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THERMAL MODEL FOR THE BALTORO–MUZTAGH KARAKORAM

M.P. SEARLE

Department of Geology, University of Leicester, Leicester, LE1 7RH, U.K.

ABSTRACT

Following the Eocene (50 Ma.) collision of the Indian and Karakoram plates, crustal thickening and shortening in the Karakoram north of the Neo-Tethyan suture zones resulted in a widespread regional Barrovian metamorphism (M2) south of the Karakoram batholith. Pelitic lithologies are characterised by the assemblage: kyanite-staurolite-biotite-garnet-muscovite-plagioclase-quartz with sillimanite-muscovite and sillimanite-K-feldspar assemblages locally developed. Hornblende and diopside-bearing marbles and garnet-bearing amphibolites are also widespread. The age of this high pressure-high temperature metamorphism is constrained as post-50 Ma. (age of India-Asia collision) and pre-37 Ma. (age of cross–cutting, post-collisional granite plutons).

Intrusion of the 21 Ma. Baltoro batholith comprising compositions ranging from biotite monzogranite to two-mica leucogranite caused a high temperature-low pressure thermal aureole of contact metamorphism in the country rock. Andalusite-bearing hornfels along the northern contact of the batholith indicates maximum pressures of 3.5 kbars (350 MPa). A 75° increase in temperature in kyanite-sillimanite grade gneisses approaching the granite contact along the Baltoro glacier is modelled as the thermal upwarping of pre-36 Ma. Barrovian metamorphic isograds around the 21 Ma. contact aureole isotherms along the margins of the Baltoro batholith. Post-metamorphic folding of the early Barrovian metamorphic isograds is related to thrust culminations along the hanging-wall of the Main Karakoram Thrust — a reactivated breakback thrust along the older Shyok suture zone.

INTRODUCTION

The Karakoram mountains are situated north of the Shyok suture zone (SSZ), the Ladakh-Kohistan arc-batholith and the Indus suture zone (ISZ) in the Baltistan and Ladakh regions. The collision between the Indian plate and the Asian plates (Karakoram and Lhasa blocks) and the closing of Tethys occurred after the Lower Eocene at ca. 50–45 Ma. (Patriat and Achache, 1984; Besse et al., 1984; Searle et al., 1987). Palaeomagnetic data, magnetic anomalies, sedimentological and structural data from the Indus suture zone all point to a 50 Ma. age of collision. Thrust and fold-related crustal shortening and thickening propagated south or southwestwards across the northern continental margin of India following collision. Polyphase

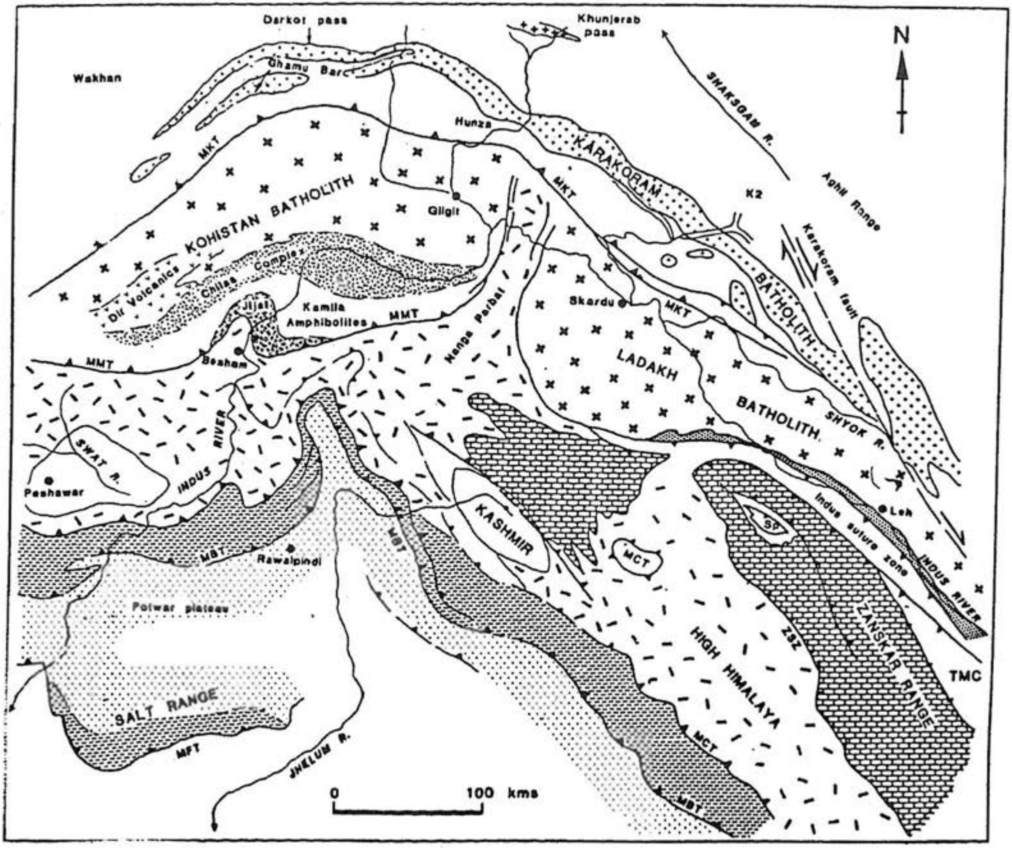

Fig. 1. Geological sketch map of the western Himalaya, Karakoram and Kohistan regions. The Baltoro glacier is shown SW of K2. The Main Karakoram Thrust (MKT) is breakback thrust following the Shyok suture zone. The MMT is the Main Mantle Thrust which carries the Kohistan arc-batholith on its hanging-wall. The MCT is the High Himalayan Main Central Thrust; the ZSZ is the Zanskar Shear Zone; MCT is the Main Central Thrust; MBT Main Boundary Thrust and MFT Main Frontal Thrust.

deformation in the Indus suture zone, Zanskar shelf sediments and High Himalaya to the south has been documented (eg. Searle, 1983, 1986; Searle et al., 1987, 1988). Widespread Barrovian metamorphism, crustal anatexis and intrusion of Miocene anatectic granites (mainly biotite ± muscovite ± tourmaline ± garnet bearing leucogranites) occurred throughout the High Himalaya zone during the Oligocene–Miocene (eg. Le Fort, 1986; Le Fort et al., 1987; Searle and Fryer, 1986).

Following the 50 Ma. collision crustal thickening and regional metamorphism also occurred to the north in the Karakoram at the same time as the main metamorphism in the High Himalaya (Searle et al., 1986, 1988). Crustal melt granites were also formed along the Karakoram, notably the Baltoro plutonic unit at ca. 21 Ma. (Parrish and Tirrul, 1988; Rex et al., 1988), the same time as the High Himalayan leucogranite plutons were formed (see Le Fort et al., 1987 for summary).

This paper describes the metamorphism and deformation of the Karakoram metamorphic complex in the central part of the Karakoram Range, northern Pakistan (Figure 1), and presents a thermal model based on a crustal-scale cross-section. It is based on four field seasons' reconnaissance mapping of the Biafo glacier region (1984, 1988), Baltoro glacier area and Braldu valley (1984, 1985, 1988) and the Hushe valley region (1986), structural, petrological and microprobe data.

METAMORPHISM AND DEFORMATION

The Karakoram metamorphic complex comprises both metasedimentary and meta-igneous units with culminations of deep crustal sillimanite-grade orthogneisses. Metasedimentary associations include both pelites and marbles of the Dumordu unit (Desio, 1964, 1979; Brookfield, 1980; Searle et al., 1986, 1988; Bertrand and Debon, 1986) typically showing at least one tectonic fabric and cut by both ductile and brittle shears. Conglomerate beds and thin orthoquartzite bands both occur within the sequence although about 60% of the rocks are relatively pure marble. The Ganschen unit (Desio, 1964; Searle et al., 1986, 1988) is dominantly mafic amphibolite, and around Askole comprises the typical assemblage : hornblende-biotite-plagioclase-garnet ± quartz ± clinopyroxene ± epidote.

In the central part of the area centred around the Chingkiang valley and upper Aling glacier area (Figure 2) a low-grade metamorphic zone is characterised by the assemblage : biotite-muscovite-chlorite-albite (meta-basalts).

A prominent belt of tectonic melange occurs immediately south of the Karakoram batholith and includes blocks of metamorphosed ultramafic rock. Serpentinised harzburgites and wehrlites contain relic olivine and pyroxene preserved within talc-Mg-chlorite-serpentine (antigorite) ± magnesite assemblages. Searle et al. (1988) also described discontinuous pods of amphibolite-grade metagabbro and basalts with cherts (Panmah unit) indicating that the whole sequence may have once been an ophiolite complex. Original emplacement-related structures related to the metasediments have been totally obliterated by the later post-collision ductile folding and shearing now observed.

Stretching lineations within the Karakoram metamorphic complex are dominantly NNE-SSW and kinematic indicators such as rolled garnet porphyroblasts, C-S fabrics, minor fold facing directions and sense of asymmetry, indicate a SSW sense of shear. The southeasterly plunge of folds and pressure-temperature conditions indicate that deeper structural levels are exposed around the Braldu valley in the western part of the area (Figures 1 and 2) and that higher levels of crust are exposed around the Chingkiang valley and north of the Thalle valley.

Structural culminations of deep crustal rocks, dominantly orthogneiss, are typified by the Dassu felsic gneiss (Searle et al., 1988) consisting mainly of biotite-K-feldspar-plagioclase-quartz-sillimanite-garnet ± muscovite gneisses which are on or above the muscovite breakdown reaction. Partial melt pods and veins of garnet-biotite ± muscovite ± tourmaline leucogranite are present and numerous pegmatite-aplite dykes are rich in tourmaline, topaz, aquamarine and beryl.

Mapping of metamorphic isograds suggests that the isograds related to regional Barrovian metamorphism are right way-up and not inverted as they appear to be along strike in the Hunza valley ca. 150 km. to the west (Broughton et al., 1985; Coward et al., 1986; Rex et al., 1988).

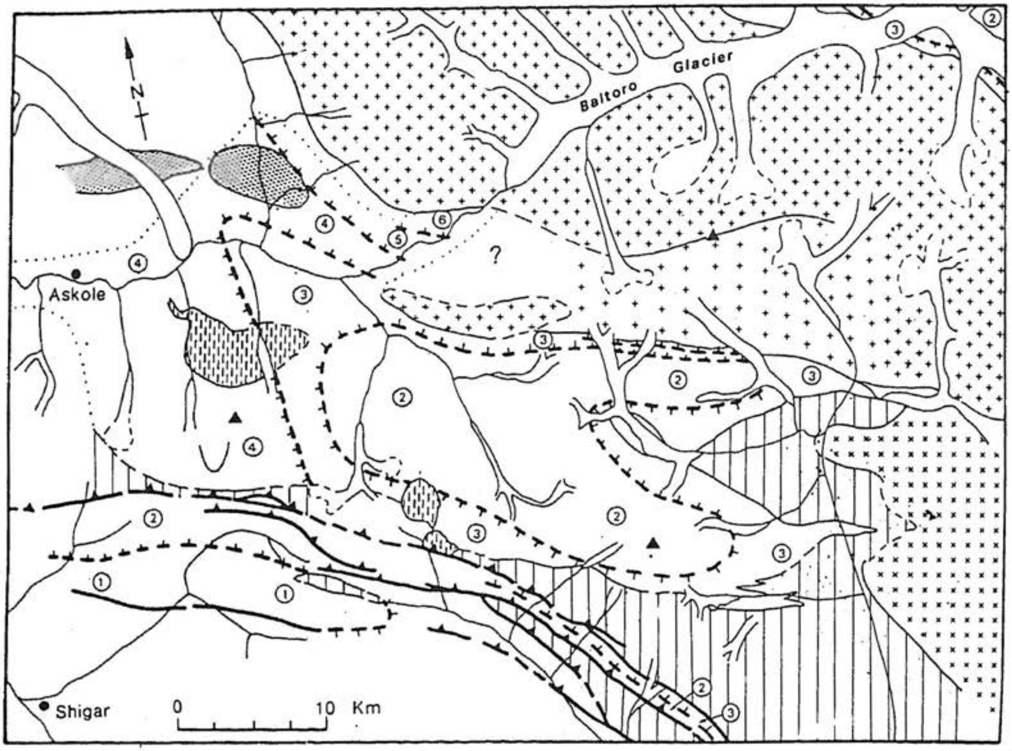

Fig. 2. Map of the Karakoram metamorphic complex south of the Baltoro glacier area showing metamorphic grade. 1 = very low grade, chlorite + white mica. 2 = low grade, Mus. + Chl ± Chlt ± Bi ± Gar. 3 = staurolite grade. 4 = kyanite grade. 5 = sillimanite grade. 6 = sillimanite grade with migmatites. Paiyu is the campsite at the granite contact near the snout of the Baltoro glacier.

BARROVIAN METAMORPHISM

The polyphase nature of metamorphism and deformation in the Karakoram metamorphic complex has already been noted and documented (Bertrand and Debon, 1986; Searle et al., 1986, 1988; Rex et al., 1988). This paper is concerned only with the post-collision metamorphism of the Karakoram. Earlier pre-collision metamorphism is dominantly of low pressure andalusite-bearing facies and is temporally and spatially associated with the Jurassic or lower Cretaceous Hushe gneiss complex (MI on Figure 3).

The main regional Barrovian metamorphism in the Karakoram metamorphic complex is constrained in age as being after India-Asia collision (50 Ma.) and prior to cross-cutting granite plutons notably the Mango Gusar two-mica granite and the Chingkiang-la pluton (36-34 Ma., Searle et al., 1988; Parrish et al., 1988).

Mapping along the Braldu gorge between Dassu, Askole and the granite contact at Paiyu, as well as along several side valleys shows that high-grade assemblages are present between the Main Karakoram Thrust and the Baltoro plutonic unit in this area. A prograde reaction series can be deduced from the replacement of staurolite by kyanite (M2a on Figure 3)

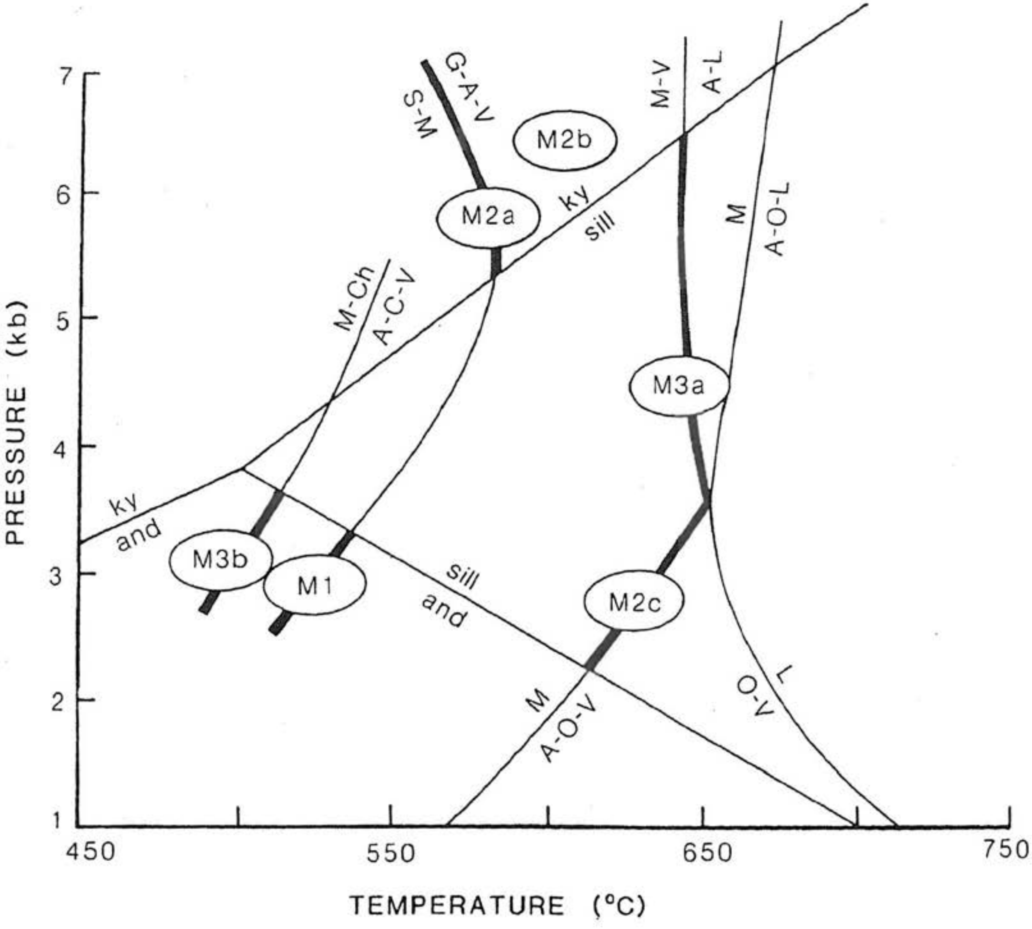

Fig. 3. Pressure–temperature grid showing key metamorphic assemblages and reactions in the Baltoro area (from Searle et al., 1986, 1988). All assemblages contain biotite and quartz. A — Andalusite, kyanite or sillimanite, C — Cordierite, Ch — chlorite, G — garnet, L — granitic liquid, m — muscovite, O — orthoclase, S — staurolite, V — vapour. See text for explanation of reactions.

and the appearance of sillimanite. Kyanite-staurolite-garnet-biotite-muscovite-plagioclase-quartz assemblages are replaced by kyanite-biotite-garnet assemblages (M2b, Figure 3) and sillimanite-biotite-garent assemblages. These rocks indicate pressures of formation between 5-6 kbar and temperatures around 550-650°C.

Around Chakpo in the Braldu valley, west of Askole, the assemblage sillimanite-garnet-muscovite-biotite-plagioclase-quartz is present. The muscovite-out reaction (M2c on Figure 3) can be demonstrated by the replacement of muscovite by sillimanite-K-feldspar without partial melting. This reaction occurred at high temperatures (620-650°C) but relatively low pressures (less than 3.5 kbar).

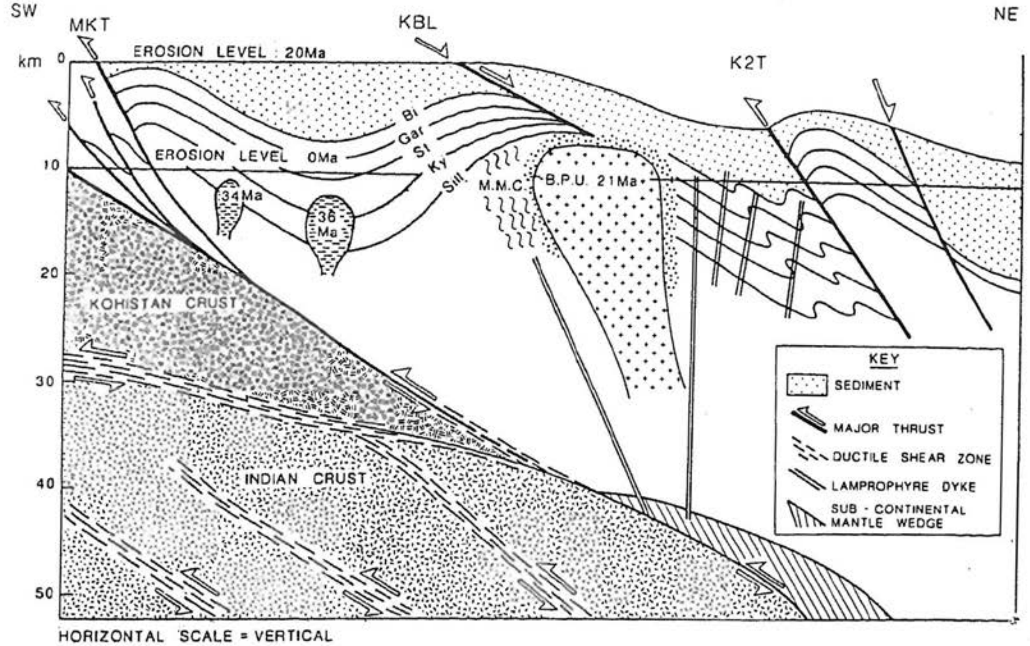

Figure 4. Thermal model for the Baltoro Karakoram at 20 Ma. based on a scale cross-section. M2 metamorphic isograds are folded on the hangingwall of the Main Karakoram Thurst (MKT) and telescoped along the normal fault of the Karakoram batholith lineament (KBL). The M2 isograds are thermally upwarped by the M3 isotherms surrounding the 21 Ma. Baltoro plutonic unit (BPU). The M2 isograds are cut by the 36–34 Ma. post-metamorphic granite plutons of Mango Gusar and Chingkiang–la. The model assumes ca. 10 km. of erosion since 20 Ma. Major ductile shear zones bound Kohistan, Indian and Karakoram crustal blocks. See text for discussion.

The Mango Gusar two-mica granite pluton cross-cuts syn-metamorphic foliation in the surrounding Dumordu and Ganschen units, and has a U-Pb zircon age of 37 Ma. (Parrish et al., 1988) and constrains the age of metamorphism and deformation as being pre-37 Ma. (i.e. middle and late Eocene).

CONTACT METAMORPHISM

The Baltoro granite ranges in composition from biotite monzogranite to garnet two-mica leucogranite and forms a major post-collision plutonic unit of batholithic dimensions, at least 100 km. long and 10—20 km. wide (Desio and Zanettin 1970; Searle et al., 1986, 1988; Rex et al., 1988). Samples from near Urdukas on the Baltoro glacier have a U-Pb zircon age of 21 ± 0.5 Ma. and monazite ages of 19.0—17.1 Ma. (Parrish and Tirrul, 1989). The Baltoro granite has intrusive contacts along both its north and south margins, and thermal metamorphism (M3) along a marginal contact metamorphic aureole is well developed.

The northern margin in the region of Mitre peak and the Vigne glacier shows that the granite was intruded into a dominantly sedimentary (Carboniferous black slates with minor limestones) or low-grade metamorphic terrane (Doksam sequence). Along the Vigne-Baltoro glaciers, the assemblage andalusite-cordierite-biotite-muscovite-chlorite-plagioclcase-quartz is present and indicates pressures of less than 3.5 kbar (M3b on Figure 3). Adjacent to the granite contact small knots of fibrolite and biotite replace cordierite and muscovite.

The southern margin of the Baltoro granite at Paiyu shows an intrusive contact into vertically foliated gneisses which have an assemblage: garnet-biotite-muscovite-quartz-plagioclase-sillimanite and granitic melt pods. The successive disappearance of staurolite, then kyanite, and the appearance of sillimanite and granite melt pods as one approaches the batholith from Bardumal to Paiyu (Figure 2) indicates an increase of temperature of approximately 75°C. Although this temperature increase approaching the Baltoro granite might be coincidental and part of regional Barrovian M2 metamorphism, it seems more likely that this temperature increase is a thermal effect of granite emplacement and thus part of M3 contact metamorphism.

DISCUSSION

Figure 4 is a thermal model for the Baltoro-Muztagh Karakoram, based on a crustal-scale cross-section of the area shown in Figures 1 and 2. The Main Karakoram Thrust (MKT) is a major late Tertiary breakback thrust following roughly the Shyok suture zone. Several splays of the MKT have been mapped between the Shigar and Thalle valleys (Figure 1) but essentially the thrust separates rocks of the Karakoram plate to the north from rocks of the Shyok suture zone and Ladakh-Kohistan arc-batholith to the south. Kohistan and Indian plate crust are shown schematically separated by major ductile shear zones and underplating the Karakoram (Coward et al., 1986, 1987; Rex et al., 1988; Searle et al., 1988).

Barrovian metamorphic isograds of M2 Eocene time are shown folded on the hanging-wall of the MKT, as deduced from isograd mapping (Figure 2). The isograds are cut by the 37 Ma. Mango Gusar two-mica granite pluton. The M2 isograds are uplifted and offset by the MKT culmination. They are also structurally telescoped along the Karakoram Batholith Lineament (KBL) — a normal fault downthrowing to the north along the line of the Baltoro granite. The KBL was postulated by Searle et al. (1988) and Rex et al. (1988) to account for the differences in P-T conditions of the rocks either side of the Baltoro granite and to provide an extensional stress regime in the upper crust to accommodate intrusion of the undeformed Baltoro granite pluton. It is regarded as a culmination collapse normal fault synchronous in time with crustal thickening and thrust deformation in the middle and lower crust, which developed in a similar environment to the massive normal fault bounding the north side of the High Himalaya zone in Zanskar (Searle, 1986; Herren, 1987; Searle et al., 1988) and Tibet (Burg et al., 1984; Burchfield and Royden, 1985).

The geometry of isograds on the Baltoro cross-section can be interpreted as the thermal upwarping of pre 37 Ma. isograds around 21 Ma. M3 aureole isotherms along the margin of the Baltoro granite. Figure 4 shows the approximate present day erosion level and assumes approximately 10 km. of erosion since 20 Ma. Uplift and erosion rates are likely to be significantly different in each tectonic belt across the Karakoram. Further breakback thrusts are postulated south-west of K2 and Broad Peak as culminations of mid-crustal gneisses are present along the K2-Falchan Kangri Range with concomitant normal faulting downthrowing the sediments of the Aghil Range to the northeast.

The validity of the thermal model presented here will be tested in the future by more precise estimates of pressure, temperature and palaeodepth from geothermobarometry of the Karakoram metamorphic complex.

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