Journal of the Geological Society, *London*, Vol. **164**, 2007, pp. 439–450. Printed in Great Britain.

Relationships between right-lateral shear along the Karakoram fault and metamorphism, magmatism, exhumation and uplift: evidence from the K2–Gasherbrum–Pangong ranges, north Pakistan and Ladakh

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Abstract: The Karakoram fault is a major NW–SE-aligned dextral strike-slip fault that has accommodated minor extrusion of thickened Tibetan crust since the Mid-Miocene. Controversy exists as to whether the fault is lithospheric in scale, resulting in synkinematic metamorphism and granite melting, or whether it is an upper crustal fault cutting through earlier metamorphic and granitic rocks. Structural, metamorphic and geochronological data from the Karakoram fault show that: (1) metamorphism and granite genesis occurred prior to strike-slip shearing, meaning that U–Pb zircon and monazite ages from deformed granites cannot be used as proxies for dating strike-slip shearing, only as a maximum age constraint on initiation of ductile shearing; (2) sheared Miocene leucogranites along the fault are equivalent to the Baltoro granite batholith, offset 40–150 km along the fault, and show a strain gradient from high ductile strain to undeformed away from the fault; (3) $^{40}Ar/^{39}Ar$ and fission-track ages of K2 orthogneisses and Gasherbrum diorite show that rocks adjacent to the fault cooled during Cretaceous to mid-Tertiary time, and were not reset during shearing, indicating that shear heating was not important; (4) the Gasherbrum diorite, adjacent to the fault, has never been at depths greater than 6 km since the early Cretaceous and less than 3 km of material has been eroded off since then. We conclude that the Karakoram fault has had no significant influence on regional metamorphism or melting, at least at levels exposed today, and is restricted to the upper–middle crust.

The Karakoram fault is a large-scale right-lateral strike-slip fault that extends at least 750 km from the Pamirs in the NW to the Kailas region of SW Tibet in the SE, where it merges with the Indus–Tsangpo suture zone, the zone of collision between the Indian and Asian plates around 50 Ma ago (Fig. 1). The Karakoram fault has been widely cited as one of the main faults bounding the extruding Tibetan crust in the continental escape model (Molnar & Tapponnier 1975; Tapponnier *et al*. 1982, 1986, 2001; Peltzer & Tapponnier 1988; Lacassin *et al*. 2004*a*,*b*). There is controversy regarding the depth, finite geological offsets, age of initiation, and slip rates of Tibetan strike-slip faults in general, and the Karakoram fault in particular.

The first school of thought (Model 1) regards the Karakoram fault as being lithospheric in scale controlling between several hundred and 1000 km of dextral offset, resulting in the large-scale eastward extrusion of the thickened crust of Tibet (e.g. Tapponnier *et al*. 1982, 1986, 2001; Peltzer & Tapponnier 1988; Armijo *et al*. 1989; Meyer *et al*. 1996; Lacassin *et al*. 2004*a*,*b*). The second school of thought (Model 2) regards the Karakoram fault as being purely upper–middle crustal, with much lower offset and lower slip rate (Searle 1996; Searle *et al*. 1998; Murphy *et al*. 2000; Phillips *et al*. 2004; Searle & Phillips 2004). In this model minimum–maximum dextral offsets are 40–150 km, respectively and long-term slip rates are between 2.7 and 10.2 mm Ma^{-1}. U–Pb zircon and monazite ages of undeformed Baltoro granites that crystallized before initiation of the dextral strike-slip fault span 25–15 Ma. Ductile shearing is constrained as occurring between 15.68 ± 0.3 and 13.73 ± 0.5 Ma from U–Pb ages of sheared leucogranites containing strong dextral C–S fabrics and cross-cutting unsheared leucogranite dykes (Phillips *et al*. 2004). Mylonites within the Karakoram fault shear zone cooled through the ductile–brittle transition between 17 and 13 Ma (Dunlap *et al*. 1998).

The key points of disagreement between the two models are the correlation of offset geological features, and the relationship of the deformation fabrics in the granites within the dextral strike-slip shear zone. This paper examines the geological and geochronological evidence for timing of initiation and amounts of offset along the fault. First, we summarize the major points of each model. Second, we describe the geological and geochronological data from the Pangong range of northern Ladakh (India) and the K2–Gasherbrum range in north Pakistan, where we have carried out detailed mapping, structural analysis, U–Pb and Ar–Ar geochronology (Searle *et al*. 1989, 1990, 1998; Searle 1991, 1996; Dunlap *et al*. 1998; Phillips 2004; Phillips *et al*. 2004). Finally, we conclude that Model 2 is the most viable model that explains the geological evolution of the Karakoram fault.

Model 1: lithospheric-scale fault, large offsets and slip rates

Proponents of Model 1 have proposed large-scale dextral offsets along the Karakoram fault of 1000 km (Peltzer & Tapponnier 1988) and >250 km (Lacassin *et al*. 2004*a*,*b*). These finite offsets were used in conjunction with offset Quaternary features, some of which were dated using cosmogenic isotopes, to obtain slip rates of 10.7 ± 0.7 mm a^{-1} (Chevalier *et al*. 2005), 10 ± 3 mm a^{-1} (Lacassin *et al*. 2004*a*) and up to 32 ± 8 mm a^{-1} (Avouac & Tapponnier 1993). Peltzer & Tapponnier (1988) proposed offsets of 1000 km based on matching granites in the Pamirs to the Gangdese granites of south Tibet, a correlation that

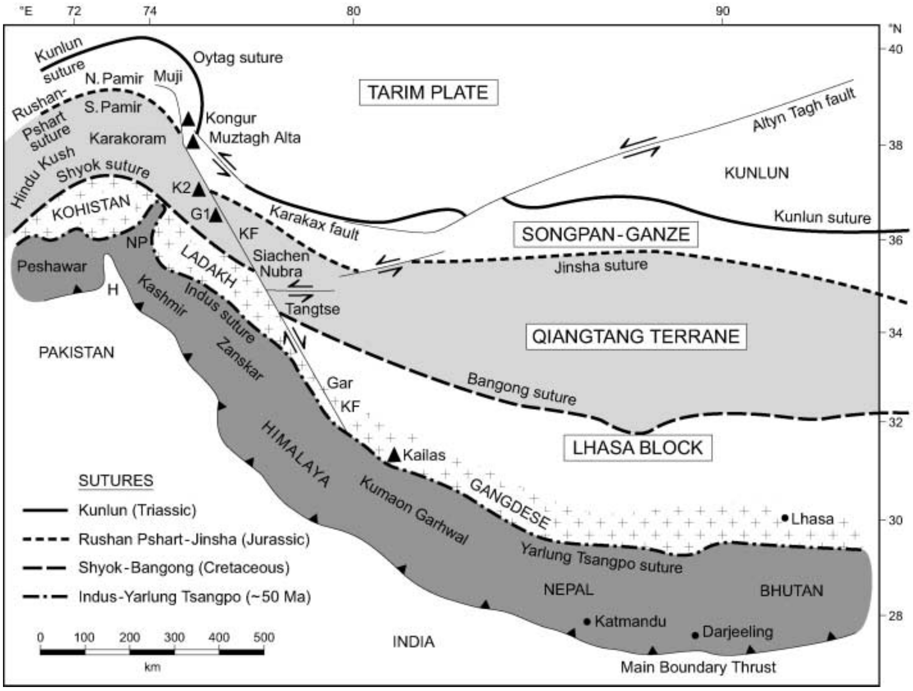


Fig. 1. Terrane map of central Asia showing major suture zones (thick lines) and their correlation across the Karakoram fault (KF).

has since been disproved (Searle 1996; Searle *et al*. 1998). Lacassin *et al*. (2004*a*,*b*) later obtained offsets of 250–300 km based on matching the Bangong suture in Tibet to the Rushan–Pshart suture in the northern Pamir. This correlation is also probably incorrect because, whereas the Bangong suture closed during the late Cretaceous (Kapp *et al*. 2003) the Rushan–Pshart suture has a Palaeozoic history culminating with unconformable deposition of Late Carboniferous–early Permian sediments (Burtman & Molnar 1993).

Proponents of Model 1 also relate the formation and intrusion of granites in the shear zone to shear heating during slip motion. If this were the case, then U–Pb ages of the granites would date the timing of active shearing. Lacassin *et al*. (2004*a*,*b*) regarded all the granites at Zhaxikang in SW Tibet as synkinematic, and therefore proposed that the Karakoram fault was active prior to 23 Ma, possibly even earlier (>34 Ma), the oldest U–Pb age of leucogranites within the shear zone. In both the Tangtse granites in Ladakh (Searle *et al*. 1998; Phillips *et al*. 2004) and the Zhaxikang region of SW Tibet (Lacassin *et al*. 2004*a*,*b*) field relationships show similar fabric development. Although Lacassin *et al*. (2004*a*,*b*) proposed that the sheared granites are synkinematic, there is no evidence for the coexistence of intrusive leucogranites with *in situ* partial melts. If these granites were formed by shear heating along the fault, they should be restricted to the fault zone and not occur outside the ductile shear zone. In Ladakh it is clear that the Tangtse granites and the Muglib granites (Fig. 2) are truncated abruptly by the later fault and exhibit a strain gradient dying out away from the strike-slip fault (Searle *et al*. 1998; Weinberg & Searle 1998; Phillips *et al*. 2004).

Model 2: upper–mid-crustal fault, lower slip rates

Proponents of Model 2 propose that the Karakoram fault cuts earlier formed metamorphic rocks and granites, that finite geological offsets are between 40 and 150 km with low slip rates between 2.7 and 10.2 mm a^{-1}, and that the fault is probably an upper and mid-crustal fault (Searle 1996; Searle *et al*. 1998; Phillips *et al*. 2004). In this context the upper crust is arbitrarily defined as the seismogenic layer above the 300 °C isotherm and the onset of quartz plasticity. Likewise, the middle crust is arbitrarily defined as the layer beneath this, in which mylonites deform by plastic flow and aseismic creep but feldspars may retain rigidity up to about 450 °C (Imber *et al*. 2001). Temperatures in the lower crust should be sufficiently high that the rocks would flow laterally rather than be cut by the fault, although water content and metamorphic conditions obviously are important factors as well as simple lithostatic pressure.

Searle (1996), Searle *et al*. (1998) and Phillips *et al*. (2004) matched the mid–late Cretaceous Shyok suture zone in Ladakh and Pakistan to the Bangong suture zone in Tibet (Kapp *et al*. 2003) and linked the Tangste–Muglib type leucogranites in Ladakh to the Baltoro granites in north Pakistan (Searle *et al*. 1992) across the fault. In SW Tibet mapping has shown that the Karakoram fault offsets the *c*. 13 Ma South Kailas thrust by *c*. 66 km (Murphy *et al*. 2000). In this model, the Kohistan–Ladakh terrane is correlated with the Lhasa block of south Tibet, a correlation supported by the geochemical and geochronological equivalence of the Kohistan, Ladakh and Gangdese granite batholiths (102–50 Ma). Several workers have correlated the Bangong (and Shiquanhe) sutures to the Shyok suture, on the basis of mapping and geochronology (Matte *et al*. 1996; Searle 1996; Dunlap & Wysoczanski 2002). The Karakoram terrane is the offset equivalent of the Qiangtang terrane, north of the Shyok–Bangong–Nujiang suture zone (Fig. 1).

Proponents of Model 2 propose that the granites along the Karakoram fault zone formed prior to motion along the fault and that shear fabrics were superimposed later. In this case the U–Pb ages of the granites give a maximum age of initiation of the ductile shear along the fault. Phillips *et al*. (2004) bracketed the age of ductile shearing as between 15.68 ± 0.52 Ma and 13.73 ± 0.28 Ma, the U–Pb ages of the older foliation-parallel

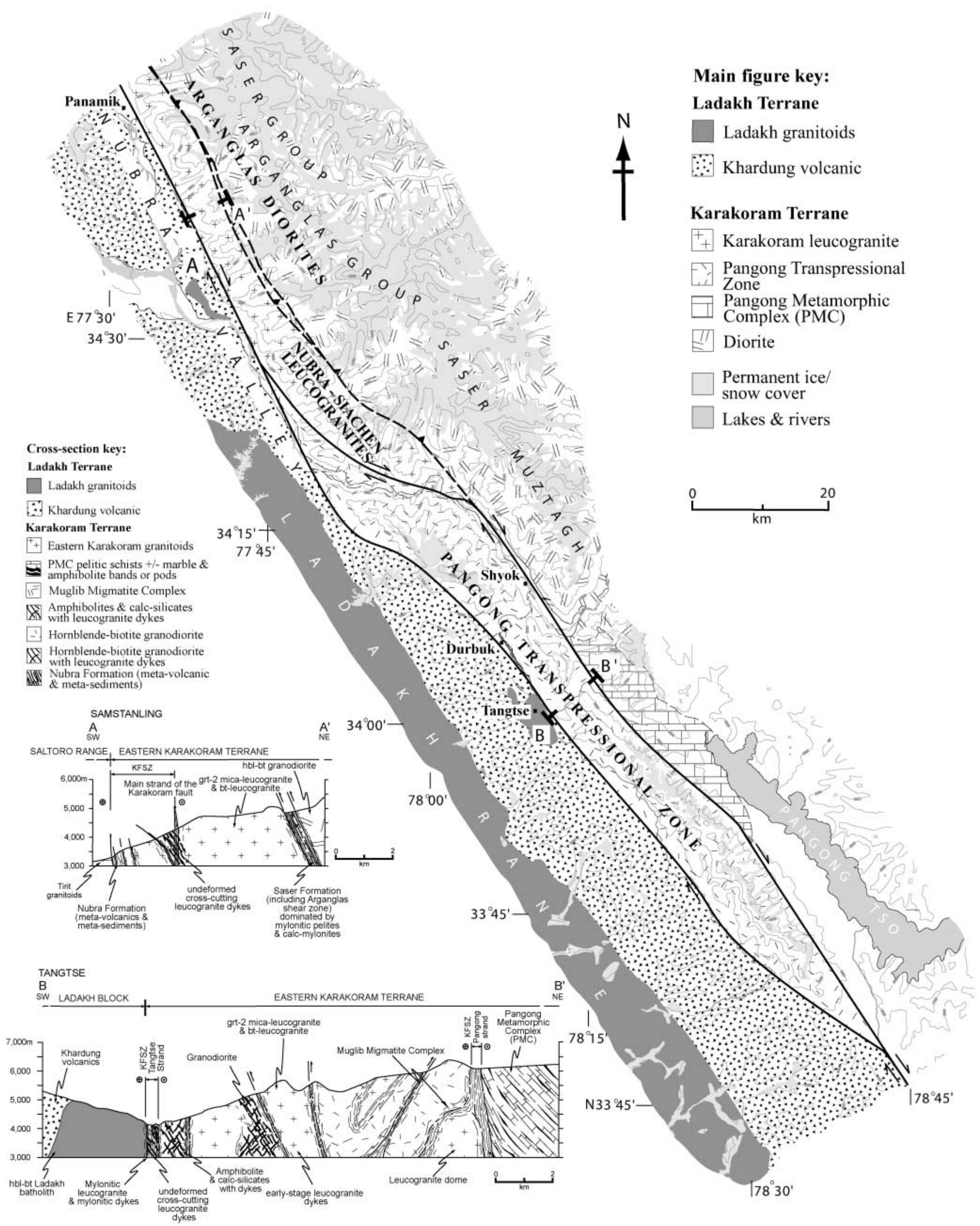


Fig. 2. Geological map of the Karakoram fault zone in northern Ladakh and two cross-sections across the fault zone, after Phillips (2004) and Phillips *et al*. (2004).

granite sills and the later cross-cutting undeformed granite dykes. All the granites are cut by the later brittle strike-slip fault and the granites show a decrease in strain away from the fault (Searle *et al*. 1998; Weinberg & Searle 1998; Phillips *et al*. 2004).

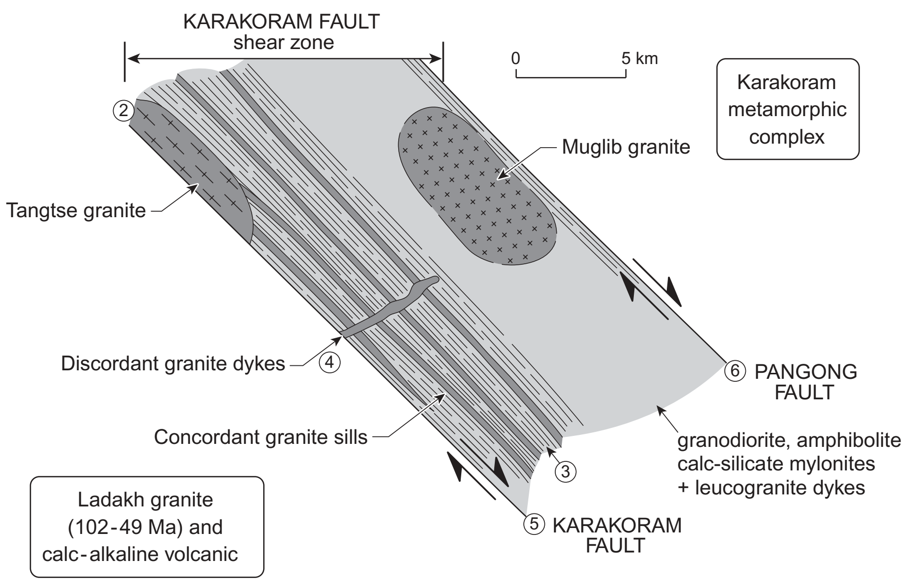
We now discuss the three critical areas where deep crustal metamorphic and granitic rocks are exposed along the Karakoram fault zone: the Pangong range in northern Ladakh, India, and the K2–Gasherbrum ranges in north Pakistan.

Pangong range

The Karakoram fault follows the Shaksgam valley NE of K2 and the Siachen glacier southeastward into the Nubra–Tangtse–Pangong region of northern Ladakh, NW India (Fig. 2). Here, a major splay branches off to the north, termed the Pangong fault, which cuts entirely through Karakoram terrane rocks, and has evidence of Quaternary slip (Brown *et al*. 2002). The main Karakoram fault separates Late Cretaceous–Palaeocene Ladakh hornblende- and biotite-bearing diorites, granodiorites and granites and the Khardung volcanic sequence including calc-alkaline andesites, dacites and rhyolites to the SW from Karakoram terrane metamorphic rocks, migmatites and crustal melt granites to the NE.

The geology and U–Pb geochronology of the Ladakh sector of the Karakoram fault has been described previously by Searle *et al*. (1998), Weinberg *et al*. (2000) and Phillips *et al*. (2004). Figure 3 is a summary diagram of the structural relationships and age data from the Tangtse region. Between the main Karakoram fault and the Pangong fault, exhumed middle or deep crustal gneisses and granites are exposed. K-feldspar + hornblende + biotite orthogneisses, amphibolites and calc-silicates are equivalents of the Karakoram metamorphic complex (Searle & Tirrul 1991). These rocks have been intruded by a network of leucogranite dykes and sills and are partially mylonitized and deformed. At least three sets of leucogranite intrusions have been mapped: an early set 1 series of foliation-parallel sills that are deformed and contain a mylonite fabric; a later set 2 series of leucogranite dykes that cross-cut the ductile mylonites and set 1 sills, but are themselves cut by the brittle strike-slip bounding the ductile shear zone; and larger plutons of leucogranite, such as the Tangtse or Muglib plutons (Searle *et al*. 1998; Weinberg & Searle 1998; Phillips 2004; Phillips *et al*. 2004), which are also cut by both faults.

Geochemistry, isotope chemistry and U–Pb ages of the leucogranites at Tangtse and Muglib show that they are equiva-



Age (Ma)		Chronology	Reference
<11-14 ka	6	Active strike - Slip faulting Pangong fault	Brown *et al.* 2002
		Pseudotachylytes - palaeo-earthquake melts	
8-7		Cooling of mylonite $^{40}Ar/^{39}Ar$ 350°C isotherm	Dunlap *et al.* 1998
	5	Brittle strike-slip faulting	
13.73±0.28	4	Crystallisation of discordant sills U-Pb ID-TIMS	Phillips *et al.* 2004
	3	Ductile mylonite fabric	
15.55±0.74	2	Crystallisation of Tangtse granite and concordant sills U-Pb ID-TIMS	Phillips *et al.* 2004
21-15	1	Main Intrusion of Baltoro granites (K7, Masherbrum, Trango) U-Pb ID-TIMS	Thow 2004; Searle *et al.* 1992; Parrish & Tirrul 1989

Fig. 3. Summary of the structural relationships at Tangtse on the Karakoram fault with U–Pb geochronological constraints.

lent granites to the younger granites in the Baltoro batholith (Fig. 4; Searle *et al*. 1992; Phillips 2004; Phillips *et al*. 2004; Thow 2004). U–Pb crystallization ages span 25–15 Ma along the Baltoro batholith in Pakistan and 22–14 Ma in Tangtse–Muglib. The steeper cooling curve in Tangtse–Muglib granites can be attributed to a phase of rapid transpressional exhumation and cooling concomitant with initiation of dextral shear along the Karakoram fault, whereas the more steady-state cooling of the undeformed Baltoro granites in Pakistan results from their being far removed from the fault. Offsets along the Karakoram fault are >40 km and <150 km since *c*. 15 Ma and corresponding long-term slip rates are between 2.7 and 10.2 mm a^{-1} (Phillips *et al*. 2004).

K2 gneiss

The mountains of K2 (8611 m), Broad Peak (8047 m), the Gasherbrum peaks (8068 m), Sia Kangri (7422 m) and the Saltoro Kangri (7742 m)–K12 (7428 m) range along the Pakistan–China border form a line of 7–8 km high mountains at least 80 km long that parallels the southwestern margin of the Karakoram fault (Fig. 5). Another line of 7 km high mountains along the Teram Kangri (7464 m)–Apsarasas (7245 m) range follows the southern margin of the Shaksgam fault, a prominent splay of the Karakoram fault, for over 50 km towards the east (Fig. 5). Regional mapping of this extreme terrain, as far as possible, has been accomplished by Desio (1980), Desio *et al*. (1991) and Searle (1991). The geology of the upper Baltoro glacier and K2 region is shown in Figure 6.

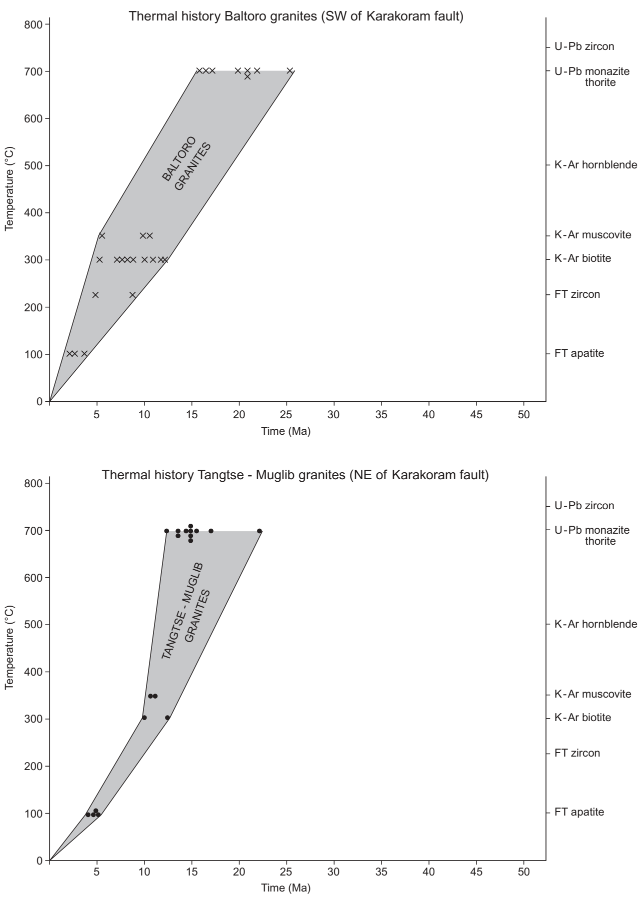


Fig. 4. Temperature–time diagrams summarizing all the geochronological data for the Baltoro granites in north Pakistan (west and SW of the fault) and the Eastern Karakoram granites in Ladakh (NE of the fault). Age data for Baltoro rocks are from Parrish & Tirrul (1989), Searle *et al*. (1989, 1990), Schärer *et al*. (1990) and Krol *et al*. (1996); age data for Tangtse are from Dunlap *et al*. (1998), Searle *et al*. (1998) and Phillips *et al*. (2004). FT, fission track.

Whereas K2 is composed mainly of orthogneisses and paragneisses intruded by a suite of garnet + tourmaline + muscovite + biotite leucogranites (Fig. 7), the Gasherbrum range (Fig. 8) is composed largely of Permian massive shelf facies limestones (Shaksgam Fm), Urdok conglomerates and Triassic–Lower Jurassic massive limestones (Aghil Fm). A prominent zone of granodiorite, quartz diorite and amphibolite (Sughet granodiorite) has been mapped north of K2 (Desio *et al*. 1991), and these rocks may link west to the pre-collisional Cretaceous Hunza granodiorites (Crawford & Searle 1992). These rocks are similar to the K2 orthogneisses (Searle *et al*. 1990; Searle 1991) and are interbedded with paragneisses including marble and pelite, and intruded by leucogranitic dykes. The Karakoram fault cuts obliquely across these metamorphic and sedimentary rocks and is well exposed along the upper reaches of the Shaksgam valley in southernmost Xinjiang (Fig. 9).

North of K2, from Sughet Jangal (K2 base camp on North Ridge route) to the Aghil pass, several splays of the Karakoram fault offset the Permian–Triassic limestones (Desio 1980; Desio *et al*. 1991). These faults have a significant throw down to the NE as well as a minor amount of dextral strike-slip motion. The Karakoram fault actually cuts across the northerly flowing Broad Peak north, Gasherbrum north and Urdok glaciers and clearly affects the topography (Fig. 5). From the India–Pakistan ceasefire line the Karakoram fault cuts across the mountains at the head of the Siachen glacier and then follows the south bank of the Siachen, SE to the Nubra valley in northern Ladakh. NE of the Karakoram fault in the Siachen glacier–Nubra valley region, the batholith is composed of biotite + muscovite + garnet leucogranite (Nubra–Siachen leucogranites), correlated with the Baltoro leucogranite, and the Arganglas hornblende–biotite diorites, correlated with the K2–Sughet orthogneiss.

A sample of biotite + hornblende + K-feldspar orthogneiss from the south face of K2 gave a U–Pb zircon age of 115–120 Ma and $^{40}Ar/^{39}Ar$ hornblende cooling ages of 111 ± 3 Ma and 90.6 ± 1.8 Ma (Searle *et al*. 1989, 1990; Searle 1991). Mica separates from the leucogranite dykes that cut the K2 orthogneiss gave K–Ar cooling ages ranging from 70 to 58 Ma (Searle *et al*. 1989) indicating that the K2 massif had already cooled well below 300 °C before crystallization of the massive Baltoro monzogranite–leucogranite batholith (*c*. 25–15 Ma; Parrish & Tirrul 1989; Searle *et al*. 1992; Thow 2004) and well before initiation of the Karakoram strike-slip fault. Rapid Pliocene denudation of the upper *c*. 6 km of K2 is shown by fission-track dating of apatites and zircon. One zircon separate from 6600 m altitude gave an age of 32 ± 6 Ma and apatites from 5300–8611 m altitude gave ages of 2.1 ± 0.6 Ma to 4.3 ± 1.4 Ma (Foster *et al*. 1994). Only the last *c*. 3.7 km of denudation since 4.3 Ma could possibly be related to transpressional uplift along the Karakoram fault; the entire cooling history from 120 Ma to at least 32 Ma relates to regional uplift–erosion–exhumation processes prior to, and unconnected with, strike-slip shear along the Karakoram fault.

Gasherbrum diorite

The Gasherbrum diorite intrudes massive limestones of the Permo-Triassic Shaksgam and Aghil Formations north of the

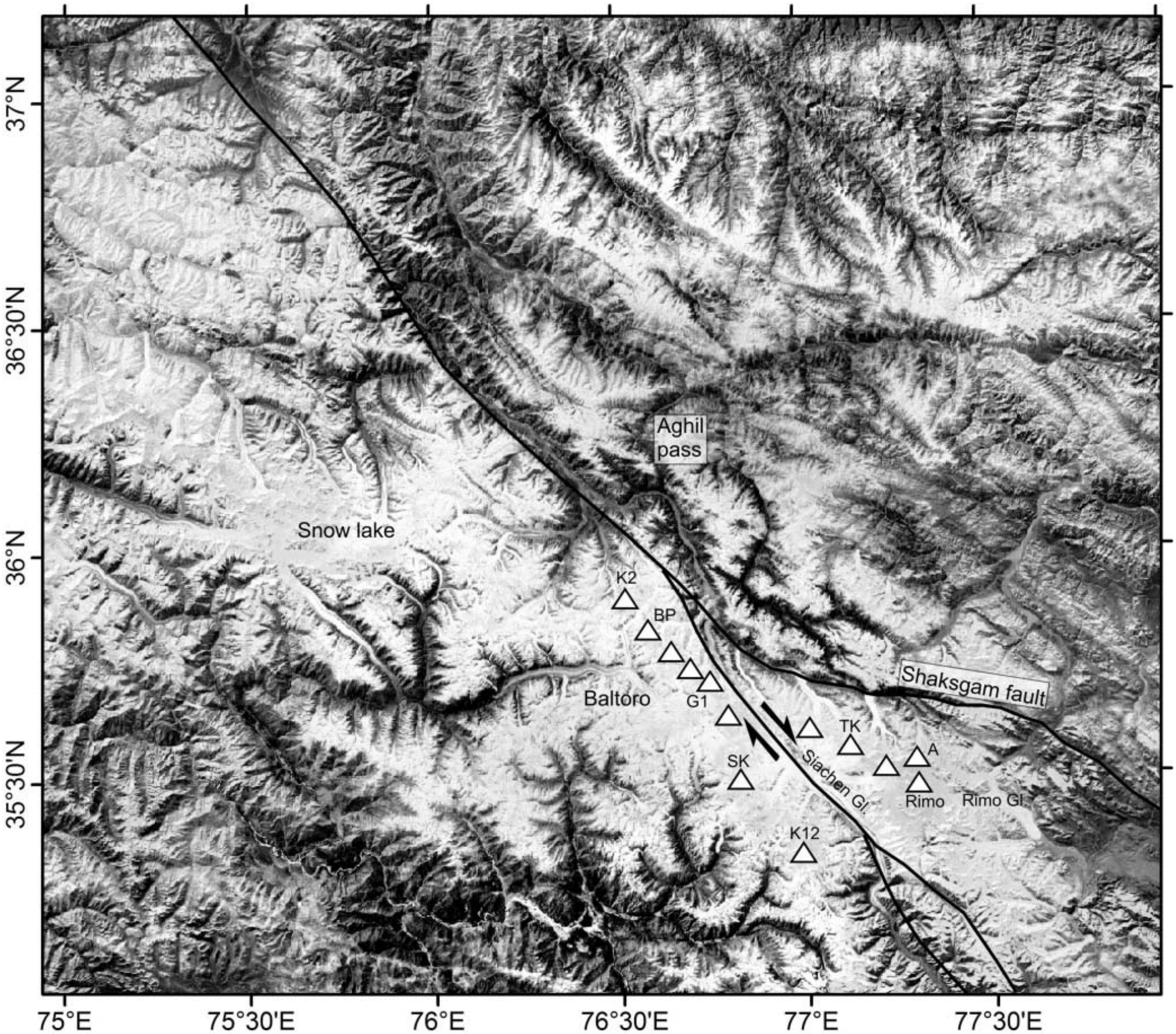


Fig. 5. Landsat photo of the K2–Gasherbrum ranges, showing the trace of the Karakoram fault, and a major splay, the Shaksgam fault. Triangles are some of the main peaks above 7000 m altitude. BP, Broad Peak; TK, Teram Kangri peaks; SK, Saltoro Kangri; A, Apsarasas peaks.

Baltoro granite batholith (Searle 1991). The intrusive contact is mostly vertical and extends right up to the summit of Gasherbrum IV (7925 m). Fission-track zircon ages from diorite samples collected between 4900 and 7150 m elevation gave ages ranging from 125 to 31.4 Ma (Cerveny *et al*. 1989). Annealing of fission tracks is a time- and temperature-dependent process. Apatite loses all of its fission tracks (total annealing) at temperatures of *c*. 105 °C, whereas fission tracks in zircon completely anneal at about 225 °C. There is no consistent pattern between age and elevation in the Gasherbrum IV samples, whereas normally one should expect an increase in age with increased elevation. The Cretaceous zircon fission-track age indicates that these rocks were never deeply buried (zircon annealing temperatures of *c*. 175–225 °C) since 125 Ma.

Whereas the Baltoro granite batholith and southern Karakoram underwent extensive crustal thickening, metamorphism and melting throughout the Cenozoic (Searle & Tirrul 1991; Searle *et al*. 1992; Fraser *et al*. 2001), the northern Karakoram shows little erosion and slow exhumation rates prior to the Pliocene–Quaternary. It seems highly probable therefore that the entire Karakoram region was topographically high since the Late Cretaceous. Only the final extreme topography seen today along the K2–Broad Peak–Gasherbrum range must have been created during Plio-Pleistocene time, when intense glaciation accelerated the erosion rates across the Karakoram. U–Pb and fission-track data from both K2 and Gasherbrum show that the Karakoram fault had no effect at all on metamorphism or melting in rocks adjacent to the fault, and only a limited effect (<3 km) on erosion–exhumation of rocks adjacent to the fault during the last 3–4 Ma.

Correlation of offset geological features

Peltzer & Tapponnier (1988) proposed *c*. 1000 km of dextral offset along the Karakoram fault, matching granites in the Pamir to the Gangdese granites of south Tibet. As noted by Searle

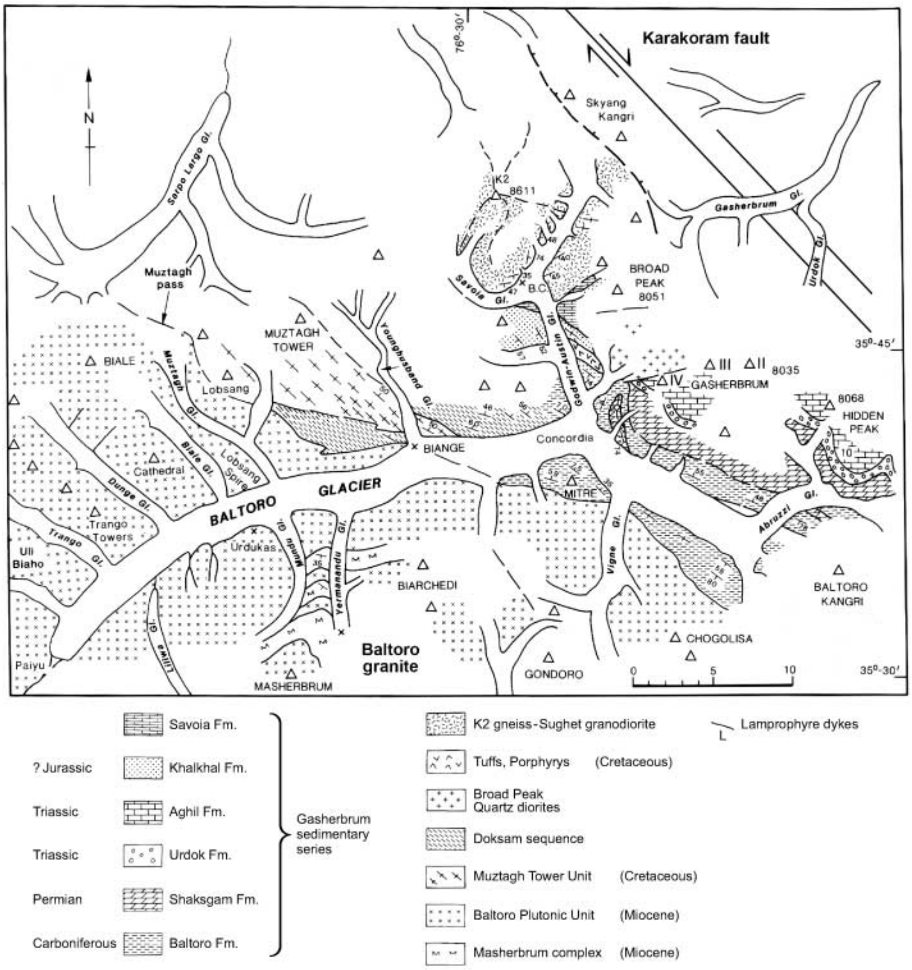


Fig. 6. Geological map of the upper Baltoro glacier and K2 region, after Searle *et al*. (1990) and Searle (1991).

(1996), these granites were never part of the same batholith and cannot be used to constrain offset. The Pamir granites are dominantly late Palaeozoic to Jurassic in age (Burtman & Molnar 1993), whereas the Gangdese–Ladakh granites range in age from *c*. 102 to 49 Ma (Schärer *et al*. 1984; Weinberg *et al*. 2000). Geochemistry and geochronology suggest that the granites in the southern Pamirs and Qiangtang terranes are similar. Zircon ages show that distinct magmatic phases occurred at *c*. 575–410 Ma, *c*. 250–210 Ma and *c*. 195–147 Ma (Schwab *et al*. 2004). Robinson *et al*. (2004) also correlated the southern Pamir–Hindu Kush–Karakoram terrane to the Qiangtang terrane, and the central Pamir to the Songpan–Ganzi terrane.

Lacassin *et al*. (2004*a*,*b*) suggested an offset of >250 km based on the correlation of the Bangong Nujiang suture in Tibet with the Rushan–Pshart suture in the Pamirs. Very little is known about the Rushan–Pshart suture in Tadjikistan, to which Burtman & Molnar (1993) assigned a Mesozoic age. Russian stratigraphic work shows that the Rushan–Pshart zone consists of an upper Palaeozoic to Jurassic volcano-sedimentary succession representing a rift margin or ocean basin succession that was closed during the Late Jurassic or Early Cretaceous (Vlasov *et al*. 1991; Schwab *et al*. 2004).

We suggest that the Rushan–Pshart suture zone may correlate across the Karakoram fault to the Jinsha suture in central–north Tibet (Fig. 1), and that the southern Pamir, together with the Hindu Kush (Hildebrand *et al*. 2000, 2001) and Karakoram (Searle 1991; Fraser *et al*. 2001) terranes correlate with the Qiangtang terrane of central Tibet (Kapp *et al*. 2003, 2005). Furthermore, we correlate the Shyok suture separating the Karakoram to the north from the Kohistan–Ladakh arc terrane to the south with the Bangong suture in south–central Tibet (Kapp *et al*. 2003, 2005). The Late Cretaceous–Palaeocene Kohistan–Ladakh granite–granodiorite batholith is the same as the Gangdese batholith of south Tibet. These granitic rocks, together with extensive Palaeocene–early Eocene calc-alkaline volcanic rocks across the Lhasa block, suggest that the southern margin of Asia was a magmatically thickened Andean-type continental margin, both in crustal thickness and elevation, prior to the collision of the Indian plate (England & Searle 1986). The Indus suture zone in Ladakh is continuous with the Yarlung Tsangpo suture of Tibet.

Deformation fabrics

Continental strike-slip faults are commonly composed of a seismically active upper crustal brittle fault that continues through a thermally controlled transition at *c*. 10–15 km depth into ductile shear zones in which deformation occurs by aseismic viscous creep or ductile flow. The crustal thickness beneath the Karakoram and Pamir, between 70 and 90 km, is the greatest known anywhere in the world (Wittlinger *et al*. 2004). Temperatures at the base of the crust probably reached *c*. 1000–1100 °C after dehydration melting, fluid–melt metasomatism and melt injection (Hacker *et al*. 2005). At these temperatures and

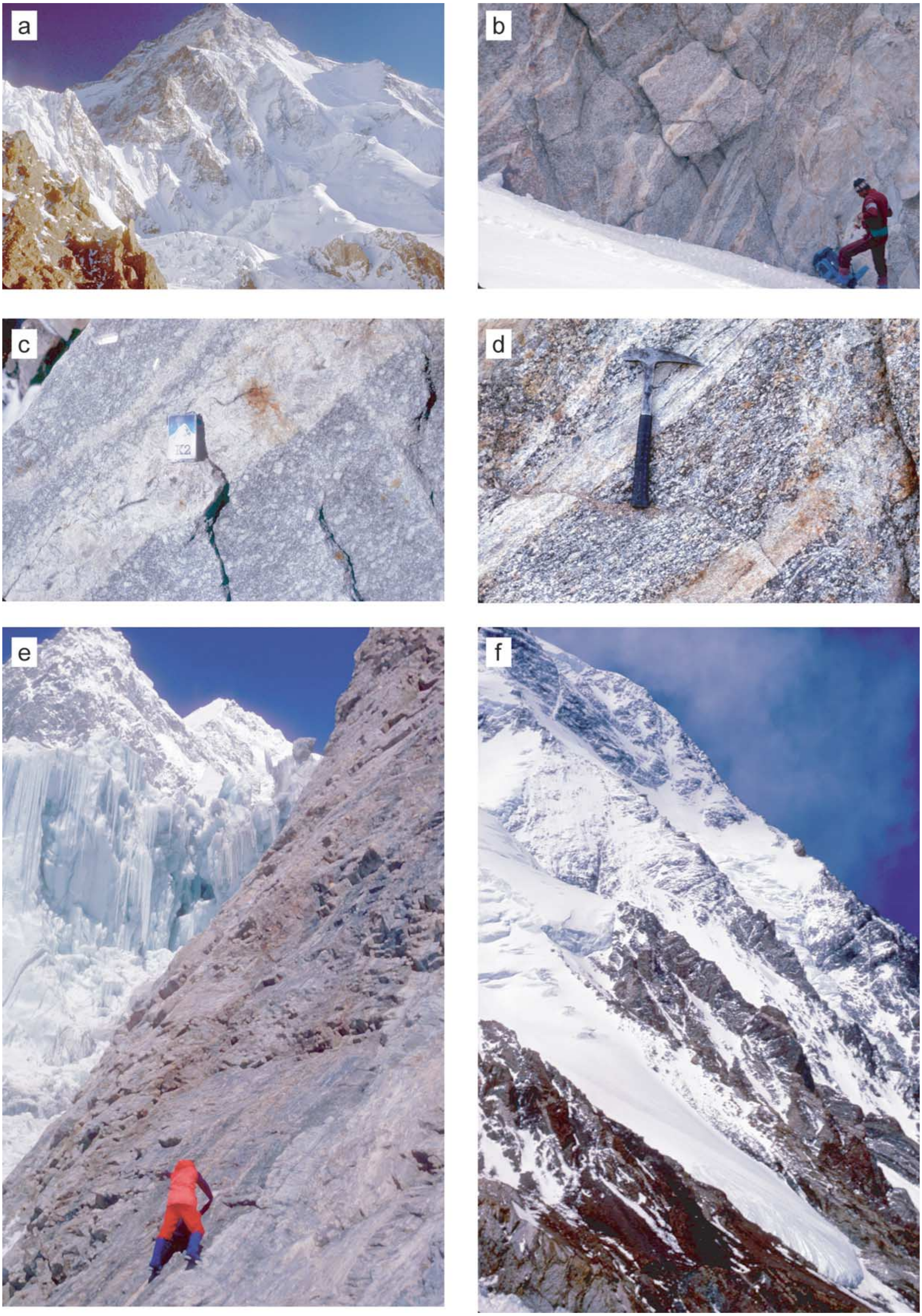


Fig. 7. (**a**) South face of K2 from the Godwin–Austin glacier. (**b**) Steep foliation in K2 orthogneisses interbedded with less common calc-silicates and pelites, south face of K2. (**c**, **d**) Typical K-feldspar–biotite orthogneisses intruded by two-mica garnet leucogranite dykes, south face of K2. (**e**, **f**) South face of K2 showing prominent foliation in K2 gneisses.

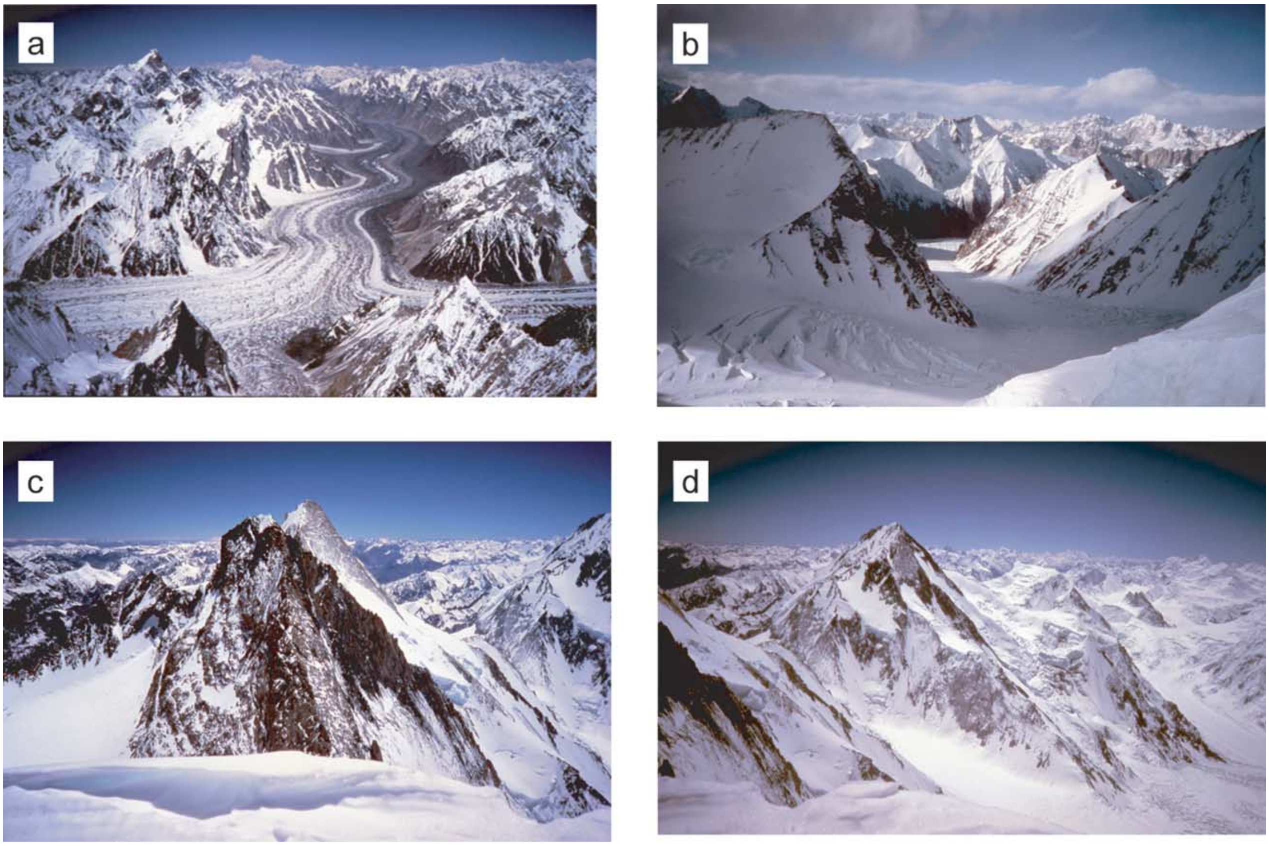


Fig. 8. (**a**) View west down the Baltoro glacier from the summit of Gasherbrum IV (7925 m). Foreground geology around Concordia, the meeting of Godwin–Austin glacier (right), Baltoro glacier and the South Gasherbrum glacier (left) includes black slates of Carboniferous Singhie Fm and pale-coloured Permo-Triassic limestones. The northern contact of the Baltoro granite cuts across Mitre peak left of Concordia. Cutting across the Baltoro glacier middle distance are the Karakoram batholith granites around Masherbrum (7821 m) on the left. The mountain in the farthest distance is Nanga Parbat (8125 m) at the western Himalayan syntaxis. (**b**) View north towards the Aghil pass from G IV; the Karakoram fault cuts across the North Gasherbrum glacier at the bottom of the valley ahead. (**c**) Gasherbrum III (7952 m) from the summit of G IV, showing Triassic Aghil Formation limestones intruded by Gasherbrum IV–Broad Peak quartz diorites. (**d**) Gasherbrum 1 (Hidden Peak; 8068 m) from summit of G IV, mostly composed of Triassic massive limestones of the Aghil Fm. On far right are the Indira col (5766 m) and Conway Saddle passes leading over to the Siachen glacier. All photos courtesy of Tim Macartney-Snape.

pressures, the lower crust beneath the Karakoram and Pamir would have to be either in high-pressure granulite or eclogite fields depending on water content. There is strong evidence from central–south Tibet of muscovite dehydration melting temperatures at shallow levels of the middle crust (15–18 km depth; Nelson *et al*. 1996). These temperatures are well in excess of the brittle–ductile transition, and these data alone suggest that extending the Karakoram fault down to the lower crust is unlikely. Ductile flow processes operate at these high temperatures, not brittle seismic faulting.

The dextral C–S fabrics described from leucogranites along the Karakoram fault at Tangtse (Searle *et al*. 1998; Phillips *et al*. 2004) and Zhaxikang (Lacassin *et al*. 2004*a*) were clearly superimposed onto the granite after crystallization at temperatures around 400–500 °C. The U–Pb ages of the granites must therefore give maximum age constraints on the initiation of strike-slip shear. U–Pb ages of the granites cannot provide ages of active shearing, as suggested by Lacassin *et al*. (2004*a*,*b*).

Discussion

Global positioning system (GPS) measurements from the Ladakh Himalaya suggest that present-day convergence across the western Himalaya is 18.8 ± 3 mm a^{-1} and that right-lateral slip parallel to the Karakoram fault cannot be more than *c*. 3.4 mm a^{-1} (Jade *et al*. 2004). This active rate is in agreement with a Quaternary rate of slip of 3–4 mm a^{-1} based on cosmogenic isotope dating of Quaternary terraces and moraines along the Pangong fault (Brown *et al*. 2002). Recent InSAR (satellite radar interferometry) studies have shown that right-lateral slip along the Karakoram fault cannot be at present any more than 3 mm a^{-1} and that there is no evidence for any other active, major right-lateral fault in western Tibet (Wright *et al*. 2004). Surprisingly for such a prominent fault as the Karakoram fault, there is very little seismic activity, suggesting either that earthquake recurrence time-scales are several hundred years or more, or that the fault is no longer active.

Analysis of Landsat photos suggests that some strands of the Karakoram fault may be active today. The Shaksgam fault (Teram Shehr fault of Searle 1991) appears to cut across the terminal moraine of the Kyagar glacier and dextrally offset the course of the Singhie glacier. Both the Urdok and Staghar glaciers appear to follow different splays of the Karakoram fault. Structural data combined with U–Pb geochronological data from deep crustal metamorphic and granitic rocks in the K2, Gasherbrum and Pangong ranges clearly show that all the metamorph-

Fig. 9. (**a**) Karakoram fault running along the Shaksgam valley, north of K2. (**b**) Karakoram fault gouge, Shaksgam valley. (**c**) Permian Shaksgam Fm and Triassic Aghil Fm limestones cut by a splay of the Karakoram fault, North Gasherbrum glacier. (**d**) Carboniferous Singhie Fm black slates and Permian Shaksgam Fm limestones cut by Shaksgam fault, a splay of the Karakoram fault, snout of the Urdok glacier. All photos courtesy of Chris Breemer.

ism and magmatism occurred prior to slip along the fault. Leucogranites along the Karakoram fault were all produced by regional middle or lower crustal melting during the Miocene, and are unconnected to the fault. Dextral strike-slip fabrics were subsequently imposed on the granites following crystallization. Ductile shearing along the Karakoram fault is tightly constrained at between 15.68 ± 0.3 and 13.73 ± 0.5 Ma from U–Pb ages of sheared leucogranites and cross-cutting undeformed leucogranite dykes at Tangtse (Phillips *et al*. 2004). Brittle strike-slip faulting occurred after 13.7 Ma. None of the leucogranites cross-cut the brittle faults bounding the ductile shear zone. Pangong mylonites in the Karakoram fault shear zone cooled in two phases, the first between *c*. 17 and 13 Ma and the second between *c*. 9 and 7 Ma (Dunlap *et al*. 1998). On either side of the Pangong mylonites, rocks of the Karakoram metamorphic complex to the NE and Ladakh batholith rocks to the SW cooled much earlier.

Leucogranites at Zhaxikang in SW Tibet have very similar field relationships to the Tangtse examples and we dispute the synkinematic origin proposed by Lacassin *et al*. (2004*a*,*b*). There is no evidence for *in situ* melting along the Karakoram fault and the granites were clearly at sub-solidus temperatures when the ductile shear C–S fabric was imposed. If frictional heating along the fault did produce high enough temperatures for crustal melting, then *in situ* melting and high P–T conditions should be expected along the fault trace. Along most of the fault trace, including the Gasherbrum and Aghil ranges, unmetamorphosed sedimentary rocks are exposed along the fault. Indeed, the metamorphism at K2 was mid-Cretaceous in age, prior to any slip along the Karakoram fault, and all the granites along the Baltoro and Siachen batholith were intruded prior to fault slip.

Conclusions

(1) The Karakoram fault was initiated after regional metamorphism and granite emplacement along the Baltoro and Tangtse plutons. Leucogranite melting did not result from dominant shear heating along the fault and therefore the U–Pb ages of granites provide a maximum age of fault initiation.

(2) Minimum–maximum dextral offsets along the Karakoram fault are 40–120 or 150 km, respectively and long-term slip rates are between 2.7 and 10.2 mm a^{-1} (Searle *et al*. 1998; Phillips *et al*. 2004). Key pinning points are the northern and southern margins of the Baltoro granite plutons, correlation of the mid-Cretaceous Shyok and Bangong suture zones, and the offset of the antecedent Indus River (Gaudemer *et al*. 1989; Searle 1996). The correlation of the Late Cretaceous Bangong suture in Tibet with the pre-middle Jurassic Rushan–Pshart suture in the Pamirs as suggested by Lacassin *et al*. (2004*a*,*b*) is incorrect.

(3) Dextral strike-slip C–S shear fabrics were superimposed at lower temperatures on granites that were emplaced earlier in the crust. A strain gradient along the fault is marked where strain decreases away from the fault. The suggestion that Baltoro–

Tangtse granites along the Karakoram fault are synkinematic and that the fault must have been active prior to 23 Ma (Lacassin *et al*. 2004*a*,*b*) is not correct.

(4) Middle Cretaceous K2 orthogneisses and the Gasherbrum quartz diorite intrusion adjacent to the Karakoram fault were formed during a pre-collision phase of subduction-related magmatism. The K2 gneiss cooled to below 350 °C during the mid-Cretaceous, showing that shear heating temperatures did not exceed that during active slip on the fault.

(5) Zircon fission-track ages from the Gasherbrum diorite, immediately SW of the Karakoram fault, vary from early Cretaceous to middle Tertiary, with no consistent pattern between age and elevation (Cerveny *et al*. 1989). The Gasherbrum diorite has never been at depths greater than 6 km since the early Cretaceous and less than 3 km of material has been eroded off since then.

(6) U–Pb, $^{40}Ar/^{39}Ar$ and fission-track age data combined with structural mapping suggest that the Karakoram fault did not exert any influence on crustal metamorphism or melting, and had only limited influence on topographic uplift (3 or 4 km) and exhumation–erosion processes.

(7) Restored cross-sections across the Indian plate shelf margin in Ladakh (Corfield & Searle 2000) show that the upper crust was shortened by at least 85 km. This shortening has to be balanced in the lower crust by underthrusting Indian shield lower crust northwards beneath the Kohistan–Ladakh terrane and the southern Karakoram by at least this amount. This suggests that the Karakoram fault may only be an upper–mid-crustal feature, and did not extend into the lower crust or upper mantle.

These observations and all the structural, metamorphic and geochronological data support Model 2, where dextral shear offsets along the Karakoram fault are limited to 40–150 km during the period $<$15.7 Ma. The data do not support the model of rigid block tectonics, frictional heating producing granite melting along strike-slip faults, or large-scale continental extrusion of Tibet.

This work was carried out with NERC grants NER/K/S/2000/951 to M.P.S. and NER/S/A/2000/03515 to R.J.P. Thanks go to Richard Walker for processing Landsat images, Fida Hussein Mitoo for local assistance, Randy Parrish, Ernie Rutter, Dan Faulkner, Peter Molnar, Erik Brown and Vinod Gaur for discussions, and to Chris Breemer and Tim Macartney-Snape for use of their photographs. We also thank Mike Murphy and Dickson Cunningham for helpful reviews.

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Received 30 April 2006; revised typescript accepted 18 May 2006.
Scientific editing by Ian Alsop and Dickson Cunningham