, 1970). Two major types of high-grade gneisses are present in K2, (1) plagioclase-hornblende gneiss and (2) biotite-hornblende-K feldspar megacrystic orthogneiss. These are interbanded with garnet-diopside bearing marbles and clinopyroxene-hornblende bearing psammites. Metammorphic grade is in the amphibolite facies and several narrow, late-stage chlorite-rich shear zones cut the sequence. Talc-tremolite-serpentine assemblages were also found along some ductile shear zones and in one locality, sillimanite needles. Leucogranitic pegmatite dykes (containing green garnet + muscovite + biotite ± tourmaline) intrude the K2 gneiss, and skarns containing massive red garnet and green diopside have developed at the pegmatite-marble contacts. Foliations in the K2 gneiss along the south face of K2 strike NNE 028/48°E on average, and stretching lineations trend due south.

The contact between the K2 gneiss and the Savoia and Khalkhal Fms. sediments is faulted on the south face of Broad Peak and lies unexposed beneath the Savoia glacier along the south and west flanks of K2.

BALTORO PLUTONIC UNITS OF THE KARAKORAM BATHOLITH

The 600 km long Karakoram batholith is made up of several plutonic units of diverse mineralogy, geochemistry, structure and age (Debon *et al.,* 1986). A U-Pb zircon age of 95 ± 4/6 Ma from a biotite-hornblende granodiorite from the Hunza Valley (Le Fort *et al.,* 1983) is the only reliable crystallisation age for an intrusive unit within this composite batholith. Rb–Sr and K–Ar methods give younger ages and are interpreted by Le Fort *et al.* (1983) as post-intrusive thermal events.

The Baltoro Plutonic Unit is 15–20 km wide and extends for at least 100 km along strike from Snow Lake in the WNW to the Masherbrum and Chogolisa glaciers in the ESE. It is a prealuminous pluton composed of medium to coarse grained biotite granodiorite to garnet two-mica granite, intruded by leucogranitic dykes. Quartz, plagioclase, alkali feldspar, muscovite, biotite and garnet form the main mineral assemblage in the medium to coarse-grained monzogranites. Plagioclase is typically zoned whilst alkali feldspars are megacrystic with inclusions of muscovite. These alkali feldspars are interpreted as late magmatic or metasomatic phenocrysts and can reach up to 10 cm in length. Muscovite, biotite and quartz occur as interstitial crystals. This relatively homogeneous granite is well represented in the spectacular mountains of the Trango Towers, Cathedral and Urdukas peaks (Fig. 2). Unlike the High Himalayan leucogranite intrusions from the Nepal (Le Fort, 1981; Vidal *et al.*, 1982) and Indian Himalaya (Searle and Fryer, 1986), tourmaline, which is indicative of a high boron content, is mainly absent. Garnet becomes a significant phenocryst phase in leucogranite bodies and pegmatite-aplite dykes, but is also variably developed in the batholith itself, roughly increasing in abundance towards the southern contact along the Biafo and Baltoro glaciers.

Both the northern and the southern contacts of the Baltoro Pluton are intrusive. The northern contact has been studied at Biange on the north bank of the Baltoro glacier and along the southern edge of the upper Baltoro glacier at Mitre and Chogolisa mountains. A well developed contact metamorphic aureole is exposed along the flanks of the Vinge glacier and Mitre peak near Concordia. Metamorphic protoliths are Baltoro black slates with minor limestone-marble and quartzite layers. Progressive high temperature-low pressure mineral assemblages in hornfels include biotite, andalusite (chiastolite) and sillimanite. The assemblage andalusite-cordierite-biotite-muscovite-chlorite-plagioclase-quartz is present and adjacent to the granite contact small knots of fibrolite sillimanite and biotite replace cordierite and muscovite. The andalusite is very common, the large euhedral chiastolite crystals showing hour-glass texture. The granite contact is sharp and near vertical. Along the east flank of the Vigne glacier pegmatite dykes radiate out from the margin of the granite into the adjacent andalusite and sillimanite-bearing hornfels and amphibolites. Comparatively few pegmatite dykes intrude the country rocks north of the granite in contrast to the dense network that intrude the metamorphic terrain to the south. High up on the north face of the Mitre peak a few stoped blocks of reddish-black hornfels are enclosed within the light-coloured granite.

The southern margin of the Baltoro Pluton at Paiyu near the snout of the Baltoro glacier is also intrusive into vertically foliated gneisses which contain garnet, biotite, muscovite, quartz, plagioclase, sillimanite and granitic melt pods. The contact is vertical both along the Baltoro glacier and at the Uzun Brakk-Brainta Brakk glaciers some 50 km west along the Biafo glacier system. The Latok peaks north of this are composed of similar garnet-bearing leucogranites and biotite granodiorite as along the Baltoro glacier. The fabric in the marginal part of the granite is vertical, parallel to the schistosity in the metamorphic rocks. The southern part of the batholith in the Masherbrum area comprises a large migmatite terrain with a vast network of leucogranites intruding biotite-rich gneisses, restite and leucosome material. Xenoliths at the contact of the batholith represent material assimilated at very high levels of granite emplacement. Apart from one single observation of a sillimanite gneiss xenolith between Liliwa and Urdukas, the central part of the batholith is totally barren of assimilated exotic material. However, local developments of elongate stringers with high modal biotite may represent metasedimentary "ghosts".

In general the Baltoro granitoids show little strain and no strong foliation is developed, unlike the high-grade metamorphic terrain to the south, which shows high ductile strain. The Baltoro plutonic unit is characterised by a complete absence of mafic dykes, the absence of an extrusive volcanic component and the abundance of leucogranitic crustal melt material.

KARAKORAM METAMORPHIC SERIES

South of the Karakoram batholith along the Baltoro glacier-Braldu River transect, a high-grade metamorphic terrain consists of a wide variety of metasediments, orthogneisses and migmatites intruded by a network of garnet, biotite ± muscovite leucogranitic dykes and veins (Zanettin, 1964). The dominant metasedimentary lithologies are amphibolites with garnet, biotite and clinopyroxene, medium and coarsely crystalline marbles in places also with hornblende, clinopyroxene and garnet, and metapelites containing garnet, mica, and aluminosilicates with some spectacular coarse grained kyanite-staurolite-garnet-biotite-muscovite schists. Protoliths of these metamorphic rocks must have been approximately even proportions of impure muddy carbonates and shales with minor volcanics, possibly representing a collapsed passive-type continental margin. It is possible, although not yet demonstrated, that the metamorphic series south of the batholith represents the metamorphosed equivalents of the sediments exposed in the Gasherbrum Range and Broad Peak, north of the batholith.

Most of the pelitic rocks between the Karakoram batholith and the Main Karakoram Thrust (MKT) are characterised by the assemblage kyanite-staurolite-garnet-muscovite-biotite-plagioclase-quartz, which is univariant in the seven-component system $SiO_2-Al_2O_3-FeO-MgO-Na_2O-K_2O-H_2O$. This indicates minimum PT conditions of 550°C and 5.5 kbar (St. Onge, 1984). Towards the batholith margin at Paiyu (Fig. 1) over a distance of 5 km, one successively observes the disappearance of staurolite, the replacement of kyanite by sillimanite, and the appearance of granitic pods. The inferred reaction sequence (Fig. 3) corresponds to an increase of about 75°C. The reaction that initiates partial melting is : muscovite + biotite + plag + quartz + vapour $\rightleftharpoons$ Al_2SiO_5 + melt pods. The increase in metamorphic grade up to partial melting approaching the granite contact strongly suggests a close spatial and temporal correlation between the age of metamorphism and the age of genesis of the Baltoro granite magma.

South of Bakhor Das a separate granitic pluton occurs within the metamorphic rocks. It is composed of a non-foliated, medium-fine grained monzogranite containing biotite, minor muscovite but no garnet. Low pressure, high temperature mineral assemblages including wollastonite occur in marbles immediately adjacent to the granite contact.

Along the Braldu gorge west of Askole (Fig. 1), a composite prograde reaction can be deduced from the replacement of staurolite and kyanite by small knots of muscovite and sillimanite which define an east-plunging lineation. Some of the muscovite knots have relict kyanite or staurolite in the cores. West of

Mango Gusar (Fig. 1), the high-grade Karakoram metamorphic series is juxtaposed along a steep NE-dipping fault (MKT) against sub-biotite grade rocks of the Shyok suture zone. Adjacent to the MKT, kyanite, garnet and staurolite are syntectonically retrogressed to muscovite and chlorite-bearing assemblages. East of Mango Gusar structures plunge towards the east and in the higher structural levels metamorphic grade decreases to lower greenschist. The lowest grade assemblages are biotite-muscovite-quartz-plagioclase (pelite) and epidote-actinolite-chlorite-albite (meta-basalt). This suggests that metamorphic isograds are normal and not inverted as they appear to be along strike in the Hunza Valley (Broughton *et al.,* 1985).

Some unusual occurrences of ophiolitic material were discovered along the Panmah valley and in float that was derived from the Chongking valley east of Bakhor Das. Ultramafic rocks encased in marble along the lower Panmah valley include the Ca-free assemblage forsterite + enstatite + Mg–chlorite + spinel, displaying a high T annealing texture, and compatible with the grade indicated by adjacent pelites (Fig. 3). Ultramafic rocks from the Chongking valley consist of orthopyroxene, olivine and Mg–chlorite in a matrix of nephrite. Metasediments along the valley are mainly at greenschist grade. The age of these ophiolitic rocks is unknown but it is possible that they could represent a much older cryptic suture within the Karakoram metamorphic series.

STRUCTURE

The high-grade metamorphic terrain between the Karakoram batholith and the Shyok suture shows a complex structural history involving at least three "phases" of deformation. A prominent schistosity with an average shallow NE dip, and associated isoclinal folds was produced during D1. These structures are refolded by ubiquitous, macroscopic SW–verging folds (F2). Both sets of structures were apparently developed at peak metamorphic conditions, and are refolded by very large upright open folds (F3). Finite stretching lineations defined by quartz rods, sillimanite, hornblende and muscovite alignment have a very consistent easterly plunge parallel to both F2 and F3 hinges, suggesting that they are all products of a progressive deformation. The orientation of stretching lineations defined by retrograde assemblages adjacent to the MKT are indistinguishable from higher grade lineations, and oblique to the MKT. This is interpreted to mean that ductile deformation in the hanging-wall and thrusting onto the Shyok suture zone are related and both are the expression of a non-coaxial general (3–D) strain.

Structures become less systematic in the migmatite belt along the southern margin of the batholith. Leucosome material (garnet, biotite±muscovite leucogranite) has been segregated from the restite material and intruded the country rock to the south as a network of leucogranitic dykes and veins. These occur throughout the metamorphic domain but are more abundant in the northern

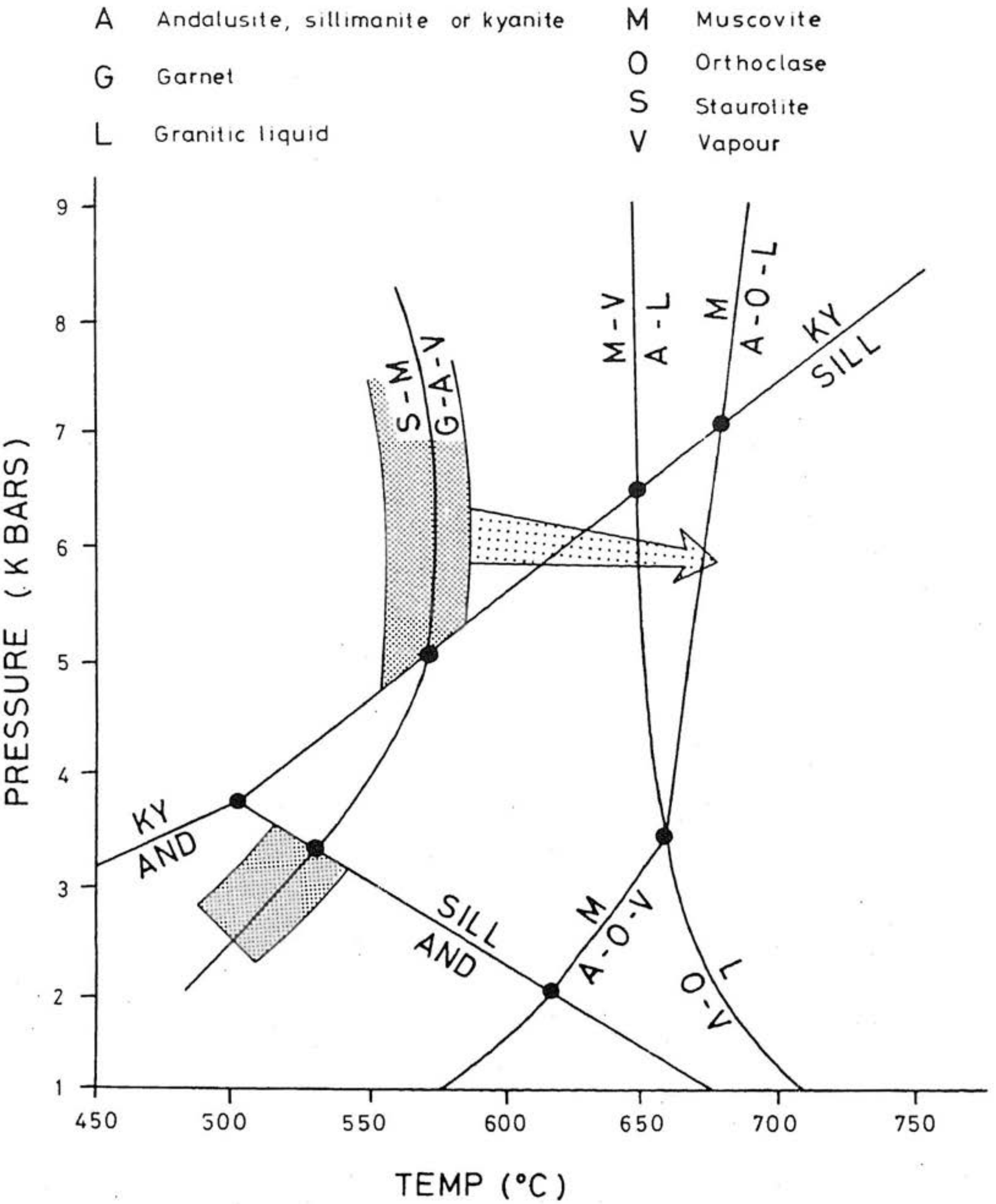

Fig. 3. Pressure-temperature petrogenetic diagram for pelites in the Karakoram metamorphic series. The arrow indicates the inferred sequence of reactions over c. 5 km as one approaches the Karakoram batholith at Paiyu on the Braldu River (see Fig. 1).

part, north and east of Askole and along the Biafo glacier. Deformation in the migmatites is totally ductile with early veins ptygmatically folded with the schistosity and later veins cross-cutting the early structures.

North of the batholith low-grade metamorphic rocks occur along the northern margin of the Baltoro glacier from Biange to Concordia. The fabric in these rocks is not distinct from the fabric south of the batholith. In the Broad Peak area east of Concordia NW–SE lineations are sub-horizontal. We propose that these lineations are related to the Karakoram strike-slip which shows at least 150 km of dextral shear along a NW–SE direction (Molnar and Tapponnier, 1978; Ni and York, 1978). The Karakoram fault along the northern side of the Karakoram Range is one of the largest strike-slip faults of Central Asia and has been related to the indentation of a northward projecting promontary of Indian crust (the Nanga Parbat wedge) to the west (Coward, 1983). The northward trace of the Karakoram fault extends to the northern side of Broad Peak and K2 in Chinese Xinkiang.

SUMMARY

1. The Karakoram batholith is a composite intrusion of probable late Cretaceous-Tertiary age. The Baltoro plutonic units within the batholith are made up of compositions ranging from biotite granodiorite to two mica-garnet leucogranite. There are no mafic compositions, no mafic dykes and no volcanic components.

2. Both northern and southern contacts of the batholith are intrusive. The northern contact aurole on Mitre peak shows a HT/LP metamorphic imprint (sillimanite and andalusite hornfels) on a black shale-limestone sequence in the north. A maximum depth of formation of 12.5 km (c. 3.75 kbars) is indicated by the presence of andalusite. The southern margin of the granite intrudes sillimanite-grade gneisses with a mineral assemblages that includes muscovite and granitic melt pods. The P–T conditions of the gneisses (> 550°C, > 5.5 kbars) suggest a minimum depth of formation of 17.5 km. This indicates that at least 5 km of structural relief exists between the deeper, southern contact and the shallower northern contact.

3. A prominent migmatite complex extends along the southern margin of the Baltoro granite in the Masherbrum area. Leucosome material is composed of garnet-two mica leucogranite of similar composition to parts of the batholith and the late stage dyke network that intrudes the metamorphic series to the south.

4. Metamorphic isograds show normal upward-decreasing P–T conditions and are not inverted as they appear to be along the Hunza Valley.

5. Regional metamorphism is probably roughly contemporaneous with generation of the Baltoro granite, and does not post-date the batholith. The

Karakoram granite along the Baltoro glacier is relatively undeformed, unlike the southern part of the Hunza Valley section.

6. The second phase of deformation in the metamorphic series is dominated by progressive ductile shearing showing consistent south or southwest directed thrusting. Finite stretching lineations are oblique to the regional trend of the MKT but can be regarded as the result of a combination of early ductile southwest-directed thrusting and simultaneous or later vertical right-lateral (dextral) shear aligned NNW–SSE.

7. The MKT is a major late-stage breakback (out-of-sequence) thrust that places sillimanite and kyanite grade rocks along its hangingwall over low-grade greenschist or unmetamorphosed sediments and volcanics of the Shyok (northern) suture zone. This view is consistent with the very recent K–Ar age dates (Miocene-Pliocene) from the Karakoram belt (D. Rex pers. comm.), and high uplift rates as derived from fission-track data (Zeitler *et al.,* 1982; Zeitler, 1985).

8. Major compositional, structural and metamorphic differences exist between the Baltoro-Biafo glacier region and the Hunza valley suggesting that the Karakoram batholith does not represent a continuous intrusion along strike. The Hunza section shows both I and S–type compositions (Debon *et al.,* 1986) and has more extensive migmatites and pegmatite vein network whereas the Baltoro section shows more uniform S–type compositions. The southern margin of the batholith in Hunza is thrust towards the south and metamorphic isograds in its footwall are apparently inverted (Coward *et al.,* 1986). In the Baltoro and Biafo glacier sections the southern margin is intrusive and the metamorphic isograds are apparently right way-up.

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