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# The Pangong Injection Complex, Indian Karakoram: a case of pervasive granite flow through hot viscous crust

R. F. WEINBERG[1,2] & M. P. SEARLE[2]
[1]*Research School of Earth Sciences, Australian National University, Canberra ACT 0200, Australia*
[2]*Department of Earth Sciences, Oxford University, Parks Road, Oxford, OX1 3PR, UK*
*(e-mail: Roberto.Weinberg@earth.ox.ac.uk)*

**Abstract:** In the Karakoram Range of NW India, the Tangtse gorge cuts across deep crustal rocks exhumed by transpression along two strands of the dextral Karakoram fault. Crustal leucogranitic magmas pervasively intruded amphibolites and migmatites in the form of sheets that locally coalesced and expanded to form kilometre-scale plutons. Sheets resulted from slow seeping of granite into foliation planes (magma wedging) rather than from dyking, driven by magma buoyancy and possibly syn-intrusive tectonic deformation. High temperature of the country rocks at the time of intrusion is inferred from similar crystallization ages of the intrusive leucogranite and *in situ* partial melt in the migmatites, and reflected in the ductile structures developed. Whereas low country rock viscosity inhibited dyking, high temperature freed the magma from the constraints of freezing and permitted pervasive intrusion. The injection complex exposed along the Tangtse gorge, rather than representing the final emplacement structures, represent transient structures of the granite pathways on their upward journey to build the Karakoram batholith, which crops out a few kilometres north, at structurally shallower levels. We suggest that pervasive magma flow is a transitional step between magma segregation at the source and later rise through cold crust and it may be one of several factors controlling whether dyking or diapirism becomes dominant during late ascent.

**Keywords:** Karakoram, granites, emplacement, dykes, diapirs.

Discussion regarding mechanisms of felsic magma transport through the crust has concentrated on two processes: diapirism and dyking (e.g. Lister & Kerr 1991; Clemens & Mawer 1992; Petford *et al.* 1993; Rubin 1993*a*, *b*; Weinberg & Podladchikov 1994; Weinberg 1996). Based on field evidence, a group of workers has proposed that magma transport may be neither by dykes nor diapirs but by pervasive flow, driven by a combination of magma buoyancy and tectonic deformation, and controlled by local anisotropies (low-pressure sites) such as foliation, fold hinge lines and axial surfaces, boudin necks, fractures and even mineral lineation (e.g. Brown 1995; Collins & Sawyer 1996; Brown & Solar 1998). Pervasive flow is a relatively slow process which evolves at rates compatible with tectonic deformation and which involves the widespread migration of relatively small magma batches (characteristic length scales of the order of dm to tens of m, not to be confused with the grain-scale melt flow through porous media that occurs during melt segregation at the source). Because pervasive magma flow has neither the speed of dykes nor the volume of diapirs, magma is exposed to rapid freezing. Development of pervasive flow must therefore rely on the high temperature of the surrounding rocks (see example in Weinberg 1997) and may be limited to crustal zones undergoing partial melting, their immediate surroundings and other anomalously hot parts of the crust.

Despite its limitations, pervasive magma flow may be a fundamental step in magma transport, linking magma segregation at the source with later magma ascent through colder visco-elastic or elasto-plastic (brittle) crust. As argued by Brown (1994) and Weinberg (1996) the initial stages of magma segregation and transport may control whether dyking or diapirism controls later magma ascent, a proposition that is further developed here. This paper starts with a description of the geological setting of the eastern Karakoram area and general characteristics of Karakoram Himalayan leucogranites, followed by a review of relevant literature on magma transport. Then the Pangong Injection Complex cropping out in the Tangtse gorge is described, where granite sheets, formed by pervasive magma flow into hot and low viscosity rocks, coalesced to form kilometre-sized granite sheeted complexes (plutons). The mechanism of magma intrusion and its significance in the broader context of magma transport are then discussed.

## Geology of the eastern Karakoram

This paper describes field relations between a two-mica garnet leucogranite, the Tangtse leucogranite, and its country rocks, cropping out in the eastern Karakoram, in Ladakh, NW Indian Himalayas. More specifically, we concentrate on the Pangong Injection Complex exposed in a NE SW-trending gorge roughly perpendicular to the regional foliation and bounded north and south by the two main strands of the NW–SE-trending dextral Karakoram fault, approximately 5 km apart (Fig. 1).

The Tangtse leucogranite is part of the young phase of intrusive rocks forming the Karakoram batholith (Fig. 1a). This batholith is *c.* 700 km long, cut by the Karakoram fault, and composed of older granodiorite–tonalite phases (120 85 Ma) such as the Hushe gneiss, the K2 gneiss and the Muztagh Tower gneiss (e.g. Searle 1991) and younger phases (25–20 Ma; Parrish & Tirrul 1989; Schärer *et al.* 1990) composed mainly of two-mica garnet leucogranite and biotite monzogranite (known as the Baltoro granites in

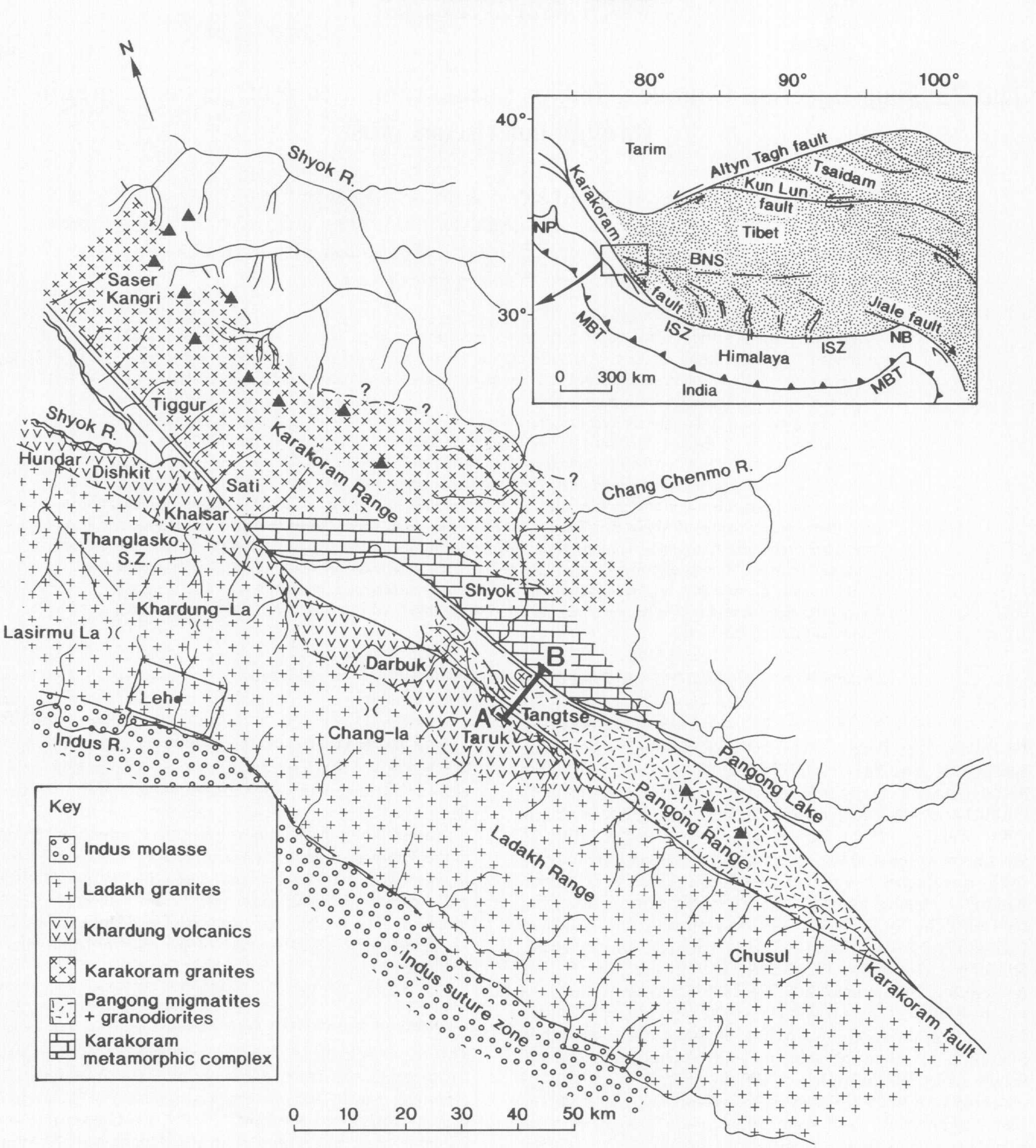


Fig. 1. (a).

Pakistan, Searle *et al.* 1992) west of Fig. 1a. The leucogranite has similar modal and chemical composition to the Baltoro granite and crystallized at *c.* 17 Ma (U–Pb zircon age, Searle *et al.* 1998).

The Tangtse gorge dissects the Pangong Range, a deep crustal block bounded by the two strands of the Karakoram fault. This block has been pushed upward and southeastward, from beneath the Karakoram batholith, by transpressional movement along the fault since its initiation at approximately 17 Ma (Searle *et al.* 1998). These latter authors estimated that the Pangong block was exhumed by *c.* 18 km relative to its surroundings. The high-grade metamorphic rocks now exposed in the Tangtse gorge include minor calc-silicates and metapelites, predominant amphibolites and migmatitic orthogneisses, all intensely intruded by sheets of the Tangtse leucogranite. This leucogranite is markedly different from the biotite–hornblende granite produced by *in situ* partial melting of the orthogneiss. The low mafic mineral content of the leucogranite (colour index <10) suggests a density lower than the more mafic surroundings (colour index >20), implying that, in Tangtse, leucogranites had not attained their neutral buoyancy level when they solidified.

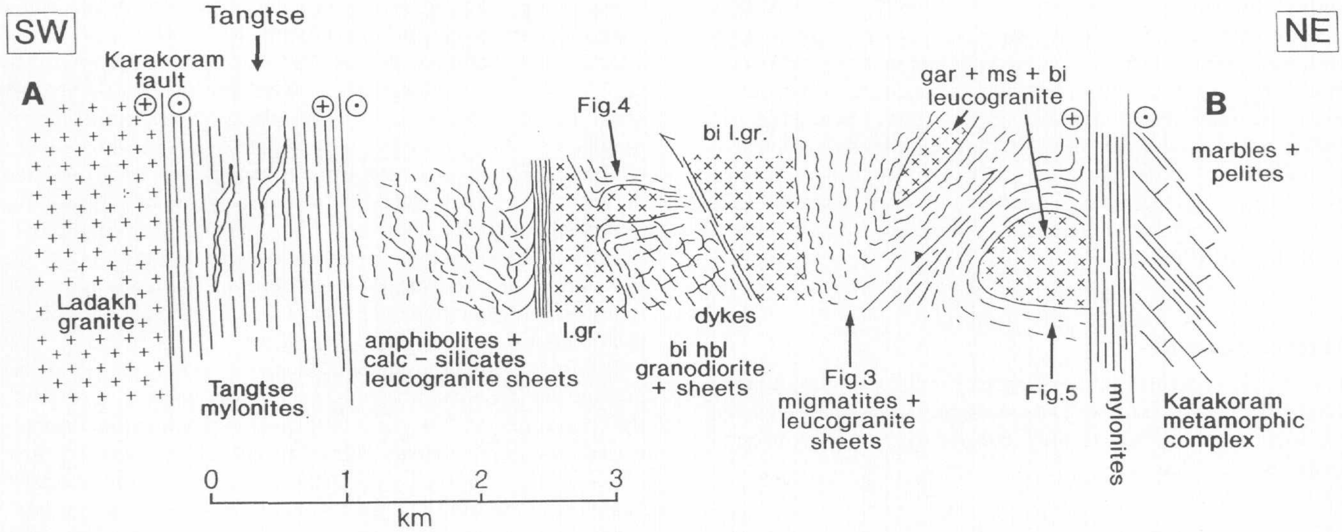


**Fig. 1.** (**b**).

**Fig. 1.** (**a**) Geological map of the dextral Karakoram fault in Ladakh, NW India (after Searle *et al.* 1998). The fault is divided in two strands and transpressional movement led to the pop up of a wedge of high metamorphic grade rocks that now form the Pangong Range and are well exposed by the cross-cutting Tangtse gorge. The Karakoram granite (equivalent to the Baltoro granite in Pakistan) corresponds to melts extracted from crustal rocks during continental collision. The Pangong migmatites and granodiorites are the older metaluminous granites into which Karakoram granites intrude. (**b**) Schematic cross section of the exposures in the Tangtse gorge, linking the two strands of the Karakoram fault. Leucogranites intrude high-grade rocks pervasively forming the Pangong Injection Complex. The locations of Figs 3, 4 and 5 are indicated. Vertical scale equal to horizontal scale.

South of the southern strand of the Karakoram fault, the Ladakh Range is underlain by rocks belonging to the calc-alkaline Ladakh batholith and its related volcanic edifice, the Khardung Formation. Ar–Ar analyses of Ladakh granitoids suggest that these rocks have not experienced temperatures above 150°C since 36 Ma (Dunlap *et al.* in press). In this area of northwestern India, Karakoram leucogranites have not been found south of the Karakoram fault, suggesting that the leucogranites were emplaced just before or during the early stages of movement on the Karakoram fault; several other lines of evidence have been described in detail by Searle *et al.* (1998).

Rocks north of the northern strand of the fault, are mainly greenschist-facies sedimentary and volcanic rocks of the Karakoram Metamorphic Complex intruded by leucogranites of the Karakoram batholith. The main batholith crops out 15 km north of the Tangtse gorge, but Karakoram Metamorphic Complex rocks immediately north of the northern strand of the fault, between the Tangtse gorge and the village of Shyok, are intensely intruded by leucogranite sheets (Fig. 1).

Geographical, geological and geochemical relations strongly suggest that the Tangtse leucogranite is part of the Karakoram batholith, and that Tangtse and the Pangong block represent a deep section exhumed southeastward from beneath the Karakoram batholith by transpressional movement between the two strands of the Karakoram fault.

## Karakoram and Himalayan leucogranites

The highly peraluminous, tourmaline-bearing, two-mica leucogranites cropping out along the High Himalayan chain are relatively small (kilometre-sized) bodies associated with sillimanite-bearing migmatites and numerous dykes. In contrast, the mildly peraluminous monzogranites and leucogranites in the Karakoram form a huge plutonic unit (the Baltoro unit, over 100 km in length) within the Karakoram range in Pakistan (Searle *et al.* 1992) that continues eastward in India for another 150 km. In Pakistan, the Baltoro granite has vertical intrusive contacts along both northern and southern margins and it intruded the country rocks as dykes. The melt source region of the Baltoro is not directly seen (Searle *et al.* 1992).

The leucogranites along the Himalayas are generally sited immediately beneath the South Tibetan Detachment, a shallow, north-dipping, normal fault. Synchronous normal faulting and melting suggest a cause and effect relationship, and that faulting may have controlled granite emplacement. Examples are the Gangotri (Searle *et al.* 1993; Scaillet *et al.* 1995) and the Shisha Pangma leucogranites (Searle *et al.* 1997). The Gangotri leucogranite bodies (the Bhagirati megaboudins of Searle *et al.* 1993) were fed by hundreds of dykes (Scaillet *et al.* 1996) that gave rise to a single large laccolith emplaced syn-tectonically into an extensional shear zone between gneisses and sedimentary cover. Deformation lead to the break up of the laccolith into large-scale, imbricated boudins. Their roofs and floors show intense interleaving between granite sheets and black shales, due to granite wedging (Searle *et al.* 1993, figs 5, 6b & 9), similar to structures observed in the Tangtse gorge.

In Shisha Pangma and Langtang, Nepal, leucogranite migration seems to have been mostly controlled by gently dipping foliation surfaces. These sheets coalesced and ballooned at their final emplacement level (Searle *et al.* 1997).

The $H_2O$ content of granite magmas strongly controls the depth at which they solidify (e.g. Johannes & Holtz 1991). According to Searle *et al.* (1992) the Baltoro magmas originated through fluid-absent melting of a biotite-rich pelite to produce voluminous, $H_2O$-undersaturated magma, capable of rising through the crust. Whereas it has been argued that the Baltoro granite in Pakistan was hotter and drier than

Himalayan leucogranites (Searle *et al.* 1993), there is now considerable evidence that even the latter were $H_2O$-undersaturated. Harris *et al.* (1995) based on geochemical modelling, suggested that Himalayan leucogranites resulted from the fluid-absent melting of muscovite. Scaillet *et al.* (1995) determined experimentally that these Himalayan leucogranites were undersaturated; this was further confirmed by evidence for the vertical mobility of these magmas (e.g. Gangotri leucogranite magmas decompressed by 3 to 7 kbar; Scaillet *et al.* 1996).

## Magma transport

This section is divided into two parts. Firstly, the limitations of dyking for granite transport are assessed, then a brief review of previous work on structurally controlled pervasive magma ascent is presented.

### *Dyking*

The term *dyke* has been used rather broadly to describe planar, preferentially (but not necessarily) steeply dipping, cross-cutting, magmatic intrusions. The term *dyking*, the mechanism through which dykes are formed, refers to the specific process of elastic cracking of country rock by tensional stresses concentrated at the tips of magma-filled fractures (e.g. Lister & Kerr 1991). However, not all described 'dykes' result from dyking; many sheet-like bodies may arguably result from other processes, such as pervasive magma flow. Although this terminology problem is generally unimportant, we consider that it becomes crucial when discussing mechanisms of magma transport.

Lister & Kerr (1991) showed that, for dykes of any geologically significant dimension, the resistance of the rock to fracture is very much less than the available driving pressure. Dykes will tend to be oriented parallel to the direction of maximum compression. Despite dykes being independent of crustal weaknesses for their propagation, the stresses at their tips may interact with these weaknesses and lead to their reorientation (Lister & Kerr 1991).

Wickham (1987) used the well-known ability of pore pressure to trigger rock fracturing to show that, during partial melting of rocks submitted to external stresses, magma pore pressure can give rise to fractures perpendicular to the direction of maximum compression, parallel to foliation planes. Pressure gradients drive melt from the pores to the cracks, giving rise to foliation-parallel sheets. However, this mechanism does not explain the origin of *intrusive* sheets of similar orientation. Although magma pressure in a sheet may drive fracturing, due to concentration of elastic stresses to the sheet tip, it cannot be equated with pore pressure, as has been done in some examples in the literature, to explain foliation-parallel sheets. Pore pressure is entirely independent of magma pressure in a sheet. If, however, pore pressure is high and rock anisotropy produced foliation-parallel fractures, these provide weakness planes that may be exploited by intruding magmas.

Dyking may be severely constrained because it exposes magma to rapid freezing, particularly during the early stages of dyke growth. Several papers have shown how, given a large enough initial dyke, felsic magmas can rise rapidly through the crust as dykes to produce upper crustal batholiths (e.g. Bruce & Huppert 1990; Clemens & Mawer 1992; Lister & Kerr 1991; Petford *et al.* 1993). The estimated critical widths for self-propagating dykes are well within common felsic dyke widths found in nature (Petford *et al.* 1993). Rubin (1993*a*, *b*; 1995) showed that particular conditions are necessary for relatively high-viscosity felsic magmas to overcome this initial growth stage. Based on Rubin's work, Weinberg (1996) argued that it may be the ability of dykes to grow in the hot magma source, where magma is protected from freezing, that controls later magma transport. If dykes in the source grow to form a long and well-connected network, high magma pressure allows rapid and effective dyke propagation through cold crust. If, however, such a network does not develop, dyking is inhibited, and magma accumulates and may rise diapirically (Weinberg & Podladchikov 1994).

Rubin (1993*a*) showed that, depending on an elastic index, and on the viscosity ratio between country rocks and magma, the crustal response to magma stresses may vary from entirely elastic, for high viscosity ratios, to entirely viscous, for low ratios. In between the two extremes, there is a region of mixed behaviour in which the dyke tip encounters an elastic response whereas the main body encounters a viscous response and expands sideways into deforming wall rocks, but the sheet tends to maintain a high aspect ratio (>10).

Another factor limiting dyke propagation is the sharpness of the dyke tip. This is a function of the viscosity of the wall rock and the viscosity ratio between country rock and magma, and controls the concentration of elastic stresses at dyke tips. Blunt tips, developed in low-viscosity rocks, do not concentrate stresses as efficiently as sharp tips, and may hamper dyke propagation (e.g. Clemens & Mawer 1992; Rubin 1993*a*). This seems to have been the case in the Grenville Province, Quebec, described by Corriveau & Leblanc (1995) where dykes stalled when they reached a low-viscosity marble-rich layer. Magma then accumulated and rose as diapirs.

In summary, whereas dyking is potentially an efficient mechanism of transporting felsic magma, the initiation of dykes is strongly inhibited by magma freezing, and dyke propagation is inhibited by high magma viscosity and low country rock viscosity.

### *Pervasive flow*

Based on field evidence, some workers have proposed an alternative mechanism to dyking and diapirism, in which magmas rise by exploiting crustal weaknesses (e.g. Hutton *et al.* 1990; D'Lemos *et al.* 1992; Brown 1994, 1995; Grocott *et al.* 1994; Collins & Sawyer 1996; Brown & Solar 1998). These authors concluded that magma is driven upward by buoyancy, assisted to different degrees by contemporaneous tectonic deformation (the 'deformation enhanced ascent' of Brown 1994). Brown (1995) and Collins & Sawyer (1996) described migmatite terrains in which magma intruded pervasively, parallel to anisotropies such as foliation planes, fold hinges, layering, mineral lineation and boudin necks. During intrusion, magma is distributed widely in small pockets (metre scale) of low buoyancy stress. If, as proposed by these authors, deformation plays a fundamental role in pumping magma upward, magma migration must develop slowly, at rates compatible with tectonic deformation.

## The Pangong Injection Complex

Extensive intrusion of leucogranites into the high-grade rocks of the Pangong Range produced the Pangong Injection

**Fig. 2.** Viscous flow of leucosomes plus melanosomes into a narrow crack or a boudin neck in a more competent layer. The flow pattern suggests a low compounded viscosity of the migmatite layers underneath the dark more competent layer.

Complex. Geochronology and field observations suggest a hot and ductile environment that deformed under magma stresses and controlled the style of magma migration.

### *Hot country rocks*

Zircon U–Pb dating of the Tangtse leucogranite, using the Sensitive High Resolution Ion Microprobe (SHRIMP) yielded a crystallization age of $17.8 \pm 0.6$ Ma (Searle *et al.* 1998), indicating that the granite is contemporaneous with the 24–17 Ma High Himalayan leucogranites (e.g. Shisha Pangma $17.3 \pm 0.2$ Ma, Searle *et al.* 1997) and with the 20–25 Ma Baltoro two-mica garnet leucogranite of Pakistan.

Zircons from leucosomes of the *in situ* migmatites, which the leucogranite intrudes, have also been dated using the SHRIMP. Results suggest a two-phase growth of zircon crystal rims at approximately 20 and 17 Ma around older $106 \pm 1.6$ Ma cores (Searle *et al.* 1998). However, due to uncertainties in the data related to Pb-loss and the effects of high U content, these authors interpreted the data as representing a melting phase that occurred between 20 and 17 Ma, broadly contemporaneous with leucogranite intrusion. In the field, however, we were unable to find unambiguous evidence for the coexistence of the intrusive Tangtse leucogranite melts with *in situ* partial melts. Irrespective of whether the two melts coexisted, the inference is that, at the time of leucogranite intrusion, the surrounding rocks were at or close to the granite solidus temperature. This is clearly borne out by the ductile structures which formed in response to leucogranite intrusion.

### *Low-viscosity structures*

Structures developed during partial melting of the country rocks suggest very low compounded viscosity of the leucosome plus melanosome layers (Fig. 2). During leucogranite intrusion, hot, possibly still partially molten, country rock (migmatites, amphibolites and metapelites) continued to behave in a ductile fashion. Although planar, cross-cutting, dyke-like sheets developed locally, most sheets intruded parallel to the foliation and formed irregular bodies. This gave rise to complex structures (Fig. 3) reminiscent of the complex 'viscous folds' of high-melt-fraction migmatites (McLellan 1984). Like 'viscous folds', these structures developed because of

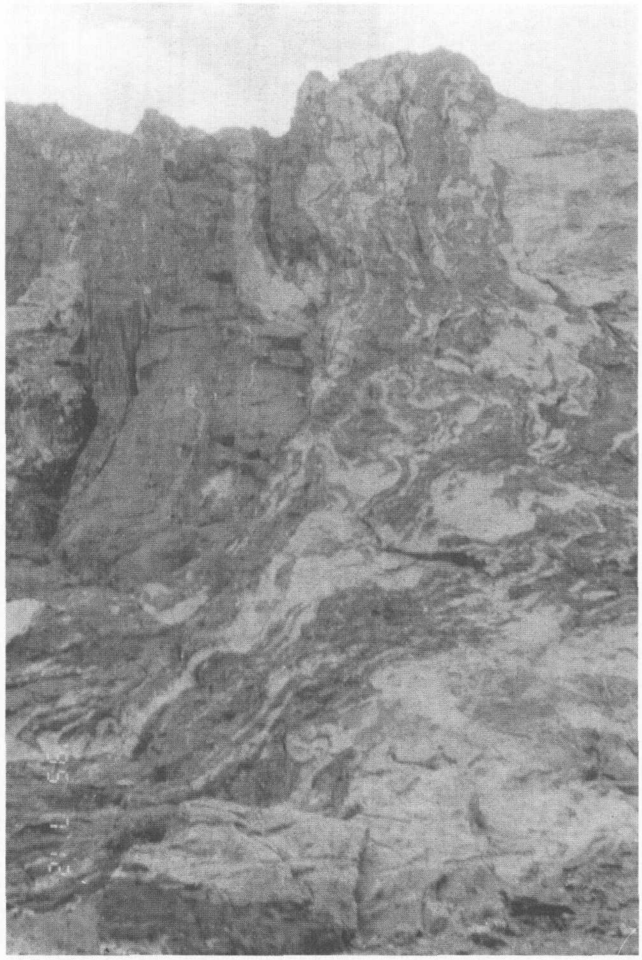

**Fig. 3.** Voluminous intrusion of leucogranite sheets into hot rocks gave rise to convoluted patterns where narrow screens of wall rock in between sheets were easily folded. In this melt-rich environment, the general viscosity was low and allowed development of irregular, non-planar sheets with decimetre to metre scale blisters (balloons). Height of the rock wall approximately 100 m. See Fig. 1b for location.

voluminous granite intrusion and low country rock viscosity. In contrast to the small leucosomes in McLellan's (1984) study, the buoyancy stress of individual sheets in Tangtse could have been sufficient to deform their low-viscosity wall rocks. The large-scale structures in Tangtse may therefore have developed by a combination of tectonic and magmatic stresses.

Granite sheets underwent post-magmatic deformation, caused by movement on the Karakoram fault, which overprinted intrusive structures and produced granite foliation, boudinage of the competent granite sheets, and mullions of the less competent mafic rocks. It is most likely that the early foliation into which granites intruded and late foliation development were part of a continuous deformation process. Based on regional observations, Searle *et al.* (1998) argued that movement along the Karakoram fault began after granite emplacement. However, their considerations do not exclude the possibility of granite having intruded during the early stages of movement on the fault. In this case, granite intrusion would have been contemporaneous with the development of early foliations.

Figure 4 shows a laccolith-shaped body formed by coalesced granite sheets dipping NW (into the plane of the photo). The

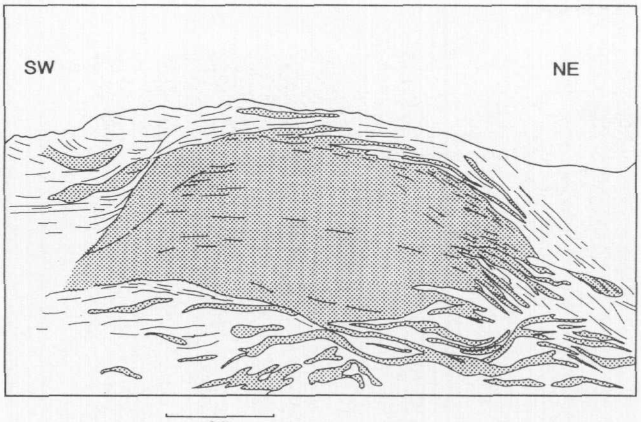


**Fig. 4.** Magmatic wedging, where one or several magma sheets intruded pre-existing foliation, wedged it open and expanded pushing the country rock aside to form a single large body. On the northeast side of the body, the early stage of the process was frozen in. Granite from the main body intrudes the country rock *lit par lit* as narrow sheets.

surrounding foliation is conformable with the main granite body. The top contact is characterized by a gradational zone, several metres wide, in which narrow sheets intrude the foliation. The NE margin (right-hand-side of Fig. 4) is characterized by a foliation-parallel decrease in volume and number of granite sheets. Topographically below the area in Fig. 4 (not shown), there are cross-cutting planar sheets that may have resulted from local initiation of dykes where the country rocks responded elastically.

We interpret the structures as resulting from the coalescence and lateral expansion of several sheets while they were in the process of wedging open the country rock foliation. This is best exemplified by the frozen structures on the NE margin of the body, where numerous sheets intrude and wedge the country rock. Because of the post-magmatic overprinting, the conformable country rock foliation cannot be used as evidence of sheet expansion (ballooning). Whereas we have no direct evidence the ballooning of this particular body, there are two indirect lines of evidence to suggest that it did occur. Firstly, small sheets in the country rocks have expanded into weaker zones to form small (metre-sized) rounded blisters (details in Fig. 3). Secondly, most observed structures are ductile, suggesting that rock flow is the most likely space-making mechanism.

Figure 5 shows a kilometre-sized pluton showing similar structures to the laccolith-shaped body of Fig. 4. The pluton is surrounded by granite sheets conformable with the margin of the main pluton, except for sheets on the right-hand-side of the figure, which leave the pluton at high angles to its margins. The number and width of granite sheets decrease gradually away from the plutons margins and, within the pluton, there are numerous screens of the dark wall-rock. These features suggest that the pluton grew by the coalescence of sheets and that the dark bands are remaining screens or country rock separating different sheets. Structures representative of the early stages of pluton growth are still exposed at the pluton's immediate surroundings, where fewer and less voluminous sheets intrude the country rocks (e.g. Fig. 3).

During post-intrusive deformation, the pluton behaved as a rigid body around which the less competent surrounding rocks, including the less voluminous granite sheets, was wrapped. The sheets at high angles to the pluton margin define a region interpreted as a strain shadow during deformation. Similar to Fig. 4, post-intrusive deformation prevented us from unambiguously demonstrating the viscous ballooning of granite into the country rocks. However, judging by the generally low viscosity of the country rocks during intrusion, this is the most likely mechanism for opening space for the pluton.

## Discussion

### *Intrusion mechanism*

The sheets in Tangtse could be interpreted as resulting from dyking as follows: (a) elastic fracturing of crustal rocks submitted to stress concentration at dyke tips gave rise to the sheets. Later viscous response of the walls gave rise to their non-planar shape and the growth of balloons/blisters. As the injection complex developed, the compounded viscosity decreased and viscous folds developed (McLellan 1984). The convoluted patterns and small-scale balloons differ considerably from the shapes of expanded dykes in visco-elastic rocks as envisaged by Rubin (1993, fig. 1). This is most likely because Rubin considered a homogeneous visco-elastic medium whereas, in Tangtse, local viscosity changes lead to complex shapes. (b) General orientation of sheets parallel to foliation resulted either from the switching of $\sigma 1$ and $\sigma 3$, due to changes in regional stresses, or because of interaction between dyke tips and local anisotropies.

However, the general impression gained from field observation does not entirely agree with dyke intrusion as outlined above. Although dyking may have played a role, evidence supports an alternative, slow, pervasive, magma migration through preferential channelways, driven by magma buoyancy and syn-intrusive tectonic deformation in a way similar to that proposed by Brown (1995) and Collins & Sawyer (1996).

The crux of the matter is that low country rock viscosity inhibits dyking (by blunting of dyke tips) and high temperature permits pervasive seeping flow (by freeing magma from the constraints of freezing). As discussed above, dyke propagation relies on the concentration of magma stresses at dyke tips. Magma stresses applied to the dyke walls are transferred and concentrated elastically at the tips, cracking the country rock. If the walls respond to the magma stresses as viscous fluids, there will be no transfer of stress from the walls to the tip, and dyke propagation may be hampered. Blunt tips, characteristic of crack propagation through low viscosity rocks, may further inhibit dyke propagation.

Crustal resistance to dyke propagation is negligible once a dyke grows beyond a very modest size (Lister & Kerr 1991). Geologically significant dykes may therefore propagate independently of pre-existing crustal weaknesses. Magma migration in Tangtse, on the contrary, seems to depend on these weaknesses. More importantly, magma in Tangtse was trapped in large volumes at a depth at which it was still buoyant. If magma was travelling in dykes only minor volumes would have remained at this crustal level.

There are two likely alternative explanations. Firstly, magmas were travelling in dykes that stalled and spread pervasively when reaching this low viscosity zone. Secondly, and our preferred one, magmas were never migrating in dykes, but were slowly moving upward through Tangtse, by seeping into the foliation planes in a hot environment. They were frozen in the process by regional temperature changes, possibly related to rapid exhumation. In either case, dyking was not the

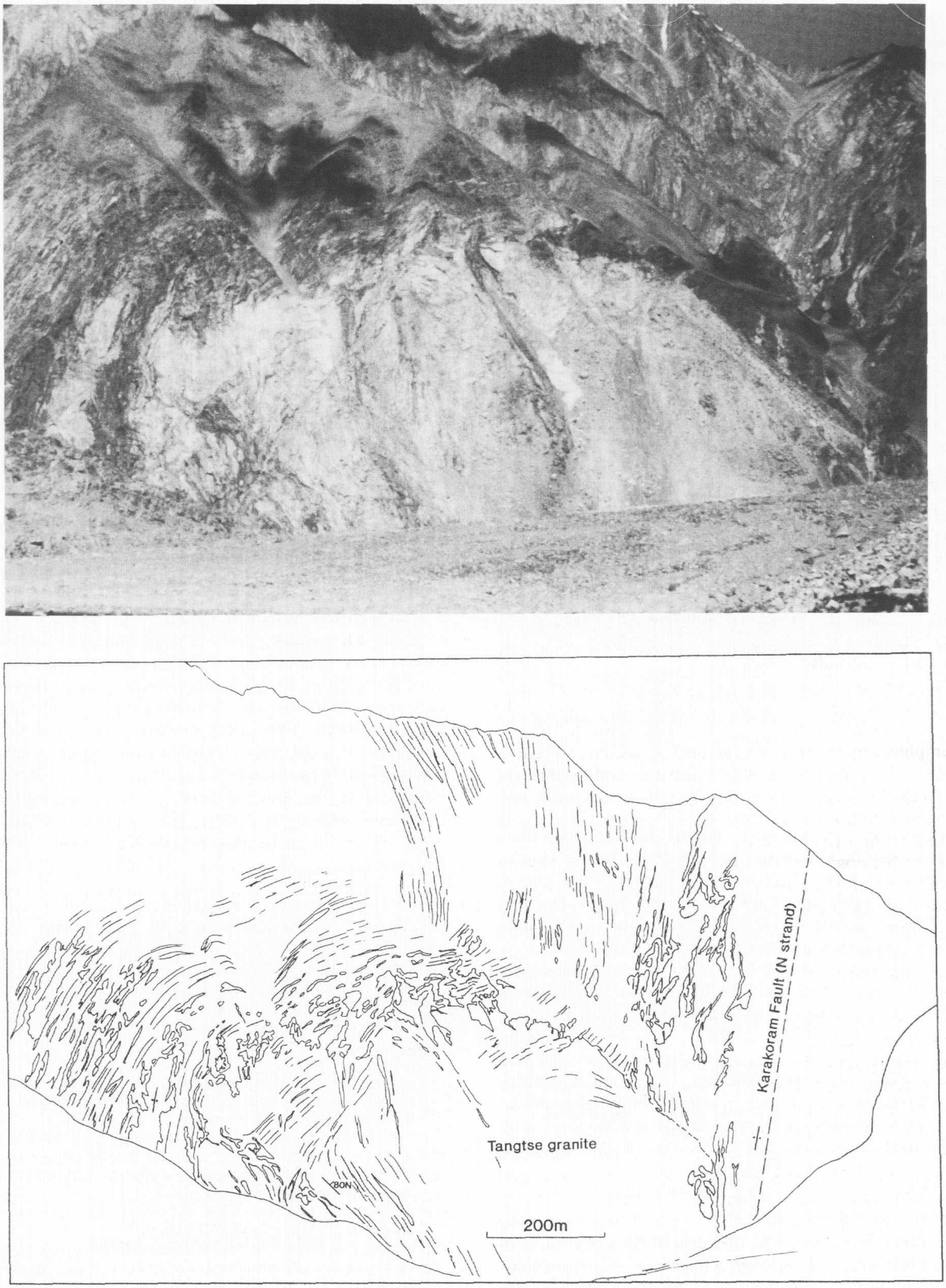


**Fig. 5.** (**a**) Photograph and (**b**) line drawing of the Tangtse pluton at the NE end of the gorge (Fig. 1b), a granite sheeted complex showing preserved screens of darker country rocks and numerous conformable sheets intruding its surroundings. On the far side of the pluton (NE, right-hand side), sheets leave the body at a high angle to the margin indicating a strain-shadow region.

preferred mechanism of magma migration through this particular crustal section. The difference between the two alternatives above is simply whether this section represents the final emplacement level or the pathways of granitic magma to the Karakoram batholith.

### *Magma pathways or emplacement level?*

The structures exposed in Tangtse could be interpreted as resulting from the final emplacement of the leucogranites or as representing the dynamic pathways of granites on their way to the higher level Karakoram batholith. Based on two indirect arguments, we favour the latter possibility. Firstly, the leucogranites in Tangtse have not reached their neutral buoyancy level. Secondly, this is a section of deep, high-grade, metamorphic rocks exhumed from beneath the presently exposed greenschist-facies level of the Karakoram batholith.

Given favourable conditions, it should be possible to decide between the two alternatives by investigating the widths and temperatures reached in the contact aureoles around magma sheets. Sheets through which large volumes of magma have travelled would present disproportionately wide and hot contact metamorphic aureoles (Clemens & Mawer 1992). However, in Tangtse this cannot be seen because of the widespread, high metamorphic grade of the country rocks, combined with the pervasive character of the intrusion.

Granite magma pathways are envisaged here as a dynamic environment in which several laccolith-shaped bodies and plutons (like Figs 4 and 5) are interlinked and feed each other through narrow magma sheets. We imagine these chambers as transient, rather than fixed in size and place, continuously evolving driven by tectonic deformation, magma buoyancy, magma availability and local permeability of the system: expanding, contracting, and slowly rising. We believe the exposures in Tangtse to represent a snapshot of this process.

### *Sheeted complexes*

We suggest that the pervasive magma flow, as described above, gave rise to kilometre-sized sheeted plutons. Hutton (1992) summarized the characteristics of several well known sheeted granite complexes, including the Main Donegal Granite (Pitcher & Berger 1972), the Ox Mountains Granite (McCaffrey 1992) and the Great Tonalite Sill (Hutton & Ingram 1992; Ingram & Hutton 1994). These bodies were formed by the coalescence and interdigitation of granite sheets 1 to 10 m wide, giving rise to sheet widths of 300 m (Ox Mountains) to 2 km (Main Donegal). The granite sheeted complexes at Tangtse are composed of sheets 1–10 m wide and differ from those previously described in that their country rocks were hot before granite injection (with temperatures close to the solidus of quartz-diorite/amphibolite) and responded to the magmatic stresses as low-viscosity fluids.

### *The role of tectonic deformation*

Pervasive flow, as proposed by Brown (1995) and Collins & Sawyer (1996), results from magma buoyancy combined with tectonic deformation. These authors attributed considerable importance to the pumping of magma through the crust by tectonic deformation, but did not discuss the important constraints on the process imposed by magma freezing. In Tangtse, syn-magmatic structures have been obscured by post-magmatic deformation. The structural complexity exhibited by the intrusions is believed to result from the interaction between magmatic and tectonic stresses superimposed on rock-strength anisotropies. However, the relative importance of magmatic and tectonic stresses in driving magma migration could not be assessed.

### *Control of pervasive flow on later ascent mechanisms*

Two primary structures resulted from the inferred pervasive magma flow in Tangtse, sheets and sheeted plutons. As magmas rise, lower temperatures inhibit pervasive magma flow and another, more focused mode of magma transport is required. At this point, several factors control the preferred mode of transport. One of them is the geometry and dynamics of particular structures growing during pervasive flow (see Weinberg 1996). If pervasive flow gives rise to a long network of interconnected sheets, high magma pressure may easily fracture the colder crust and give rise to dykes. On the other hand, if magma pressure is low, or magma viscosity high, dyking may be inhibited and the high buoyancy stress of the kilometre-sized sheeted plutons may allow their rise as diapirs.

## Conclusion

In this paper, the pervasive intrusion of the Tangtse leucogranite, into hot country rocks, is described. The high prevailing temperature inhibited dyke propagation and permitted slow pervasive magma flow through mainly pre-existing foliation planes, probably assisted by pressure gradients imposed by deformation. Low-viscosity country rock flowed under combined magmatic and tectonic stresses resulting in complex structures, non-planar magma sheets and decametre- to kilometre-sized balloons/blisters in places where sheets coalesced and expanded into particularly weak zones. Following Brown (1994) and Weinberg (1996), we suggest that early, pervasive magma flow may play a fundamental role in determining the preferred ascent mechanism during later stages.

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