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Karakoram fault zone rocks cool in two phases

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Abstract: The Karakoram fault zone of Ladakh, India, is a major strike-slip boundary along which the tectonic evolution of Tibet has been accommodated. In this paper $^{40}Ar/^{39}Ar$ isotopic age data are integrated with structural and metamorphic data to infer an exhumation history for granites and low- to intermediate-grade metamorphic rocks exposed adjacent to two strands of the fault zone. Near Tangtse, leucogranites which crystallized *c.* 17 Ma ago are cut by the Karakoram fault zone, indicating that fault movement was initiated subsequent to 17 Ma. The $^{40}Ar/^{39}Ar$ data give temperature-time histories which indicate that the <17 Ma metamorphic rocks within the fault zone were exhumed differentially relative to the adjacent (and already cooled to <150°C) Ladakh Batholith, while cooling progressively through amphibolite to below greenschist facies temperatures.

Two phases of rapid cooling of Karakoram fault zone rocks are evident, one at *c.* 17 Ma to *c.* 13 Ma, and another, following an intervening period of relatively slow cooling, starting at *c.* 8 Ma and continuing until at least 7 Ma. Uplift since *c.* 17 Ma via dextral oblique thrusting has resulted in exhumation from amphibolite facies metamorphic conditions, possibly with a larger thrust component from 17 to 13 Ma, followed by a change to dominant strike-slip motion at about 13 Ma. Rapid cooling starting at *c.* 8 Ma at greenschist facies temperatures is probably the result of renewed oblique thrusting. It is notable that the two episodes of rapid cooling recorded in Karakoram fault zone rocks coincide with episodes of exhumation in the Pakistani Karakoram and also in southern Tibet.

Keywords: Himalayas, Karakoram, Ladakh, $^{40}Ar/^{39}Ar$, K-feldspar.

The *c.* 17–0 Ma Karakoram fault zone (Searle *et al.* 1998), which bounds Tibet for 700 km on its southwestern side (Fig. 1), is inferred to be one of the main strike-slip fault zones on which lateral extrusion of Tibet is accommodated (Molnar & Tapponnier 1975). Estimates of strike-slip displacement on the fault vary by almost an order of magnitude, yet a conservative estimate of finite displacement, based on offset geology along the middle of its length, is *c.* 150 km (Searle *et al.* 1998). Present day strike-slip displacement rates are apparently as high as 32 mm/a (Peltzer & Tapponnier 1988). Such displacement rates cannot characterize the history of the Karakoram fault zone, otherwise cumulative displacement would be >500 km. Although the magnitude of strike-slip displacement on the fault zone is reasonably well constrained, the relationship between fault zone displacement and exhumation of Karakoram fault zone rocks, the focus of this study, is poorly known.

The timing of crustal thickening, uplift and subsequent east–west extensional collapse of southern Tibet is under debate. Although much of the debate has focused on when and how much uplift has occurred, the picture that is emerging from geochronological and thermochronological studies is that, since about 24 Ma, abundant granite emplacement as well as rapid exhumation of metamorphic rocks has occurred within a concentrated E–W belt encompassing the High Himalaya and the Karakoram (e.g., Harrison *et al.* 1992). In view of the direct structural and kinematic link between the lateral extrusion of Tibet and formation of the Karakoram fault zone, the data presented below are expected to reflect not only the evolution of western Tibet and the Karakoram, but perhaps also on tectonism further afield in southern Tibet.

Recent work on well exposed Karakoram fault zone rocks (here called the Pangong metamorphic complex) in northern Ladakh has yielded new data on the geometry and kinematics of the fault zone, and provided some information on the timing of movement along one of the major strands (Searle *et al.* 1998). $^{40}Ar/^{39}Ar$ data presented here extends this earlier study to include a traverse across the entire Karakoram fault zone and shows that metamorphic rocks within the fault zone have cooled in two phases, nearly synchronous with rapid cooling events along strike >700 km away along the southern margin of Tibet.

Geological history

The Indus Suture (Fig. 1), which is effectively the boundary between Indian and Asian crust in Ladakh (e.g., Molnar & Tapponnier 1975), closed when the impinging Indian lithosphere collided with the active magmatic arc including the Ladakh Batholith between *c.* 52 and 49 Ma (Searle 1991). The Shyok suture, which separates the Karakoram Range from the Ladakh Batholith in Pakistan, appears to have closed in the Cretaceous (Treloar *et al.* 1989). In Ladakh, however, the Shyok suture and its lithologies have been affected by subsequent deformation, metamorphism and faulting (Srimal *et al.* 1986). Following closure of the Shyok suture the silicic Khardung Volcanics, which yield $^{40}Ar/^{39}Ar$ plateau ages of about 60 Ma (Bhutani *et al.* 1998; data of Sharma *et al.* 1978 is suspect in light of these results and also our own unpublished analyses), were erupted onto the northeastern flank of the Ladakh Batholith, and according to Rai (1982) also within a non-marine basin between the Ladakh Batholith and the

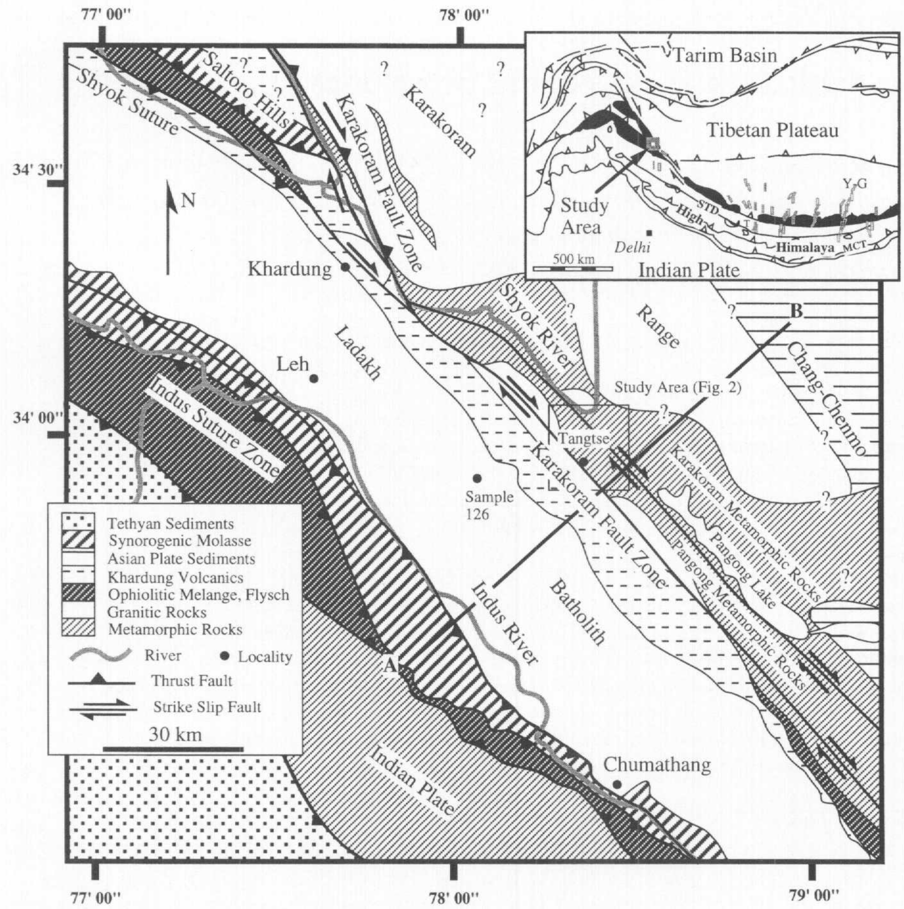

Fig. 1. Tectonic map of the region near Tangtse, northern Ladakh. Inset shows location of study area on the southwestern margin of the Tibetan plateau granitic rocks in black; extensional grabens as grey boxes; T, is Thakhola graben; Y-G, is Yadong-Gulu rift; MCT, is Main Central Thrust; STD, South Tibetan Detachment. A–B: approximate cross-section line for Fig. 5. Partially after Searle (1991).

Karakoram Range. Miocene compression resulted in shortening of this basin (in the Saltoro Hills, Fig. 1) and caused renewed exhumation and cooling of suture zone rocks and adjacent Karakoram granitoids (Brookfield & Reynolds 1990). The Khardung Volcanics are tightly folded and thrusted, and molasse derived from the Ladakh Batholith is purportedly involved in the compressional structures (Rai 1982). Leucogranites containing abundant muscovite and garnet intruded the Karakoram Range at *c*. 20–17 Ma and are thought to be melts derived from pelites in the lower crust as a consequence of crustal thickening (Searle *et al.* 1992; 1998: 17.4 ± 0.2 Ma leucogranite, spot dated by ion microprobe, present study area). The 17 Ma leucogranite in the present study area provides an important time constraint on the evolution of the Karakoram fault zone.

The Karakoram fault zone initiated after 17 Ma and cross-cuts all of the lithologies and structures cited above, including the leucogranites. In the study area near Tangtse (Fig. 1), the fault zone appears to truncate the Shyok suture, placing Karakoram granites and metamorphic rocks against the Ladakh Batholith and Khardung Volcanics. Deformation associated with the Karakoram fault zone is manifested as a 3–10 km wide subparallel array of mostly steeply to moderately north-dipping fault zones and shear zones. Deformation of the wall rocks of the fault zone occurred not only at amphibolite and greenschist facies conditions, but also at conditions of very low grade metamorphism, involving significant cataclasis. Deformation along the fault zone from *c*. 17 to *c*. 11 Ma occurred during cooling through about 750 to 350°C, and thus at cooling rates of about 80°C Ma^{-1} on average (Searle *et al.* 1998).

The cooling history of metamorphic rocks in the Karakoram Range would appear to contrast with that of the Ladakh Batholith and westernmost Tibet. The presently exposed levels of the Ladakh Batholith have remained below the closure temperature for argon loss from micas and K-feldspars since about 30 Ma (Searle *et al.* 1989 and also this study). North of the Chang-chenmo Range in western Tibet, just 50 km to the northeast of the present study area (Fig. 1), Mesozoic shelf sediments of the Asian passive margin remain relatively flat-lying and suggest that the area is not deeply exhumed (Norin 1946). In contrast, the Karakoram Range has been deeply exhumed since about 20 Ma (e.g., Searle *et al.* 1989).

Structure and metamorphism

The study area is around Tangtse gorge, where the Tangtse River cuts across the structural grain (Fig. 2). Our sampling traverse crosses the entire Karakoram fault zone, from the Ladakh Batholith in the SW to the Karakoram Range in the NE. Metamorphic and microstructural observations are reported for several localities along the traverse, including both of the main strands of the fault zone, the Tangtse and Pangong strands. The shear zones associated with these two fault strands are about 800–1200 m wide, characterized by high strains, and formed during right lateral strike-slip under greenschist to amphibolite facies metamorphic conditions.

The Tangtse shear zone deforms both the Khardung Volcanics and the *c*. 103–60 Ma (e.g., Honegger *et al.* 1982; Schärer *et al.* 1984) granites of the Ladakh Batholith (Fig. 2).

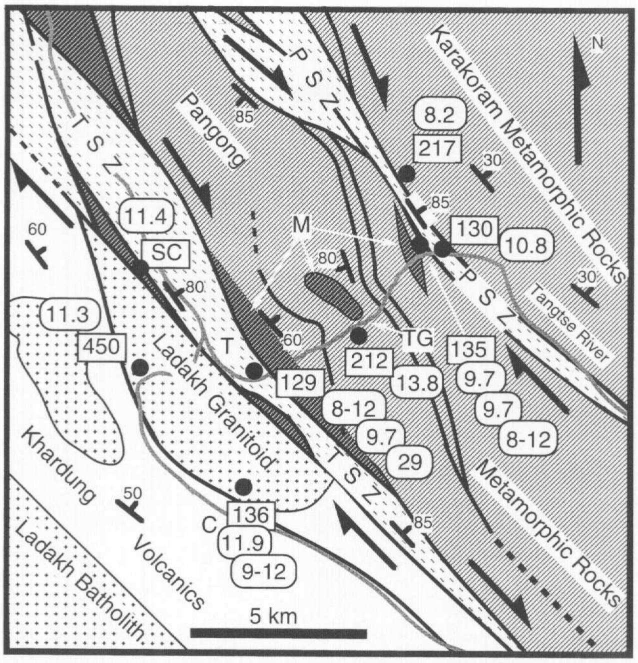

Fig. 2. Structural and lithologic map of the Karakoram fault zone at Tangtse gorge showing locations of dated samples (black dots, sample numbers in boxes) and ages (ovals). Ovals with age ranges (e.g. 8–12) are for K-feldspar. M, leucogranites (stripe pattern). SC is the locality where Searle *et al.* (1998) determined an 11.4 Ma ^{40}Ar/^{39}Ar age for muscovite from the Tangtse leucogranite. TG, Tangtse gorge; T, Tangtse village; C, Chilam village; PSZ, Pangong shear zone; TSZ, Tangtse shear zone.

The Khardung Volcanics, are mostly northeast dipping and exhibit lower greenschist facies metamorphism and a tectonic cleavage which appears to intensify toward the Tangtse shear zone. The strain aureole of the Tangtse shear zone penetrates the Ladakh granitoids and particularly the Khardung volcanics seemingly because the volcanics were easily deformed during movement on the shear zone. However, the strains within the granites and volcanics are only minor in comparison to those exhibited by the Tangtse shear zone mylonites. Only rocks of Karakoram affinity, including the young leucogranites, are found within the Tangtse shear zone proper (dash pattern in Fig. 2). This indicates that either (1) strain has concentrated preferentially in Karakoram rocks and leucogranites, or more likely that (2) deformed rocks of the Ladakh Batholith and Khardung Volcanics have been removed by structural thinning, placing highly deformed rocks of Karakoram affinity against little deformed rocks of the Ladakh Batholith and Khardung volcanics.

The Karakoram rocks of the Tangtse shear zone comprise interlayered marble, calcsilicate, granitic pegmatites and boudins of amphibolite gneisses, as well as kilometre-scale pods of strongly sheared leucogranite, all of which exhibit evidence for right lateral shear under greenschist facies conditions (in particular the Tangtse Gompa locality). The pegmatites intruded the carbonate host rocks before or during deformation related to the Karakoram fault zone, and they are interpreted to be part of the regional leucogranite suite. The amphibolite boudins were not pervasively deformed during Karakoram fault zone movement, and the gneissic fabrics within them may be relict from an earlier deformational event. In contrast, the marbles encasing the boudins exhibit extreme attenuation and flow structures, indicating that they form the rheologically weakest part of the shear zone.

Migmatitic gneisses and granitoids of the Pangong metamorphic complex form a coherent block bounded by the Tangtse and Pangong shear zones (Fig. 2). The gneisses are dominantly quartzofeldspathic and amphibolitic migmatites with coarse-grained equigranular textures; rare pelitic and calc-silicate schists are also found. The intrusive rocks are mainly coarse-grained biotite granites with rarer muscovite and garnet, and most have pronounced strain aureoles paralleling contacts with the migmatites (Weinberg & Searle 1998). The interior of the block is transected by narrow, mostly right lateral, shear zones of greenschist and amphibolite facies that are clearly associated with the development of the Karakoram fault zone. In the vicinity of the Pangong and Tangtse shear zones, the Pangong metamorphic complex exhibits strong mylonitic fabrics with a lineation that plunges shallowly toward the NW in the foliation (*c*. 20°, but locally quite variable). Feldspar deformation textures within the Pangong metamorphic complex along the margin of the Tangtse shear zone indicate that deformation occurred in the amphibolite facies during right lateral shearing (these rocks are separated from the marble–amphibolite assemblage described above by a high strain zone), whereas biotite–quartz–epidote mylonites along the margin of the Pangong shear zone indicate deformation occurred in the epidote-amphibolite facies during essentially coaxial deformation.

The central 300–400 m of the Pangong shear zone at the northeastern end of Tangtse gorge consists of muscovite-bearing carbonate mylonites that are strongly flow-folded, and contain a lineation that is weak and variable in orientation but mostly subhorizontal. These carbonates are likely to be part of the Karakoram metamorphic rocks, the main body of which outcrops immediately to the northeast of the carbonate mylonite, across a sharp sub-vertical fault contact. The Karakoram metamorphic rocks dip *c*. 40° to the northeast and include strongly deformed and lineated biotite staurolite schists, marbles, calc-schists, and quartzofeldspathic mica schists. Likely a product of Cretaceous deformation and metamorphism, the Karakoram metamorphic rocks have largely escaped deformation related to movement on the Pangong shear zone. However, a late brittle phase of deformation has opened tensional fractures in the metamorphic rocks, some of which are filled with coarse new muscovite (see age data below).

^{40}Ar/^{39}Ar results

Ten new ^{40}Ar/^{39}Ar age spectra and one K/Ar date have been obtained from two amphiboles, two muscovites, two biotites and four K-feldspars (Figs 2 and 3, Tables 1 and 2; full data tables are available as Supplementary Publication No. SUP18123 (8 pp) from the British Library Document Supply Centre, Boston Spa, Wetherby, W Yorks LS23 7BQ, or from the Society Library). These minerals provide a closure temperature range for argon of *c*. 500–150°C (e.g., Dodson & McClelland-Brown 1985; Dunlap *et al.* 1995) and the results have been used to construct cooling histories for the regions adjoining the Karakoram fault zone. However, no amphibole is available in the Ladakh Batholith and no amphibole or K-feldspar is available from the Karakoram metamorphic rocks. K-feldspars, through their domainal structure, record a range of closure temperatures (Lovera *et al.* 1993) and, thus, can provide a continuous cooling history from *c*. 350 to 150°C.

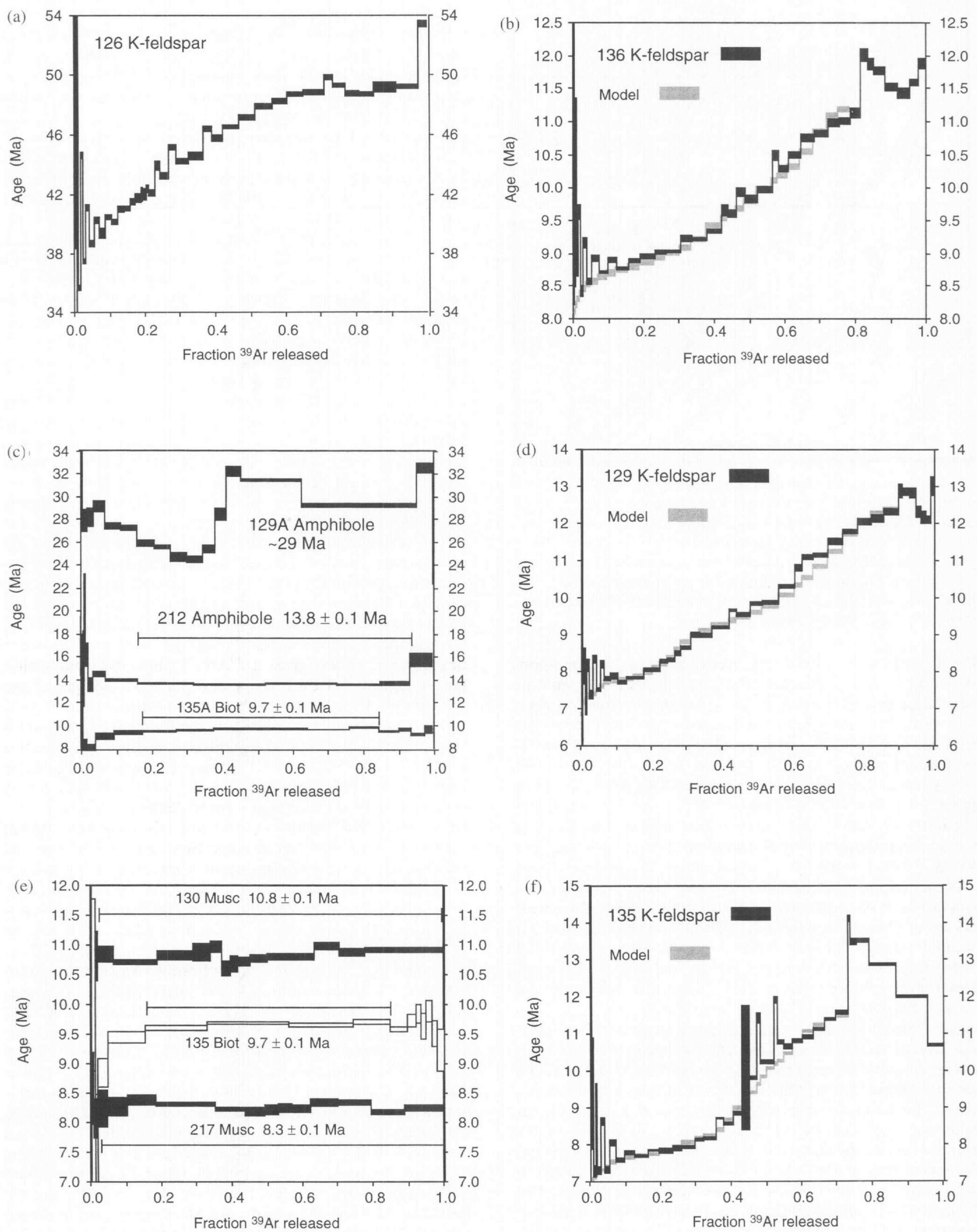

Fig. 3. $^{40}Ar/^{39}Ar$ age spectra for minerals dated from the Tangtse traverse.

Table 1. *K–Ar data*

No.	ANU#	Mineral	K (wt %)	Rad ^{40}Ar (10^{-10} mol/g)	100 Rad ^{40}Ar/ Total ^{40}Ar	Age (Ma) ± 1 σ	Locality
136	95441	Biotite	7.894, 7.914	1.630	77.9	11.85 ± 0.14	Tangtse

ANU#, Australian National University catalogue number. Decay constants are λ_e=0.581 and λ_β=4.962 E-10/y.

Table 2. *Summary of $^{40}Ar/^{39}Ar$ data*

Sample	Integrated total fusion age* (Ma) ± 1 σ	Minimum age in spectrum (Ma) ± 1 σ	Plateau age† (Ma) ± 1 σ	% ^{39}Ar in plateau
Hornblende				
129A	29.6 ± 0.3	na	na	na
212	14.0 ± 0.2	na	13.8 ± 0.1	75
Moscovite				
217	8.3 ± 0.1	na	8.3 ± 0.1	96
130	10.8 ± 0.1	na	10.8 ± 0.1	97
Biotite				
135	9.6 ± 0.1	na	9.7 ± 0.1	70
135A	9.7 ± 0.1	na	9.7 ± 0.1	67
K-feldspar				
135	10.4 ± 0.1	7.3 ± 0.1	na	na
136	10.2 ± 0.1	8.4 ± 0.1	na	na
129	10.2 ± 0.1	7.1 ± 0.1	na	na
126	46.9 ± 0.2	33.8 ± 0.4	na	na

*Total fusion age calculated from entire age spectrum.
†Weighted average age calculated from portions of age spectra indicated in Fig. 3.
na, Not applicable.

K-feldspars were stepheated according to the methods described in Lovera *et al.* (1993) where isothermal duplicate steps were employed to gain age resolution on the low temperature steps and a large number of steps were run to gain resolution on the age gradients. Using the results of thermal modelling the age gradients have been interpreted in terms of cooling rates, providing a time-temperature history for each sample.

Published K–Ar data for the granites of the Ladakh Batholith (summarized by Searle *et al.* 1989) indicate a slow cooling history subsequent to the India–Asia collision. This inference is confirmed by a detailed stepheating experiment on K-feldspar from Ladakh granite at site 126 (Figs 1 and 3a; model results will be presented in another paper). The sample exhibits an age gradient which rises smoothly from 36 to 49 Ma, indicating that temperatures greater than about 150°C have not been experienced since *c.* 36 Ma. The ages exhibited by this sample contrast markedly with those preserved in K-feldspars from the Karakoram fault zone just 15 km to the northeast in Tangtse (see below).

The Chilam biotite granite, presumed to be of Ladakh Batholith affinity due to the absence of muscovite and garnet, is undeformed except where it directly abuts the Tangtse shear zone (Fig. 2). Biotite sample 136, from undeformed granite near the village of Chilam and over 2 km from the Tangtse shear zone, has given a K–Ar age of 11.9 ± 0.1 Ma (Table 1), the timing of cooling through *c.* 300°C. K-feldspar 136 yields a $^{40}Ar/^{39}Ar$ age spectrum that rises from minimum ages of *c.* 8.5 Ma to maximum ages of *c.* 12 Ma (Fig. 3b), overlapping in age with the biotite. Along strike to the northwest, and possibly within the same granite body, biotite 450 (Fig. 2) of Searle *et al.* (1998) gives a $^{40}Ar/^{39}Ar$ age spectrum with a plateau age of 11.3 ± 0.1 Ma involving over 90% of gas release.

Two samples from within the Tangtse shear zone at Tangtse village (Fig. 2) have been dated, an amphibolite pod within the calcmylonites, sample 129A, and one of the late deformed granitic pegmatites (part of Karakoram leucogranite suite), sample 129. Amphibole 129A gives a discordant $^{40}Ar/^{39}Ar$ age spectrum with ages ranging from 25 to 33 Ma (Fig. 3c; *c.* 29 Ma bulk age, and isochron analysis suggests a similar intercept age). Aside from the first two steps, K/Ca values are between 0.07 and 0.10 indicating no significant contamination. This amphibole yields the oldest apparent ages of the traverse and suggests that the carbonate mylonites have remained below *c.* 500°C since about 29 Ma. K-feldspar 129 yields an age spectrum that rises from minimum ages of about 7.5 Ma to maximum ages of about 13 Ma, indicating cooling through the K-feldspar closure window in this interval (Fig. 3d). Searle *et al.* (1998) dated muscovite from a muscovite–garnet leucogranite deformed in the Tangtse shear zone and determined a plateau age of 11.4 ± 0.1 Ma (Fig. 2, SC locality).

Coarse-grained amphibole-bearing granitic pegmatite bodies form part of the migmatitic series of the Pangong metamorphic complex. These pegmatitic bodies appear to have crystallized from partial melts during migmatization. Amphibole from sample 212 yields a $^{40}Ar/^{39}Ar$ age spectrum that is flat for over 75% of gas release, defining a plateau age of 13.8 ± 0.1 Ma and the timing of cooling through *c.* 500°C (Fig. 3c). Quartzofeldspathic migmatite and a biotite schist, samples 135 and 135A, respectively, from the Pangong metamorphic complex deformed in the Pangong shear zone have also been dated. The biotites from these two samples yield identical plateau ages of

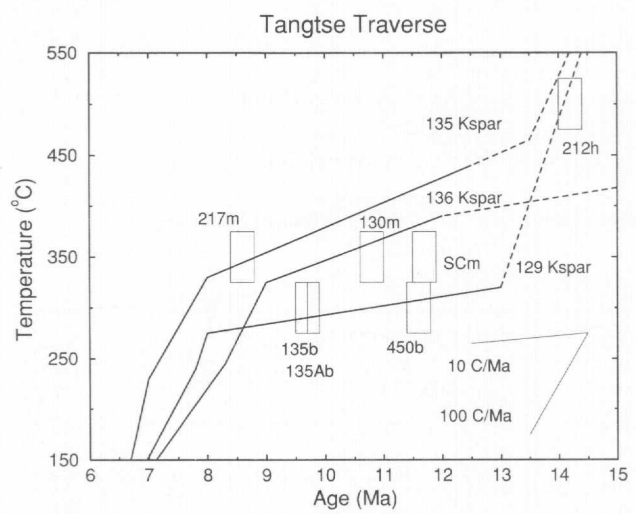

Fig. 4. Composite thermal history for the Tangtse traverse. K-feldspar thermal histories dashed where inferred. Boxes show plateau ages (box width) of micas and amphiboles, with associated errors, and estimated closure temperatures (box height) (e.g., Dodson & McCellend-Brown 1985) Cooling rates indicated in lower right corner. b, biotite; m, muscovite; h, amphibole; SCm, muscovite dated by Searle *et al.* (1998).

9.7 ± 0.1 Ma over large fractions of gas release (Fig. 3c, e), indicating cooling through *c.* 300°C at this time. K-feldspar from the migmatite gives a monotonically rising age spectrum with minimum ages of *c.* 7 Ma and maximum ages of *c.* 12–14 Ma (Fig. 3f). These results indicate cooling through the K-feldspar closure window at essentially the same time as K-feldspar 129 from the Tangtse village locality.

Carbonate mylonite sample 130 from within the Pangong shear zone (Fig. 2) contains a muscovite that defines an axial planar cleavage and yields a $^{40}Ar/^{39}Ar$ plateau age of 10.8 ± 0.1 Ma, indicating the timing of cooling through *c.* 350°C (Fig. 3e). Sample 217, a pelitic mylonite from within the Karakoram metamorphic sequence and just a few metres from the sharply defined fault contact at the boundary with the Pangong shear zone, contains coarse (2–3 mm) muscovite in tensional fractures. The muscovite yields an age spectrum that exhibits a plateau at 8.3 ± 0.1 Ma (Fig. 3e) and the preferred interpretation is that this age represents the timing of crystallization of the muscovite within the fracture.

Thermal modelling

Multidomain thermal modelling (Lovera *et al.* 1989) of the $^{40}Ar/^{39}Ar$ results from the K-feldspars has provided a continuous temperature-time history for localities 129, 135 and 136. The Arrhenius information generated from the release of ^{39}Ar is mathematically modeled by assuming a size distribution of non-interacting domains of infinite slab geometry and a single activation energy for volume diffusion (Lovera *et al.* 1993). Error in the estimation of activation energy leads to errors in temperatures of *c.* ± 20°C. The synthetic domain distributions were exposed to trial thermal histories to produce synthetic age spectra that match those of the stepheating experiment (e.g., Dunlap *et al.* 1995). The results of the thermal modelling, shown in Figs 3 and 4, are not sensitive to the number of domains, as long as an appropriate minimum number is used (i.e., a good fit to the age spectrum is obtained; usually 4 or more domains is required to achieve a good fit). Model cooling rates presented here are considered reliable to ± 20%, assuming that the cooling histories are smooth and continuous on the time scale of a few hundred thousand years. Regardless of this high apparent precision, it should be emphasized that the thermal models are interpretations which are strongly dependent on the model assumptions, and that their accuracy may be worse than the above mentioned limits.

K-feldspar 129 (Fig. 3d) is modeled using eight domains covering almost two orders of magnitude in diffusion length scale and with an activation energy for argon diffusion of 43.5 kcal mol^{-1}. The form of the age spectrum indicates that the sample is essentially uncontaminated by excess argon: the monotonically rising age spectrum is typical of the theoretically expected form in the absence of any contaminating excess argon. This is demonstrated by the close fit between the model and the laboratory degassing spectrum, which is generally not possible if significant excess argon is present. From 11.5 to 8 Ma the model requires a slow cooling rate of *c.* 10°C Ma^{-1}, followed by a rapid cooling rate of *c.* 150–200°C Ma^{-1} subsequent to 8 Ma (Fig. 4). We interpret these results to indicate that the sample has not been above 150°C for any significant period since 7 Ma.

K-feldspar 135 from the opposite side of the uplifted block of Pangong metamorphic rocks (Fig. 2) is modeled using nine domains covering two orders of magnitude in diffusion length scale with an activation energy of 54.0 kcal mol^{-1}. The activation energy is quite high, but not unrealistic compared with other studies on K-feldspars (cf. Lovera *et al.* 1997). However, note that the model would predict a closure temperature of *c.* 350°C for the associated biotites. Excess argon is not apparent in the degassing spectrum of the K-feldspar (Fig. 3f), except for some minor contamination in the early phase of gas release (first 10% or so) interpreted to be from fluid inclusions (cf. Harrison *et al.* 1994); the youngest ages in this portion of the spectrum are interpreted to approximate the true age of the sample. The model is valid from 11.5 Ma and a temperature of *c.* 410°C where slow cooling at *c.* 25°C Ma^{-1} is recorded (Fig. 4). At about 8 Ma the cooling rate must be increased to 100°C Ma^{-1} to obtain a good fit to the Arrhenius data and laboratory age spectrum. We interpret these results to indicate that the sample has not been above *c.* 240°C for any significant period since 7 Ma.

K-feldspar 136 from the Chilam granite (a Ladakh Granite) is modeled using nine domains covering 1.5 orders of magnitude in diffusion length scale with an activation energy of 49.0 kcal/mol^{-1}. As with the other two samples, excess argon appears not to be a problem. From 11.5 Ma the model records cooling through *c.* 370°C and requires a cooling rate of *c.* 20°C Ma^{-1}, a rate which is valid until about 9 Ma and *c.* 325°C when rapid cooling at a rate of 115°C Ma^{-1} is required (Fig. 4). The K-feldspar model would predict that the 136 biotite (K–Ar apparent age of 11.9 Ma) closed to argon loss at a temperature of about 370°C. Subsequent to 8.5 Ma no thermal information is obtained from the K-feldspar model, but we interpret the results to indicate that the sample has not seen temperatures higher than *c.* 250°C since that time.

Discussion

An understanding of the uplift and exhumation history of the Pangong metamorphic complex in the Karakoram fault zone relative to the adjacent blocks of the Cretaceous Ladakh Batholith and Karakoram metamorphic rocks is gained

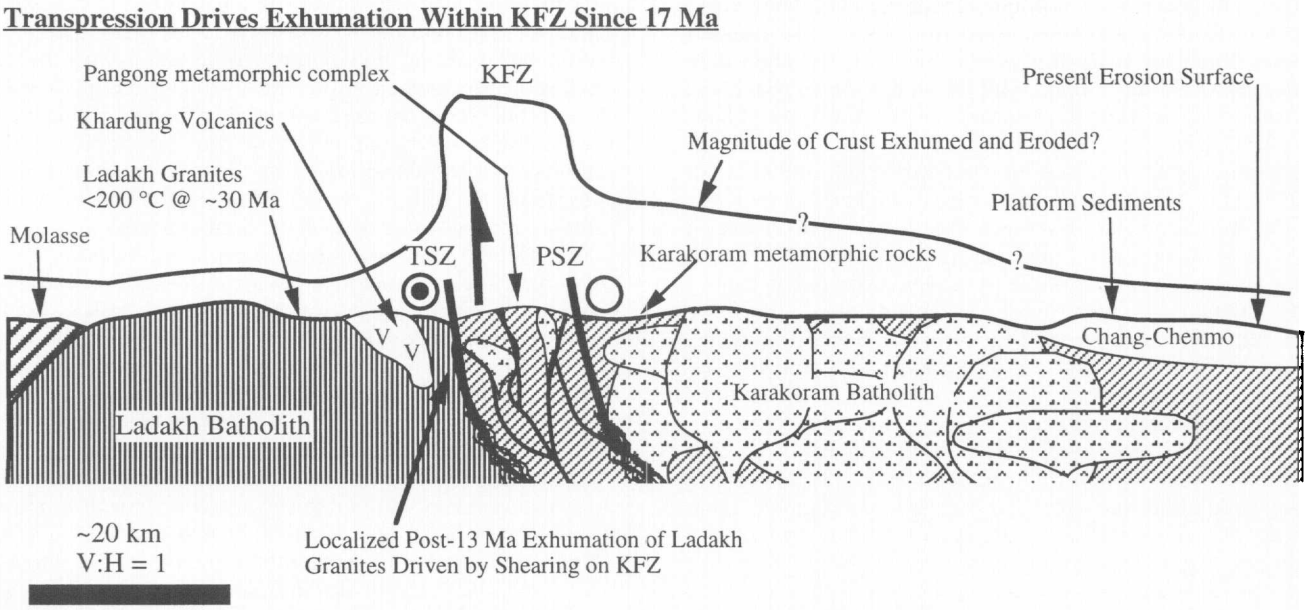

Fig. 5. Cartoon of crustal exhumation due to oblique convergence along the Karakoram fault zone.

through the integration of the field observations and laboratory results. An important finding is that the Pangong rocks have cooled through argon closure temperatures (from >500°C to less than about 150°C) much more recently (<17 Ma) than the adjacent blocks.

The strike slip deformation within the core of the Tangtse shear zone at site 129 occurred under greenschist-facies conditions subsequent to leucogranite crystallization and Pangong migmatite formation *c.* 21–17 Ma (Searle *et al.* 1998). This implies that amphibolite gneiss 129A experienced amphibolite-facies deformation and metamorphism during or before leucogranite intrusion. The 29 Ma bulk age for amphibole from amphibolite gneiss 129A is consistent with this conclusion and may indicate the timing of cooling through *c.* 500°C, probably after the gneissic fabric formed. We conclude that the site 129 amphibolite gneisses were juxtaposed with the Pangong migmatites after the migmatites had cooled to well below the temperatures of leucogranite genesis, otherwise the 129A amphibole might have been reset. The result for amphibole 212 from the Pangong rocks suggests that the juxtaposition occurred after about 13.8 Ma.

Two phases of rapid cooling are required for rocks within the Karakoram fault zone (Fig. 4), one at 17 to *c.* 13 Ma and another starting *c.* 9 Ma south of the Tangtse shear zone and *c.* 8 Ma within the Pangong metamorphic complex and continuing to <7 Ma. Thermal models for K-feldspars 129 and 135 indicate that the Pangong rocks cooled at *c.* 20°C Ma^{-1} in the interval between rapid cooling phases. Differences in model temperature during this slow cooling period from 13 to 8 Ma suggest that the northern side of the block may have been hotter in this interval (compare K-feldspars models 129 and 135), but the temperature discrepancies between the biotite results and the K-feldspar models leave us with some doubt about the absolute temperature estimates. Subsequent to 8 Ma the Pangong rocks experienced relatively rapid cooling again, at rates of *c.* 100–200°C Ma^{-1}. In contrast, results for K-feldspar 136 indicate that the Chilam granite, south of the Tangtse shear zone, experienced the onset of the second phase of rapid cooling significantly earlier at about 9 Ma. It is not possible to determine from the thermal information alone if the Chilam granite (site 136) experienced the rapid cooling phase from 17 to 13 Ma. However, it seems likely that this granite was reheated prior to 13 Ma and outgassed (as the hot Pangong rocks were upthrust against the granite), losing the Palaeogene signature which characterizes the Ladakh granites (as for example at site 126). In summary, contrasts in the K-feldspar cooling histories suggest that the onset of the second phase of rapid cooling may have been slightly diachronous across the Tangtse shear zone, but that cooling rates were similar.

Cooling from temperatures of lower crustal migmatite formation (>*c.* 750°C) to less than 150–200°C in the period from *c.* 17 to <7 Ma might best be interpreted as the result of tectonic uplift and erosional denudation in two distinct pulses. Alternatively, it has been shown that for rapid uplift and nearly constant exhumation rates (several millimetres per year) the geothermal gradient becomes compressed in the upper few kilometres of the crust (e.g., Batt & Braun 1997). It is possible that the second phase of rapid cooling is a function of material advection through compressed isotherms, rather than a change in exhumation rate. However, the time lag between rapid cooling phases (3–5 Ma) and the slow cooling rates of *c.* 20°C Ma^{-1} would suggest that compressed isotherms in the upper crust would have had sufficient time to relax in the interval 13–8 Ma, and that isotherms would not be closely spaced in the upper crust at 8 Ma.

The preferred interpretation of the isotopic data is that the initial phase of rapid cooling of the Pangong metamorphic complex from 17 to 13 Ma occurred immediately after migmatite formation and granitoid injection in the middle crust and resulted from transpressional uplift along the Karakoram fault zone (Fig. 5). The Ladakh granites and Khardung Volcanics immediately south of the Tangtse shear zone, as well as the marbles and gneisses within the Tangtse shear zone at site 129 also experienced this first rapid cooling phase after reheating to peak temperatures between 300 and 500°C. Searle *et al.* (1998) suggested that oblique thrusting on the Karakoram fault zone dominated the kinematics prior to 11.3 Ma, and that the subsequent kinematics were dominantly right-lateral strike slip. Slow cooling of Pangong rocks from 13 to 8 Ma probably reflects dominant strike-slip motion on the Karakoram fault zone, relatively slow uplift and erosional denudation, and relaxation of isotherms perturbed in the previous oblique thrusting phase. An alternative for this time interval is that the Karakoram fault zone was not moving at all, and that the *c.* 20°C Ma^{-1} cooling rate reflects the overall exhumation rate of the Karakoram at this time. The second phase of rapid cooling of Karakoram fault zone rocks (8–9 Ma to <7 Ma) from temperatures of *c.* 300°C to <200°C occurred at cooling rates >100°C Ma^{-1} in response to a second pulse of transpressional uplift probably via oblique thrusting. Such high cooling rates in this time interval are inconsistent with simple relaxation of isotherms perturbed prior to 13 Ma, so a second pulse of rapid uplift and exhumation would seem to be required.

The Pangong metamorphic rocks were exhumed from deep in the crust since 17 Ma, while in the same period the adjacent Ladakh Batholith (i.e., site 126) experienced maximum exhumation of a few kilometres (exhumation from a depth corresponding to <150°C). In addition, the presence of Mesozoic platform sediments in the Chang-chenmo Range indicates that this region may not be as deeply exhumed as the study area (Fig. 5). These observations are clearly incompatible with a simple shear type model of oblique strike-slip on the Karakoram fault zone on vertical shear planes (transport direction along lineation plunging 20°NW), which would require enormous uplift of the Chang-chenmo (*c.* 32 km for c=1 accommodated within the fault zone). However, an evolution similar to the Alpine Fault of New Zealand accounts for many aspects of the regional geology in the vicinity of the Karakoram fault zone. For instance, the rocks of the relatively cold (<*c.* 150°C) Ladakh Batholith may have acted as a comparatively rigid buttress (e.g., as does the Australian plate west of the Alpine Fault, e.g., Koons 1990), resisting internal deformation, whereas relatively hot and recently intruded Karakoram rocks to the north were exhumed from greater depths via horizontal convergence and sharp upturning of the crust (e.g., east of the Alpine fault in New Zealand there are young amphibolite facies metamorphic rocks). A tectonic evolution of this type, shown in Fig. 5, predicts exhumation of the Pangong metamorphic rocks toward the surface via extrusion on a network of anastamosing strike-slip shear zones and faults, while permitting lesser exhumation of the Ladakh and Karakoram Batholiths and the Chang-chenmo Range.

Miocene exhumation in the Karakoram and southern Tibet

The structural history and kinematic framework of the Karakoram fault zone in northern Ladakh indicates that the evolution of the fault system is closely linked with the middle to late Miocene uplift and exhumation history of the Karakoram Range. Structural and kinematic links between the Karakoram fault zone and the elevated region of southern Tibet have also been demonstrated (e.g., Searle 1996*a*). As such it is useful to compare the timing of Karakoram fault zone movement with phases of exhumation of Miocene and younger metamorphic rocks across this whole region. Below we summarize the important new findings of this study and then we comment briefly on the tectonic history of regions further afield in the Karakoram and southern Tibet.

We have previously made a case for *c.* 20 km of uplift of Karakoram fault zone rocks related to oblique thrusting in the interval 17–11 Ma, and that this uplift is linked to thickening of the southern Tibetan crust (Searle *et al.* 1998). The other main conclusion of that study, further confirmed by the detailed thermochronology presented here, is that the Pangong metamorphic rocks are the most deeply exhumed young metamorphic rocks associated with movement on the Karakoram fault zone. In addition to these findings, several new conclusions about the tectonic history of the region can be drawn. Pangong metamorphic rocks have been exhumed in response to two distinct phases of transpression along the Karakoram fault zone. This exhumation was accomplished via extrusion between the Pangong and Tangtse strands of the Karakoram fault zone, relative to the bulk of the Ladakh Batholith and Chang-chenmo region which did not experience this major Miocene exhumation. Cooling rates during the 17–13 Ma phase of transpression along the Karakoram fault zone were at least 150–200°C Ma^{-1}, which indicates that the rocks overlying the migmatites must have been removed by translation along the fault zone rather than by erosion alone. The northern margin of the Ladakh Batholith was sheared and uplifted relative to the core of the batholith during the second phase of extrusion of the Pangong metamorphic rocks from about 8 Ma to <7 Ma, resulting in exhumation from temperatures greater than about 350°C to below about 150°C. Cooling rates of >100°C Ma^{-1} experienced by the Pangong metamorphic rocks and the rocks of the upturned margin of the Ladakh Batholith during this second phase of extrusion are consistent with tectonic rather than erosion-related denudation of the rocks.

Large tracts of Karakoram metamorphic rocks that experienced peak metamorphism in the Oligocene and early Miocene subsequently experienced rapid cooling through argon closure temperatures (*c.* 500–150°C range) (Searle 1996*b*), contemporaneous with deformation along the Karakoram fault zone. This exhumation occurred shortly after widespread leucogranite magmatism in the Karakoram Range *c.* 21–17 Ma ago (Searle *et al.* 1989, 1992, 1998). The Baltoro leucogranite cooled through *c.* 500–150°C from *c.* 15 Ma to 5 Ma (Searle 1996*b*). Some 50–100 km to the west, the Hunza plutonic complex cooled through the K-feldspar closure window for diffusive loss of argon between *c.* 12 Ma and 4 Ma (Krol *et al.* 1996). The Shyok melange on the southern margin of the Karakoram cooled through hornblende and biotite closure between *c.* 16 Ma and 7 Ma (Brookfield & Reynolds 1990). Thus, while the Karakoram fault zone rocks at Tangtse were cooling relatively slowly at *c.* 20°C Ma^{-1} in the *c.* 13–8 Ma interval between phases of rapid cooling, large parts of the Karakoram were undergoing cooling at similar rates. For a geothermal gradient of 30°C km^{-1} such cooling rates correspond to exhumation rates of less than 1 km Ma^{-1} on average over the mid- to late Miocene. In the last 4–5 Ma large tracts of the Karakoram have experienced significant exhumation, as suggested by the young $^{40}Ar/^{39}Ar$ ages discussed above, the 4.3 Ma to 2.1 Ma fission track ages documented in the vicinity of K2 (Foster *et al.* 1994), and the extreme present-day topographic relief of the region. The high cooling rates (>100°C Ma^{-1}) determined for the second phase of transpression on the Karakoram fault zone starting about 8–9 Ma at Tangtse would predict exhumation of the Pangong rocks to the near-surface environment by about 6 Ma. However, the extreme topographic relief and deep erosion near Tangtse, along with evidence for active faulting, suggests that the cooling rate slowed shortly after about 7 Ma and that a third phase of transpression has affected the Tangtse region. It is interesting to note that mid-Miocene and younger exhumation of the Pakistani Karakoram has occurred over large areas whereas that at Tangtse is focused on a zone only 10 km wide. This localization of the transpressional deformation along the Karakoram fault zone near Tangtse appears to be the reason why the Pangong metamorphic rocks are exhumed from such deep levels.

In our preferred model, motion on the Karakoram fault zone changes from transpression to strike slip dominated at about 13 Ma, and then back to transpression dominated at about 8 Ma. The Karakoram fault zone is kinematically linked along strike with the N–S-oriented graben system (Fig. 1 inset) which is accommodating E–W extension of the upper crust in southern Tibet (Searle 1996*a*). The Thakhola graben (Fig. 1 'T') may have started to form by 14 Ma (Coleman & Hodges 1995). If the formation of the Thakhola graben does indeed herald the onset of E–W extension in southern Tibet, then transpression and rapid uplift along the Karakoram fault zone has immediately preceded graben formation (e.g., Searle *et al.* 1998). Interestingly, Edwards & Harrison (1997) indicate that a segment of the south Tibetan detachment SE of Lhasa was active between 12.5 Ma and 8 Ma, an interval during which transpression was limited or absent along the Karakoram fault zone. The Yadong–Gulu rift is one of the largest graben chains in southern Tibet. The crystalline rocks within the core of this rift experienced rapid cooling through K-feldspar closure temperatures at about 8 Ma (Pan & Kidd 1992; Harrison *et al.* 1995). The development of this structure coincides with renewed transpression-related rapid exhumation on the Karakoram fault zone. Although the cooling events discussed above only relate to specific areas, the available data may indicate a distinct phase of activation and reactivation of regional scale structures *c.* 8 Ma ago, involving overall N–S compression in the lower crust (Main Central Thrust) (Harrison *et al.* 1997), E–W extension of the upper crust in southern Tibet, renewed transpression along the Karakoram fault zone, and sea-floor deformation in the Indian Ocean (e.g., Harrison *et al.* 1992). Further thermochronological studies are required to confirm that these isolated events are related to an orogen-wide pulse of exhumation.

Conclusions

Exhumation of lower crustal migmatites within the Karakoram fault zone in northern Ladakh occurred in two phases, the timing of which appears to correlate with events affecting the Karakoram and southern Tibetan regions. $^{40}Ar/^{39}Ar$ data and ages of zircon crystallization indicate that rapid cooling during these phases occurred at rates of 100–200°C Ma^{-1}. Subsequent to leucogranite intrusion at *c.* 17 Ma, rapid cooling allowed accumulation of argon in K-feldspars by about 13 Ma. After an intervening period of relatively slow cooling at *c.* 20°C Ma^{-1} the fault zone rocks experienced a second phase of rapid cooling starting *c.* 8 Ma within the Karakoram fault zone (Pangong metamorphic complex), whereupon the K-feldspars cooled to below their lowest closure temperatures (*c.* 150–200°C) in less than a million years.

Exhumation in the core of the Karakoram fault zone has exposed young (*c.* 17 Ma) migmatites. The thermal history of the Ladakh Batholith and the presence of Mesozoic platform sediments in the Chang-chenmo Range both indicate that uplift has been focused within a narrow region in and adjacent to the Karakoram fault zone. Exhumation of the Pangong metamorphic complex, which are the most deeply exhumed young metamorphic rocks in this region, occurred by rapid extrusion of the middle crust along the Karakoram fault zone as a consequence of two phases of transpression, from *c.* 17–13 Ma and 8 Ma to <7 Ma. Deformation along the Karakoram fault zone in the intervening period from *c.* 13–8 Ma is interpreted to have occurred in a strike-slip dominated regime.

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