The dike swarm of the Karakoram shear zone, Ladakh, NW India: Linking granite source to batholith

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ABSTRACT

Debate regarding migration of granitic magmas arises from the fact that the physical link between migmatites and plutons and batholiths is rarely documented. Within the Karakoram shear zone, Ladakh, NW India, the synkinematic transfer of magma can be traced from the anatectic source region to the Karakoram Batholith through a complex dike swarm. Melting is due to water fluxing at upper-amphibolite facies, producing Miocene hornblende and garnet–two mica leucogranites. The anatectic zone is characterized by synmagmatic folding and shearing of migmatites, and by pervasive, irregular magma migration paths forming injection complexes. These irregular networks are linked to dike networks that are interpreted to represent a magma transfer zone characterized by a range of styles, such as (1) dike swarms parallel to the shear plane, (2) dikes following the two major foliation planes in the shear fabric, (3) magma sheets in conjugate pairs of ductile fractures, or (4) chaotic dike complexes. Network geometries are controlled by the regional stress field, strain distribution, preexisting anisotropies, and rheological contrasts. Dikes give rise to anastomosing systems with rare crosscutting relationships, and with intersections oriented parallel to the dominant mineral stretching lineation. Dikes feed a number of sills, stocks, plutons, and, ultimately, the leucogranitic Karakoram Batholith. We propose that magma developed an interlinked, continuous dike swarm from source to sink by interacting with deformation and preexisting anisotropies. Unlike theoretical and laboratory predictions, dikes are typically oriented at high angles to the maximum shortening axis, and unlike expectations, water-fluxed melting of the crust produced mobile magma that migrated to form large granitic bodies.

INTRODUCTION

Whether or not dikes represent viable and efficient pathways for magmas to feed granitoid plutons has been the subject of intense debate (Clemens and Mawer, 1992; Emerman and Marret, 1990; Petford et al., 2000; Petford et al., 1994; Rubin, 1993a; Weinberg, 1996, 1999). One of the arguments against diking as an efficient mechanism for the transport of granitoid magmas is the relative rarity of felsic dike swarms, compared to mafic dike swarms (Weinberg, 1996). It is possible nevertheless that a small number of dikes could provide transport paths for large magma volumes from the lower to the upper crust (Cruden, 1998, 2005; Jackson et al., 2003; Scaillet et al., 1995). If this is so, the question then becomes how these few structures tap into large volumes of magma initially distributed over a large volume of anatectic rocks (Cruden, 2005; Cruden and McCaffrey, 2001). This would require a mature, self-organized network of fractures and permeable magma pathways over large volumes of migmatitic source region (Bons and van Milligen, 2001; Brown, 2004; Petford and Koenders, 1998).

Another open question is dike initiation (Rubin, 1998). Magma pressure at the dike tip drives dike propagation into pristine rock. This pressure depends on dike length, and only long dikes can propagate efficiently through cold rock and avoid freezing (Rubin, 1993b, 1998). Long magma sheets could develop by means of ductile fracturing in the source region, providing the seeds for rapidly propagating elastic-brittle dikes (Brown, 2006; Weinberg and Regenauer-Lieb, 2010).

There are only rare descriptions of felsic feeder dikes or dike swarms in the literature (Hutton, 1992; Ingram and Hutton, 1994; McNulty et al., 1996; Scaillet et al., 1995), and, unlike theoretical predictions (e.g., Lister and Kerr, 1991), dikes commonly tend to be parallel to the dominant tectonic foliation rather than perpendicular (Brown and Solar, 1998a, 1998b; Vernon and Paterson, 2001; Weinberg and Mark, 2008). Alternative ascent mechanisms have been proposed, such as diapirism, pervasive flow, and shear channeling, and more than one of these might operate at the same time, and gradational changes from one to the other might occur (Brown, 1994; Brown and Solar, 1998b; Hasalová et al., 2008; Rubin, 1993a; Weinberg and Podladchikov, 1994). While pervasive flow may prevail in the partially molten lower to middle crust (Weinberg, 1996; Weinberg and Searle, 1998), alternatives are required for migration through the colder middle to upper crust (Clemens and Mawer, 1992; Petford et al., 1993; Petford et al., 1994; Weinberg and Regenauer-Lieb, 2010).

Deformation controls the sites of melt formation, segregation, and subsequent transport and accumulation (Brown, 1994; Collins and Sawyer, 1996; Hand and Dirks, 1992; Vanderhaeghe, 1999; Weinberg et al., 2009). Buildup of melt pressure in conjunction with deformation facilitate interconnection of melt pockets at grain scale and development of melt networks in the anatectic region (e.g., Brown et al., 1995; Sawyer, 1994; Stevenson, 1989; Weinberg and Mark, 2008). Magma pumping along the foliation plane, parallel to the maximum elongation direction, has been proposed as the preferential flow direction in shear zones (Brown and Solar, 1998b; Marchildon and Brown, 2003). Alternating phases of transpression and transtension in crustal-scale shear zones, associated with geometric evolution of rheologically contrasting rock types, may lead to magma accumulation in low-pressure sites, subsequent magma expulsion into a transport network, and final emplacement into dilational jogs (Brown, 1994; D'Lemos et al., 1992; McFadden et al., 2010; Weinberg et al., 2009).

These ideas are fundamentally based on field observations and contrast with experimental work of melt pathways in ductilely shearing media, which predict formation of melt accumulations on shear planes parallel or at a small angle to the maximum compressive stress (Holtzman and Kohlstedt, 2007; Katz et al.,

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2006; Kohlstedt and Holtzman, 2009; Rosenberg and Handy, 2005; van der Molen and Paterson, 1979). In partial melting experiments of granitic rocks, "squeezing" of melt from initial films between grain boundaries oriented perpendicular to the maximum compression axis into cracks oriented perpendicular to the minimum compression axis has been observed (Dell'Angelo and Tullis, 1988; Rabinowicz and Vigneresse, 2004). Thus, it seems that experiments are in many instances at odds with natural examples (Collins and Sawyer, 1996; Hand and Dirks, 1992; Marchildon and Brown, 2003; Vernon and Paterson, 2001; Weinberg and Mark, 2008).

The Karakoram shear zone in Ladakh, NW India, contains within it a complex network of leucogranitic bodies forming a dike swarm that links an exposed anatectic region to the Karakoram Batholith (Reichardt et al., 2010). It provides a rare opportunity to study magma flow networks that transfer magma from source to sink. Here, we investigate this leucogranite dike swarm from in situ leucosomes at its roots, through complex magma transport networks with varying styles, to the Karakoram Batholith.

REGIONAL GEOLOGY

The NW-SE trending Karakoram shear zone exposed in Ladakh lies in the central part of the 750-km long Karakoram fault and separates the Karakoram terrane to the NE from the Ladakh terrane to the SW (Dunlap et al., 1998; Searle et al., 1998). The Karakoram fault is part of a crustal-scale strike-slip fault system that accommodates the northward push of the Indian plate into Eurasia, and is characterized by dextral strike-slip motion.

In Ladakh, the shear zone splits into two parallel mylonitic strands (Fig. 1). The Tangtse shear zone (SW strand) dips 70°NE and separates rocks of the Pangong metamorphic complex from rocks of the Ladakh Batholith and its extrusive equivalents, the Kardhung volcanics to the SW. The Pangong shear zone (NE strand) dips steeply SW to vertical and separates the Pangong metamorphic complex from the Karakoram metamorphic complex to the NE. The Pangong metamorphic complex is composed of a ca. 70 Ma calc-alkaline suite that consists of mostly diorites, hornblende-biotite (Hbl-Bt) granodiorites, and biotite (Bt) granodiorites (mineral abbreviations after Kretz, 1983), known as the Muglib Batholith (Ravikant, 2006; Ravikant et al., 2009; Reichardt et al., 2010), a metaigneous rock sequence of Hbl-Bt gneisses ranging to amphibolites, and a metasedimentary rock sequence of Bt-psammites, Bt-pelites, and calc-silicate rocks. Minor beds of marble crop out in the Tangtse shear zone (Dunlap et al., 1998; Phillips et al., 2004; Weinberg and Searle, 1998).

The Tangtse and Darbuk-Shyok gorges, cutting perpendicular to the strike of the Karakoram shear zone through the Pangong Range (Fig. 1B), expose rocks of the Muglib Batholith and of the metamorphosed volcanic-sedimentary sequence that were migmatized at upper-amphibolite facies (Reichardt et al., 2010; Weinberg and Mark, 2008). This anatectic event gave rise to Miocene leucogranite injection complexes, local stocks and plutons of Bt-leucogranites, biotite-muscovite (Bt-Ms) ± garnet (Grt) leucogranites, and minor Hbl-leucogranites (Weinberg and Searle, 1998; Weinberg et al., 2009). Irregular leucosomes and intrusive sheets and planar dikes can be traced into plutons such as the Tangtse Pluton at the NE end of the Tangtse gorge (Weinberg and Searle, 1998; Weinberg et al., 2009) or the Darbuk Pluton at the SW end of the Darbuk-Shyok gorge (Fig. 1B).

These leucogranites are petrographically and isotopically similar to those forming the Karakoram Batholith, which crops out alongside the Nubra and Shyok valleys (Fig. 1A) from Agham to the Siachen glacier in the border region to Pakistan, and a genetic relationship has been inferred (Reichardt et al., 2010; Searle et al., 1998). This relationship is also supported by comparable crystallization ages (Reichardt et al., 2010; Weinberg et al., 2000). Leucogranite crystallization age determinations based on U-Pb ages of zircons and titanites indicate that magmatic activity in the Karakoram shear zone spanned the period between ca. 20 and 13.5 Ma (Phillips et al., 2004; Reichardt et al., 2010; Weinberg and Searle, 1998; Ravikant et al., 2009). The Tangtse Pluton (Fig. 2) is related to the Pangong injection complex (Weinberg and Searle, 1998; Weinberg et al., 2009) and has ages between ca. 18 and 15 Ma, indicating that the intrusion formed through amalgamation of multiple magma pulses (Phillips et al., 2004; Reichardt et al., 2010). The Darbuk Pluton (Fig. 1B) also yields a similar age range between ca. 20 and 15 Ma (Ravikant et al., 2009). These ages match those found for the Karakoram Batholith (Phillips et al., 2004; Weinberg et al., 2000).

The main tectonic foliation within the Pangong metamorphic complex trends generally 130° to 150° and dips steeply, parallel to the trend of the Karakoram shear zone. An ubiquitous mineral and stretching lineation plunges gently to moderately (0°–45°, generally between 20° and 45°) NW to NNW (Dunlap et al., 1998; McCarthy and Weinberg, 2010; Weinberg et al., 2009), parallel to the axis of tight to isoclinal upright folds. Geometric compatibility suggests that folding within the Pangong metamorphic complex was contemporaneous with the shearing that gave rise to the two main mylonitic Tangtse and Pangong shear zones (Weinberg and Mark, 2008). The Pangong metamorphic complex rocks were uplifted in relation to the surrounding rocks, in a pop-up structure, which resulted in exposure of upper-amphibolite-facies anatectic rocks in contrast to lower-grade rocks to the NE and SW (Dunlap et al., 1998; McCarthy and Weinberg, 2010). Ar-Ar data suggest that deformation continued from amphibolite to greenschist facies during cooling after the anatectic event as a result of transpression (Dunlap et al., 1998; McCarthy and Weinberg, 2010; Rolland et al., 2009).

Locally, mylonitic rocks of the Pangong shear zone record a greenschist-facies overprint where stretching lineations, defined by muscovite, epidote, and chlorite, plunge moderately SE, indicating reactivation with a NE-side-down component (McCarthy and Weinberg, 2010; Rutter et al., 2007). Evidence for present-day movement in the area has been reported only in one locality from the Pangong shear zone, whereas the Tangtse shear zone seems to be inactive (Brown et al., 2002). Present-day right-lateral slip over the whole length of the Karakoram shear zone recorded by satellite radar interferometry (InSAR) is of the order of 1 ± 3 mm/yr (Wright et al., 2004).

WATER-FLUXED MELTING AND MAGMA ASCENT

Anatexis in the Pangong metamorphic complex was triggered by water influx (Reichardt et al., 2010; Weinberg and Mark, 2008), as indicated by the presence of large, poikilitic and commonly euhedral hornblende megacrysts in leucosomes and melanosomes (Gardien et al., 2000; Kenah and Hollister, 1983; Lappin and Hollister, 1980; Mogk, 1992) and by the lack of anhydrous peritectic minerals in migmatites, such as sillimanite, garnet, or orthopyroxene (Fig. 3). This interpretation is in agreement with thermobarometry by Rolland and Pêcher (2001), who determined peak metamorphic conditions in the Tangtse area to be at temperatures of 700 ± 20 °C at pressures of 7 ± 1 kbar, based on the association of muscovite and sillimanite in the absence of K-feldspar in metapelites and cation exchange reactions (minerals used: Grt-Bt, Grt-Pl-Ms-Qtz, Grt-Pl-Ms-Bt, and Grt-Pl-As-Qtz; note that sillimanite is rare in the region). These conditions are just below those required for the onset of muscovite dehydration melting and well below biotite and hornblende dehydration melting.

Ascent of magma resulting from water-fluxed melting is problematic because magma would

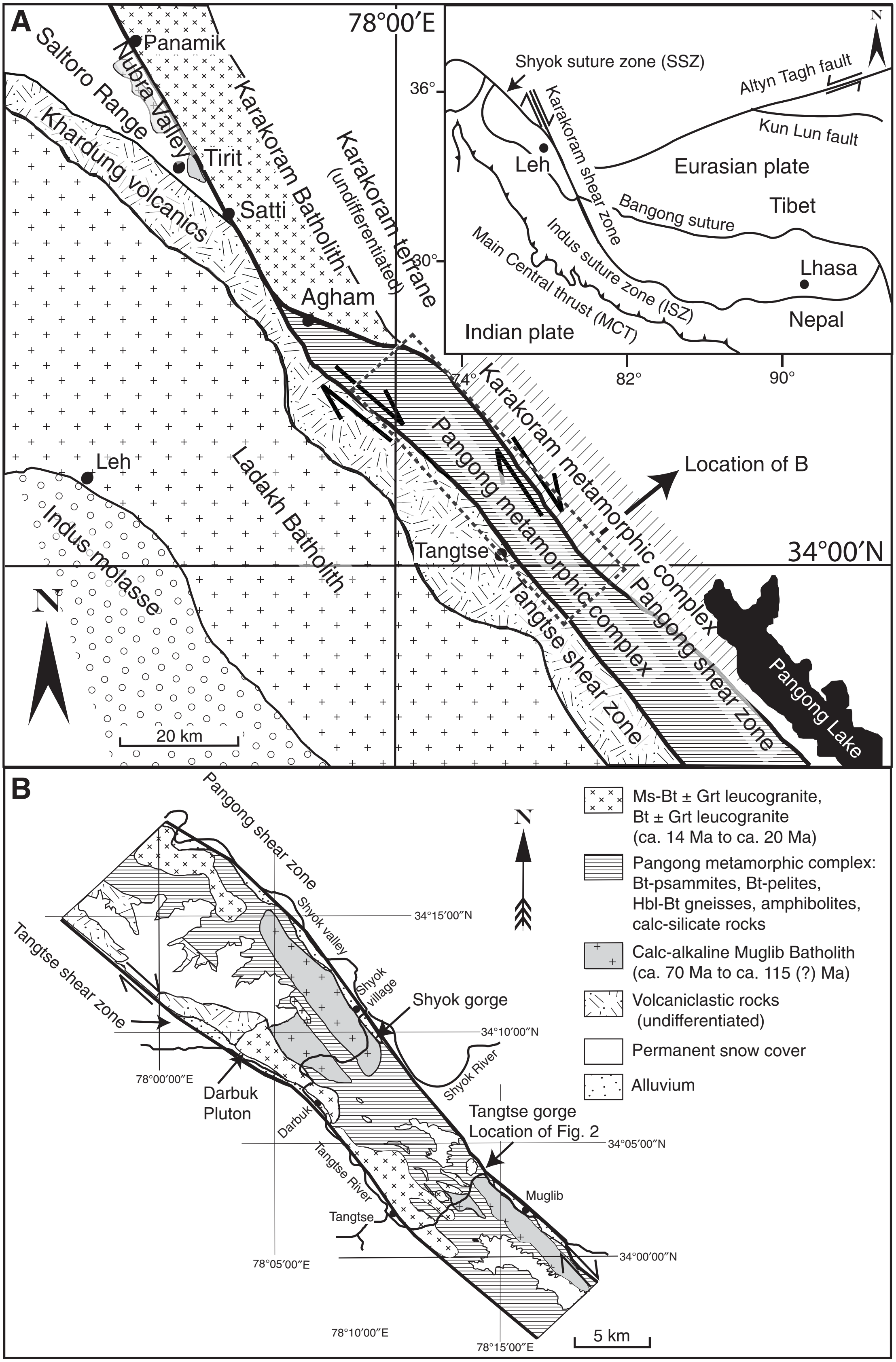

Figure 1. (A) Geological overview map of the Karakoram shear zone and bordering units. (B) Locations of outcrops, the Tangtse gorge and the Darbuk-Shyok gorge.

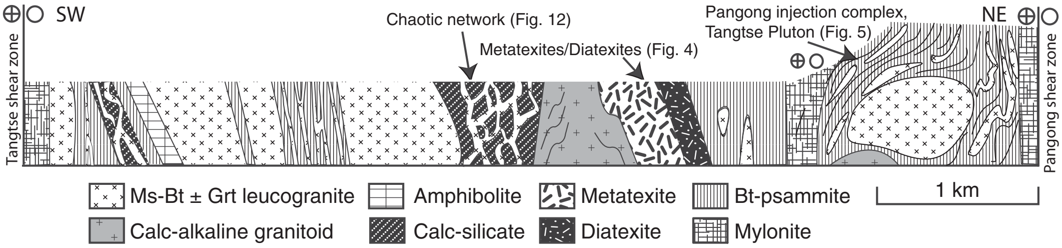

Figure 2. Geological cross section along the Tangtse gorge perpendicular to strike of the Karakoram shear zone.

tend to crystallize upon decompression due to the negative slope of the wet granite solidus (Clemens and Vielzeuf, 1987). However, ascent is possible if: (1) the magma remains water undersaturated, (2) it is heated above its solidus temperature (e.g., Weinberg, 1999), or (3) it is effectively segregated from restitic phases (Leitch and Weinberg, 2002). If external water is brought into the system, the onset of melting could take place above the wet solidus temperature but still below temperatures required for dehydration melting. As a consequence of segregation, the magma solidus may be decreased because it cannot reequilibrate with the residue, and the melt may ascend until it reaches its new wet solidus (Clemens and Droop, 1998). Over time, magma migration may heat up the surroundings, thus expanding the zone in which it is freed from freezing, gradually moving the magma front upward (Brown, 2007; Leitch and Weinberg, 2002).

In summary, upward migration of magma derived from water-fluxed melting may be possible through a combination of a degree of undersaturation, super-solidus melting, and the gradual heating up of the magma pathway. In the Pangong metamorphic complex, remnants of different types of magma flow networks formed by water-rich magmas are exposed on the way from source to batholith, and will be described in the following sections.

KARAKORAM SHEAR ZONE DIKE SWARM: LINKING SOURCE TO BATHOLITH

This section starts with a description of remnant magma flow network features in the anatectic source that are interpreted to form the roots of the complex. This is followed by a description of the metric- to kilometric-scale features of the dike swarm that forms the transfer zone, linking source to intrusions of stock to batholith dimensions. Here, we use the migmatite nomenclature of Sawyer (2008): Leucosome describes regions in the migmatite that are derived from segregated partial melt. It may consist of a combination of crystallized anatectic melt and magma that has already undergone some degree of fractionation. Metatexite describes a migmatite in which pre–partial-melting structures are still preserved, and which has undergone low degrees of partial melting (usually <20%–30%). Diatexite describes a migmatite in which pre–partial-melting structures are obliterated, and which has undergone high degrees of partial melting (usually >20%–30%) and is characterized by synanatectic flow structures.

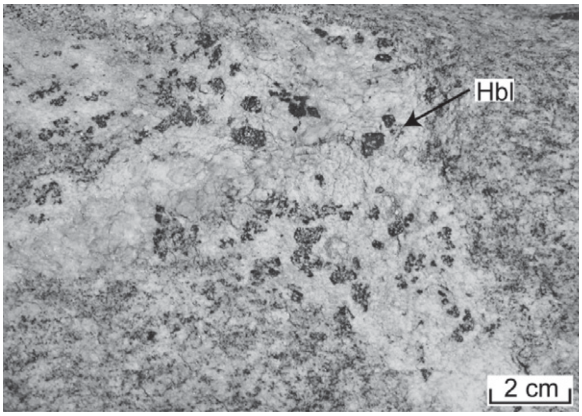

Figure 3. Idiomorphic, poikilitic hornblende megacrysts in a patchy leucosome in calc-alkaline hornblende-biotite granodiorite. Note diffuse boundaries to melanosome.

Magma Extraction Networks in the Anatectic Zone

The magma network that developed during folding and shearing of the anatectic zone is particularly well-exposed in the Tangtse gorge (Fig. 2). Migmatitic Hbl-Bt-granodiorites, Bt-granodiorites, and diorites of the Muglib Batholith have leucosomes that have diffuse boundaries with their surroundings interpreted to represent the melanosome. Migmatites in Bt-psammites may either be patchy with leucosomes with diffuse boundaries, or stromatic where leucosomes are rimmed by thin melanosomes. Metatexites and diatexites in the Tangtse gorge were described in detail by Weinberg and Mark (2008), and here we provide only an overview of the most important features.

In meter-scale folds, metatexite migmatites in the central part of the Tangtse gorge have layer-parallel leucosomes that are continuous with axial-planar leucosomes (Fig. 4). Axial-planar leucosomes commonly accommodate shearing and have diffuse boundaries against the surroundings, indicating either that melt was present during shearing, and the shear zones represented low-pressure sites into which melt segregated (Brown and Solar, 1998b; Davidson et al., 1994; McLellan, 1988), or that melt intruded into the shear zones after deformation. The first alternative is more likely because the leucogranite is petrographically continuous with the folded, layer-parallel leucosomes. Sharp, cuspate fold hinges, and the dragging of layers along axial-planar channels indicate flow along the axial plane toward the concave fold closures. Disrupted metatexite layers are commonly rotated into parallelism with the axial plane of folds, either due to flow and disruption or due to shearing (Fig. 4) (Reichardt et al., 2010; Weinberg and Mark, 2008). There are significant regions where transposition is accompanied by obliteration of premigmatization layering marking the transition from metatexite to diatexite (see diatexite regions in Fig. 2). Weinberg and Mark (2008) concluded that folding facilitated melt connectivity between layer-parallel leucosomes and axial-planar leucosomes, giving rise to magma escape pathways, and magma escape facilitated fold tightening and transposition.

Locally, leucogranite networks at the decimeter to meter scale, formed by narrow dikelets (cm to dm in width), are linked with irregular meter-wide magma sheets (Weinberg and

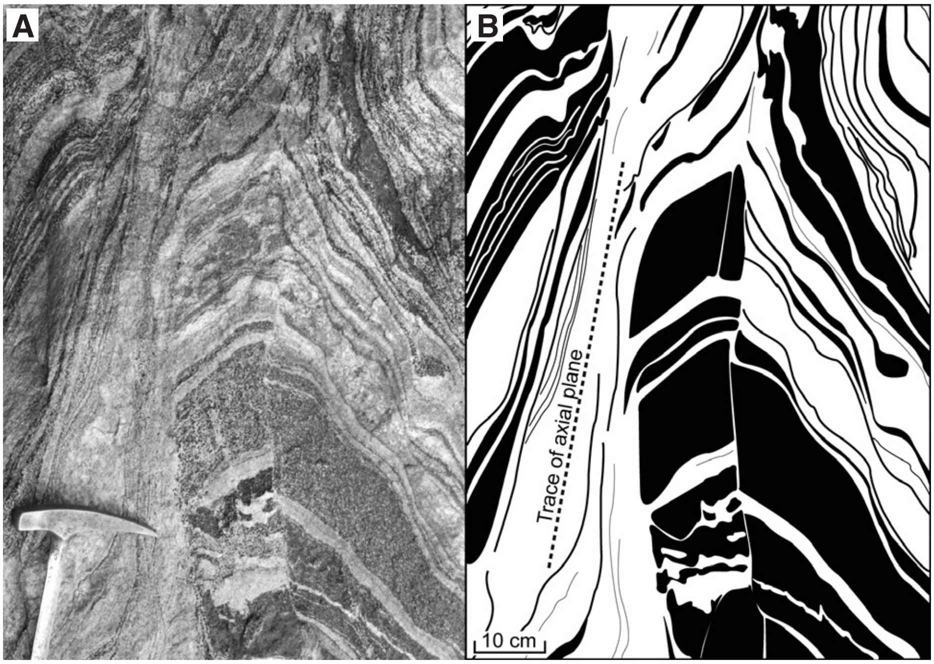

Figure 4. (A) Fold in metatexite in the central part of Tangtse gorge. (B) Line drawing of A. Note movement along the axial plane leucosome cutting through the hinge zones and transposition of layers on the left-hand side and in the top center of the image into axial-planar orientation. The trace of the axial plane is indicated with a dashed line. The leucosomes in axial-planar orientation in the left central part are continuous with layer-parallel leucosomes.

Searle, 1998). At the NE end of the Tangtse gorge (Fig. 2), magmas intrude the metasedimentary sequence, forming the Pangong injection complex, where leucogranites occupy more than 30% of the exposure (Fig. 5) (Reichardt et al., 2010; Weinberg et al., 2009; Weinberg and Searle, 1998). Intrusions here are irregular in shape, forming bulbs and tortuous sheets. The host Bt-psammite is migmatitic, as evidenced by patchy leucosomes with diffuse boundaries and leucosomes with thin melanosome rims. These migmatites were deformed viscously, enhancing the seemingly chaotic nature of the injection complex (Weinberg and Searle, 1998). Such irregular injection complexes seem to be limited to regions that underwent partial melting during intrusion.

Dike Swarms: The Transfer Zone

Dike swarms are well developed within the Karakoram shear zone and particularly well exposed in the Tangtse and Darbuk-Shyok gorges (Figs. 1B and 2). The leucosome network in migmatites links continuously with both the irregular injection complexes described previously and to a much larger-scale intrusive network of dikes. Collectively, these dikes give rise to a complex network with a variety of geometrical patterns, and they are interpreted to represent the magma transfer zone.

There are a number of magmatic phases related to the Miocene anatectic event, and these occasionally show crosscutting relationships (Fig. 6). However, these relationships are subordinate to the dominant pattern where dikes merge, diverge, and remerge continuously forming an anastomosing network without any systematic crosscutting and offsetting relationships (Fig. 7). The dikes range in width from a few centimeters to several meters, and, petrographically, it is impossible to discern the merging dikes or define a boundary between them.

Most commonly, dikes within the Karakoram shear zone are parallel to the shear zone, following the orientation of the dominant anisotropy defined by the main regional foliation, trending 130°–150°. Dikes are strongly foliated when they are within the main bounding shear zones, where they form leucogranitic mylonites. Away from the bounding shear zones, dikes are weakly foliated, and the intensity of the foliation depends on grain size, with unfoliated pegmatites grading into foliated, finer-grained Ms-Bt-leucogranite along the same dike. This relationship between foliation intensity and grain size suggests that timing of intrusion in relation to deformation cannot be addressed by using the presence of foliation alone.

Intersection between foliation-parallel dikes and those crosscutting the dominant foliation produces the interconnected networks. We measured 190 dike attitudes in exposures at the SW end of the Tangtse gorge, where an interlayered sequence of Bt-psammites, amphibolites, and calc-silicate rocks is extensively intruded. The mean strike of these dikes is 141°, and their mean dip is 69° NE, similar to the regional foliation and to the general trend of the Karakoram shear zone (Figs. 8A–8C).

Dike intersections measured directly in the field plot on a great circle parallel to both the

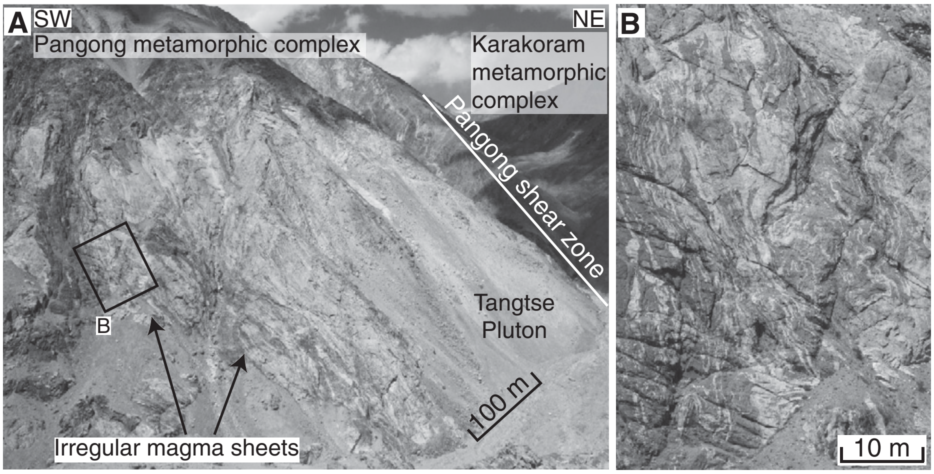

Figure 5. (A) Miocene leucogranitic Tangtse Pluton at NE end of Tangtse gorge. (B) SW margin of the Tangtse Pluton with irregular magma sheets of the Pangong injection complex. Pervasive intrusion into migmatized Bt-psammites gives rise to chaotic folds.

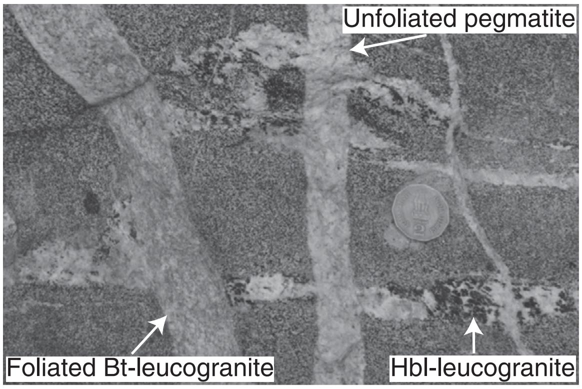

Figure 6. Relatively uncommon example of crosscutting relationships between dikes in a weakly foliated diorite. An earlier coarse-grained hornblende-bearing granitic dike is cut across by an unfoliated pegmatitic leucogranite dike (vertical dike in center), and by a biotite leucogranite that is foliated concordant to the host rock (diagonal dike on the left-hand side).

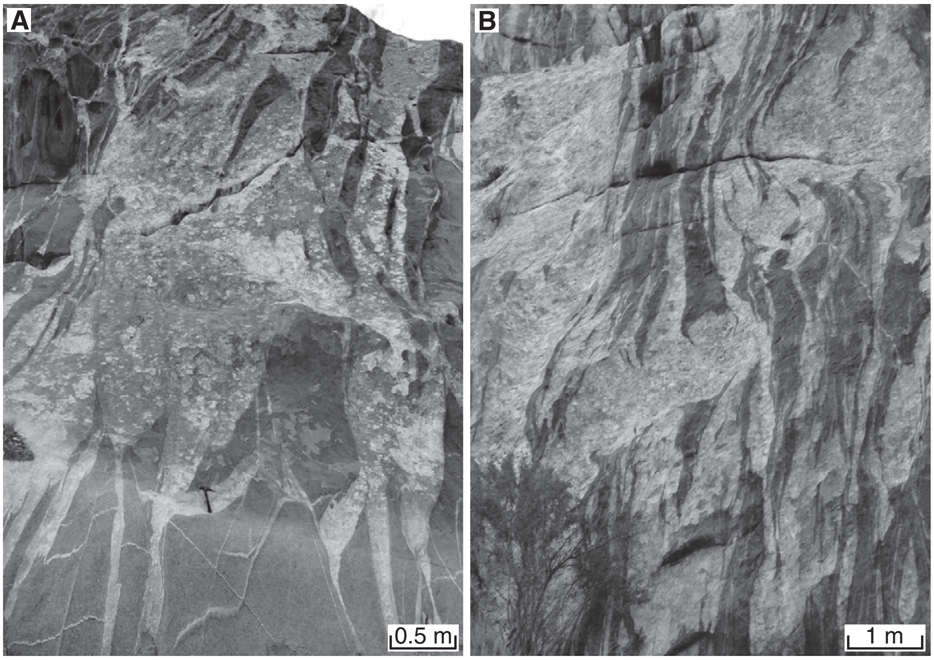

Figure 7. (A) Leucogranite dike network widening upward and merging to form a wider body that is itself further linked upward with numerous narrower dikes. (B) Example of an interconnected network of irregular intrusive bodies. Note deflection of the foliation in surrounding rocks indicative of postmagmatic shortening and moderate deformation of the irregular granitic bodies.

dominant foliation and the Karakoram shear zone and define a cluster with a mean plunge value of 39° toward 326° (Fig. 8D). This orientation is similar to the mean orientation of the mineral stretching lineation (327°/29°) on foliation surfaces and to fold axes in migmatites (Fig. 8E). In places, two or more dikes meet at a single point without truncations, defining a common intersection (Fig. 9) forming spider dikes (Brown, 2006). In every documented case, the dike intersection, had a larger diameter than the width of the merging dikes, and the intersection is parallel to the regional lineation.

In summary, dikes tend to give rise to anastomosing and continuous networks, and to define intersections parallel to stretching lineations and fold axes in surrounding rocks. Beyond these shared features, dike networks define a variety of geometrical styles, described next.

Shear Fabric Dike Swarm

This network style is characterized by dikes that intrude both the C- and S-foliations associated with oblique dextral shearing. This geometry is exposed in a vertical wall on the NE end of the Darbuk-Shyok gorge (Fig. 10). Here, leucogranite dikes intruded calc-alkaline magmatic rocks of the Muglib Batholith mainly along the dominant foliation plane parallel to the shear plane (C-plane, ~150°/subvertical), but also form an oblique set of dikes (~110°/dipping steeply SW). These oblique dikes commonly have an asymmetric wave shape, characterized by steepening dips as they merge with vertical dikes. Pinch and swell structures and boudins in some of the dikes are indicative of continued deformation after crystallization. Dike attitudes were not measured directly on this outcrop but were estimated from protruding wall surfaces, and estimates were checked against dike orientations that could be measured directly on exposures nearby. Their attitudes are shown in inset in Figure 10 and define a common intersection plunging SE, parallel to the intersection lineation between C and S foliations and perpendicular to the more general intersection defined in Figure 8D. The example in Figure 10 is the only large-scale expression of shear fabric control on diking.

Conjugate Fracture and Chaotic Dike Networks

There are two different network styles in calc-silicate layers: (1) dikes that form conjugate sets, and (2) chaotic networks. The dikes in conjugate sets cut across bedding and foliation and form a continuous network characterized by zigzagging patterns (Fig. 11A) and Y-shaped structures where dikes diverge and remerge at roughly 60° (Fig. 11B). They also typically have tortuous margins and blunt tips and lack mutual offsets when intersecting (Weinberg and Regenauer-Lieb, 2010), and, locally, they isolate rotated blocks of calc-silicate rock. The common intersection of these dikes is parallel to the regional mineral stretching lineation. This network style was described in detail in Weinberg and Regenauer-Lieb (2010) and interpreted to result from magma intrusion into ductile fractures, which developed from coalescence of pores that grew as a result of ductile recrystallization of the rock (Weinberg and Regenauer-Lieb, 2010). Magma flowed into the pores, and gradual coalescence evolved into a rapidly propagating fracture.

Chaotic networks, in contrast, lack obvious preferential dike orientation (Fig. 12A). Despite their chaotic appearance, the dikes tend to share a common intersection, parallel to the stretching lineation (Fig. 12B). This geometry implies that the chaotic geometry is best seen in planes perpendicular to lineation and suggests the absence of significant differential stresses on this plane at the time of diking. Chaotic networks are physically linked to leucogranite plutons (Fig. 12C).

Other Factors Controlling Geometry

Lithological Contacts

Control of lithological contacts on dike orientations tends to be subtle in the Karakoram shear zone dike swarm, presumably because lithological

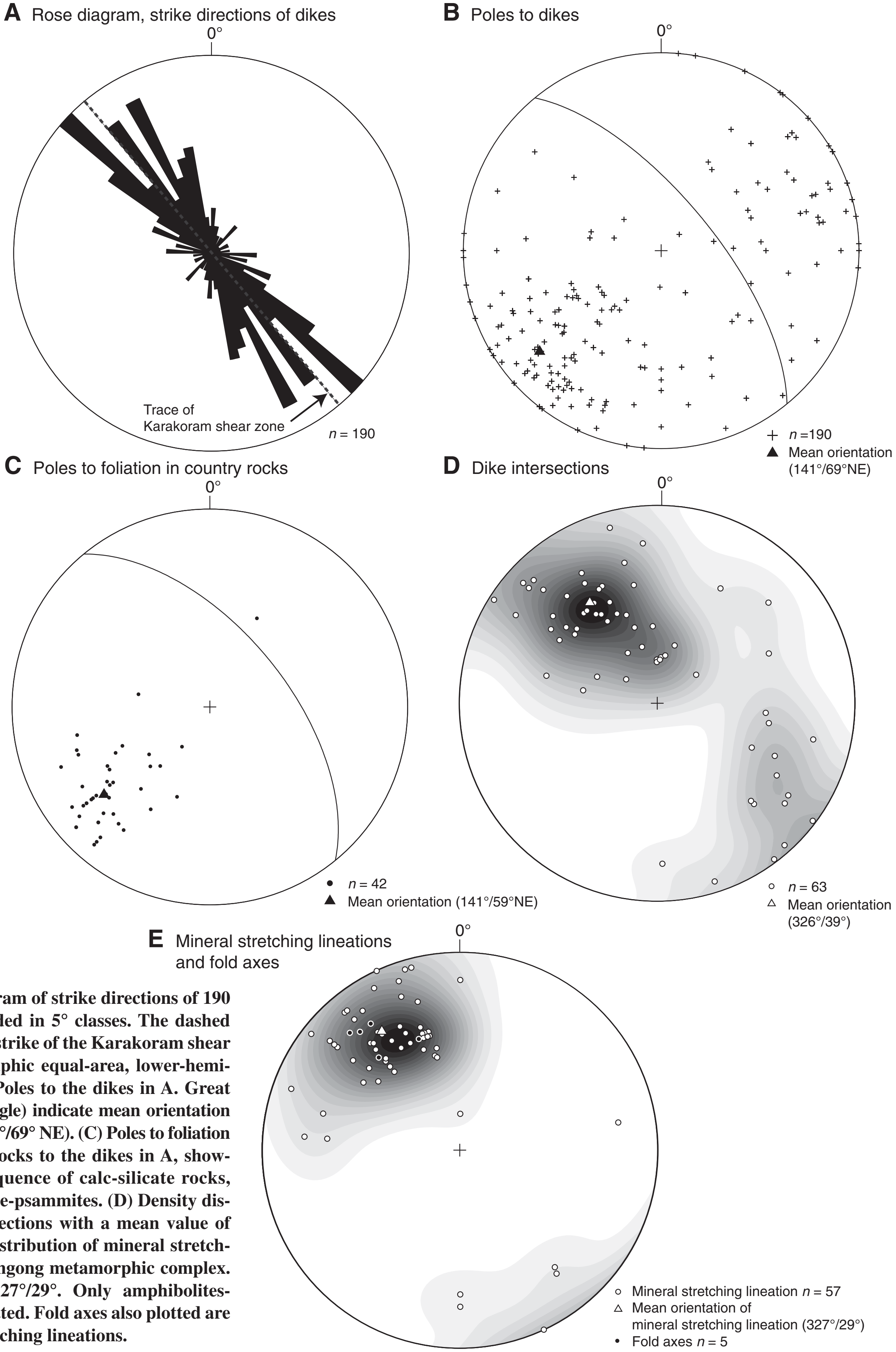

Figure 8. (A) Rose diagram of strike directions of 190 leucogranite dikes divided in 5° classes. The dashed line indicates the mean strike of the Karakoram shear zone at 140°. Stereographic equal-area, lower-hemisphere projection. (B) Poles to the dikes in A. Great circle and its pole (triangle) indicate mean orientation of all measurements (141°/69° NE). (C) Poles to foliation planes of the country rocks to the dikes in A, showing an interlayered sequence of calc-silicate rocks, amphibolites, and biotite-psammites. (D) Density distribution of dike intersections with a mean value of 326°/39°. (E) Density distribution of mineral stretching lineations in the Pangong metamorphic complex. Mean orientation is 327°/29°. Only amphibolites-facies lineations are plotted. Fold axes also plotted are parallel to mineral stretching lineations.

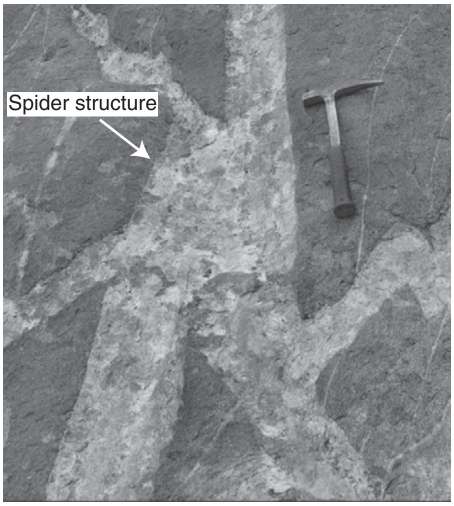

Figure 9. Spider dikes in calc-alkaline hornblende-biotite granodiorite. Dikes merge seamlessly without visible truncation of magmatic textures or modal composition.

contacts tend to be parallel to the main foliation and dike orientation. Figure 13 shows an example where a contact between a lens of calc-silicate rocks and migmatitic Bt-psammites is at high angle to the dominant steep foliation. Here, an ~0.5-m-wide, subvertical dike intruded the calc-silicate rock and deflected to form a sill parallel to and immediately below the contact with the overlying migmatite. The overlying migmatite has small-scale folds and was not intruded by the magmas that ponded below the contact.

Shearing

An important consideration regarding the geometry of the dike swarm within the Karakoram shear zone is the effect of continued deformation and rotation of solidified dikes away from their original, intrusive attitudes. Given the dextral-reverse, transpressive nature of the shear zone (Dunlap et al., 1998; Searle et al., 1998), planes would tend to rotate toward the dominant shear plane, and dike intersection orientations would tend to rotate toward the stretching direction. Rotation most likely played a role, but we estimate that in general, this is a relatively minor effect, because the total strain recorded by leucogranites forming dikes varies from negligible in coarse-grained and pegmatitic rocks to moderate in fine- to medium-grained leucogranites with a gneissic foliation. There are nevertheless cases in which high-strain zones have rotated the dike network. An example of this is shown in Figure 14, where a chaotic dike network tends to become increasingly parallel to a shear zone due to increased straining.

PLUTON GROWTH

In amongst the various networks comprising the Karakoram shear zone dike swarm, there are irregular kilometric leucogranitic sills, stocks, and plutons, such as the Tangtse and Darbuk

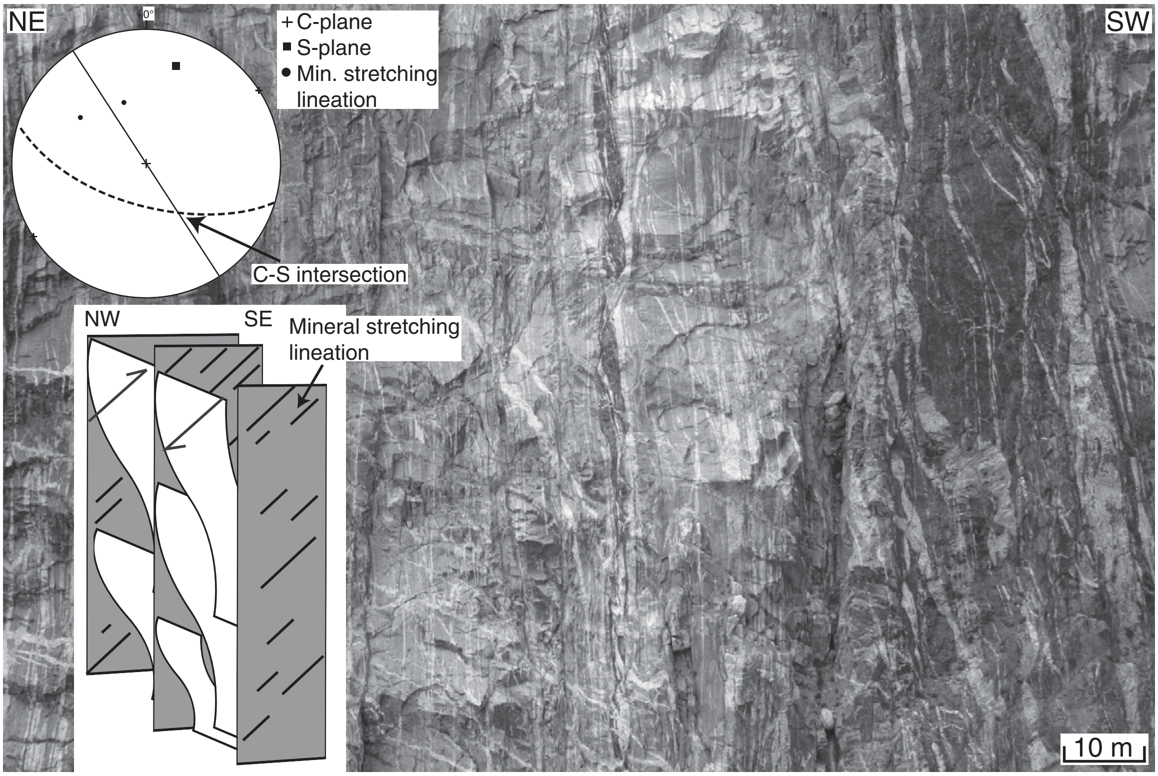

Figure 10. Leucogranite dikes in hornblende-biotite granodiorites to diorites in Darbuk-Shyok gorge. Outcrop wall is inaccessible for measurements. Most dikes are subvertical, with a subordinate group dipping steeply to the SW (to the right). These commonly have sigmoidal shapes, steepening when merging with vertical dikes, indicating a NE-side-up (left) component of shear, as determined for the Karakoram shear zone. Insets: Representative stereographic, equal-area, lower-hemisphere projections of typical C planes (solid great circle, 150°/90°) and S plane (dashed great circle, 107°/65°SW) intruded by dikes in hornblende-biotite granodiorite in outcrops in the vicinity. Other inset: Three-dimensional interpretation of diking and shearing. Note that mineral stretching lineation plunges NW and the intersection of C-plane and S-planes is almost perpendicular and plunges SE. Arrows indicate oblique (dextral and NE-side-up) shear movement.

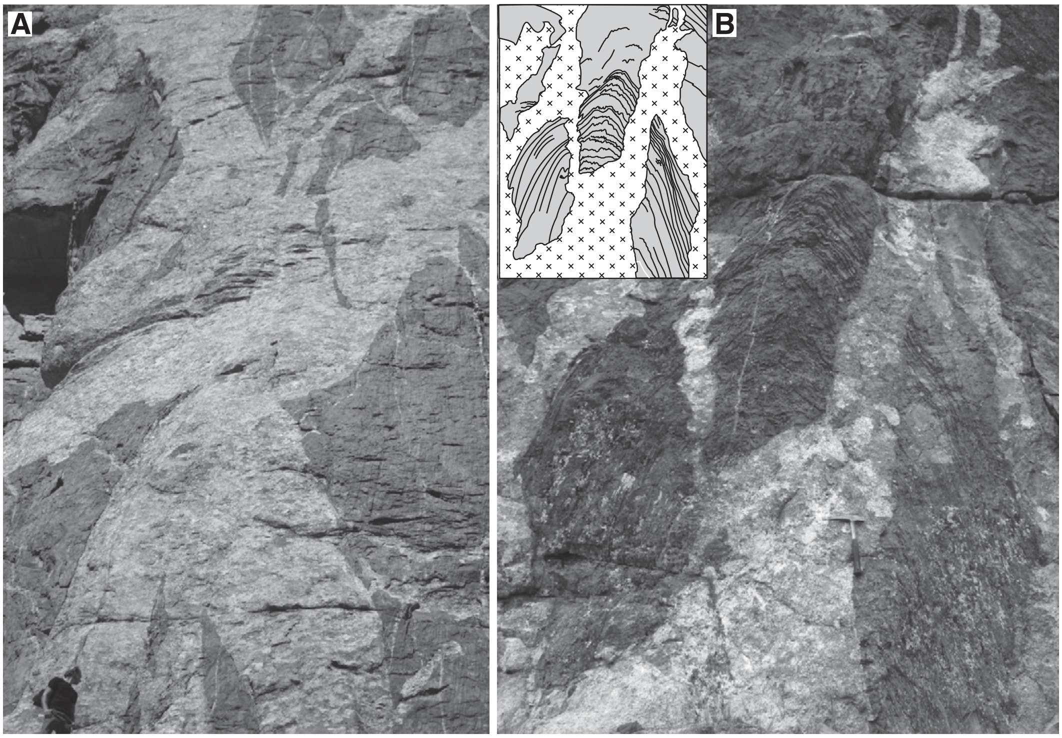

Figure 11. (A) Conjugate sets of dikes formed by ductile fracturing in calc-silicate rocks. Dikes in this outcrop are up to seven meters wide. Note person in lower left, as scale. Looking NW. (B) Interconnected dike network dissecting fold in calc-silicate rocks and forming lozenges of calc-silicate blocks in between Y-shaped fractures. Looking NW, down plunge of fold axis: 325°/20°.

Plutons (Fig. 1B). The Tangtse Pluton (Fig. 5) is a sheeted complex, where numerous dikes and irregular sheets accumulated during deformation (Reichardt et al., 2010; Weinberg and Searle, 1998) in the pressure shadow of the more competent rocks of the older, ca. 71 Ma, calc-alkaline Muglib Batholith (Weinberg et al., 2009). The foliation of migmatitic metasedimentary country rocks is deflected around the NW tip of the calc-alkaline pluton, where the Tangtse Pluton formed, reminiscent of foliation disturbance around porphyroblasts in sheared rocks at microscopic scale. The foliation is also deflected at the margins of the Tangtse Pluton, indicative of continued deformation after the leucogranites solidified (Weinberg et al., 2009). Another example of a link between pluton and dike swarm is shown for the Darbuk Pluton in Figure 15. Here, a network of dikes merges with the pluton. A combination of coalescence of dikes and wedging apart of the country rocks forms a local intrusion that in this case reaches kilometer size.

DISCUSSION

Link to Karakoram Batholith

Across a hierarchy of magma channels, in situ leucosomes connect to dike networks and feed irregular magma sheets and blobs related to the Pangong injection complex (Reichardt

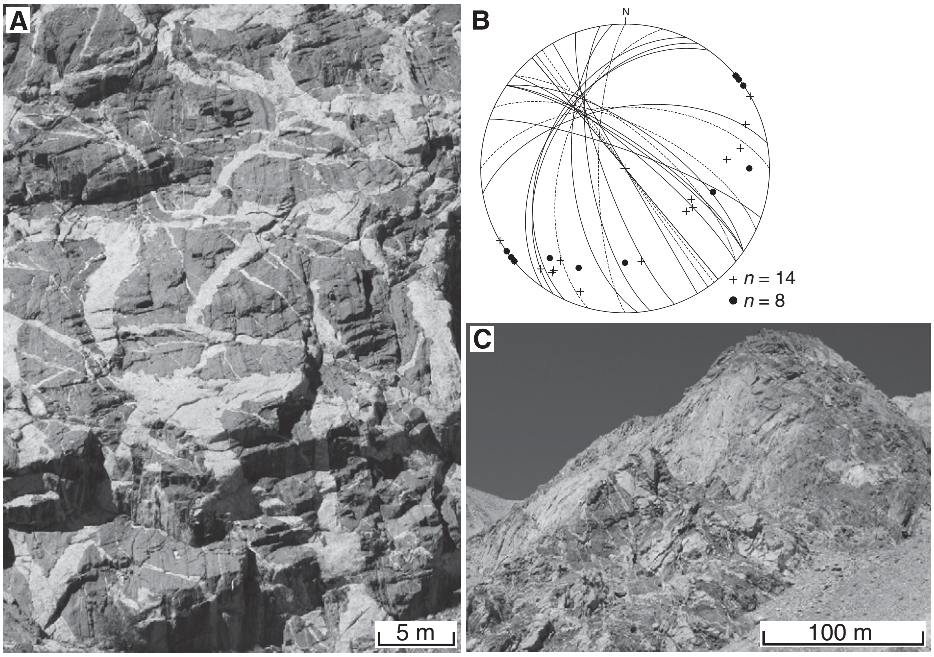

Figure 12. (A) Chaotic leucogranite dikes in calc-silicate rocks in Tangtse gorge looking NW, parallel to the plunge direction of stretching lineation. Note numerous spider dikes. (B) Stereographic, equal-area, lower-hemisphere projection of dike attitudes in calc-silicate rocks defining common intersections plunging NW, parallel to stretching lineation. Two different symbols represent measurements in two different regions of the same outcrop partly shown in A. (C) Chaotic dike network in vicinity of A linking to leucogranite pluton in upper part of photograph.

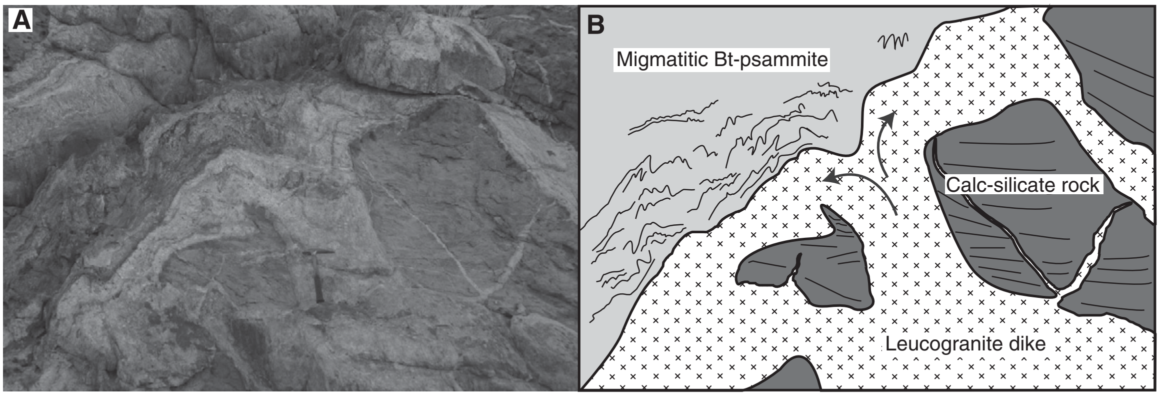

Figure 13. (A) Subvertical leucogranite dike in calc-silicate rocks deflected at contact with migmatitic biotite-psammite. (B) Line drawing of A. Arrows indicate interpreted magma-flow direction based on schlieren and faint banding in leucogranite in dike.

et al., 2010; Weinberg et al., 2009; Weinberg and Searle, 1998). Concurrently, disruption of folds and layers leads to transposition and formation of diatexites that link continuously to local magma stocks. The dike networks in the Tangtse gorge can be traced along strike to the Darbuk-Shyok gorge, ~13 km NW, where leucogranites are isotopically identical (Reichardt et al., 2010). Further NW of the Darbuk-Shyok gorge, leucogranites form an ~600-m-wide leucogranite band that trends NW-SE, parallel to the Pangong Range (Fig. 16). From here, the dike swarm can be followed along strike almost continuously along the Pangong Range to the NW to Agham and into the Karakoram Batholith (Fig. 1). Recent work has demonstrated that leucogranites of the Karakoram Batholith have similar age and isotopic composition to the leucogranites in the anatectic region in the Tangtse area (Phillips et al., 2004; Ravikant et al., 2009; Reichardt et al., 2010). Therefore, we propose that the Karakoram shear zone dike swarm is an example of a complete magmatic transfer system linking source to batholith.

We demonstrated that dike intersections typically plunge NW, parallel to fold axes and the main stretching lineation (Figs. 8D and 8E). These intersections provide a zone of higher permeability that could provide a convenient upward magma pathway toward the SE, away from the Karakoram Batholith (see also Brown, 2006; Brown and Solar, 1998b). However, whether or not magmas used this preferential path depends on whether its orientation coincided with a significant pressure gradient that drove magma transfer in that direction. Weinberg and Mark (2008) presented evidence for at least a component of magma migration at high angles to dike intersections, perpendicular to the fold axis, toward the NW. However, the main flow direction remains undetermined.

Regional Tilting?

There is a regional change in metamorphic conditions from the source in the SE to batholith in the NW. The upper-amphibolite-facies conditions recorded in the anatectic region in Tangtse contrast with greenschist-facies conditions of rocks exposed along the Nubra valley (Fig. 1A) (Weinberg et al., 2000). In between these end members, intermediate conditions are found in between Satti and Agham. In this region, rocks are generally metamorphosed at greenschist facies away from the contact with the Karakoram Batholith, and at lower-amphibolite facies close to the intensely sheared contact. There is thus a broad regional change from upper-amphibolite-facies migmatitic rocks in the SE to greenschist-facies metamorphic conditions in the NW, suggesting a gentle SE tilting of the section.

Filtering Processes

In situ melting products forming leucosomes in migmatites are related to leucogranites in dikes and larger accumulations of magmatic rocks along the Pangong Range (Reichardt et al., 2010; Searle et al., 1998). However, leucosomes are texturally and compositionally different from leucogranitic bodies. Leucosomes in Bt-psammites and pelites lack peritectic minerals but commonly contain schlieren of entrained Bt-rich melanosome (Reichardt et al., 2010). Leucosomes in metatexites and diatexites in calc-alkaline granitoids commonly contain peritectic hornblende phenocrysts, and entrained schlieren, consisting mostly of hornblende and biotite (Reichardt et al., 2010; Weinberg and Mark, 2008). In places, hornblende forms accumulations, either at the margins of leucosomes or as aggregates inside leucosomes. Diatexites essentially represent mobilized and disaggregated source rock that contains isolated rafts of amphibolite or pelitic resisters and fragments of metatexite, forming heterogeneous rock masses.

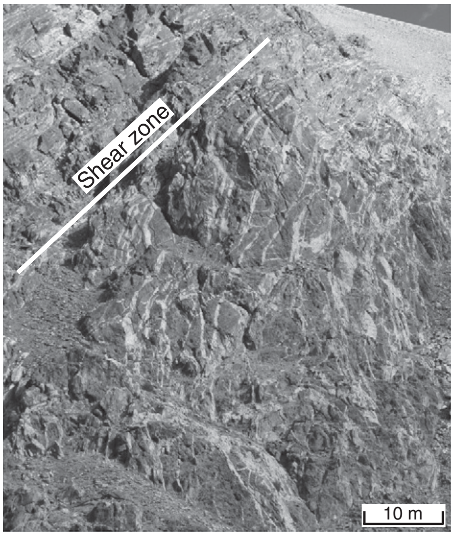

Figure 14. Gradual rotation of dikes from a chaotic orientation into parallelism with a NW-SE–trending shear zone.

In contrast, dikes in the transfer zone and associated intrusions (Figs. 5 and 15) are mostly free of peritectic minerals or residuum, forming homogeneous, leucocratic rock masses. Similarly, kilometer-long stretches of the Karakoram Batholith along the Nubra Valley are broadly homogeneous, lacking banding or significant changes in color index.

The contrast between granitic rocks in the source and in the transfer zone, plutons, and batholith suggests efficient filtering of solids in the source. An extreme process of filtering is recorded by relatively rare leucosomes in diorites, consisting mostly of hornblende and K-feldspar

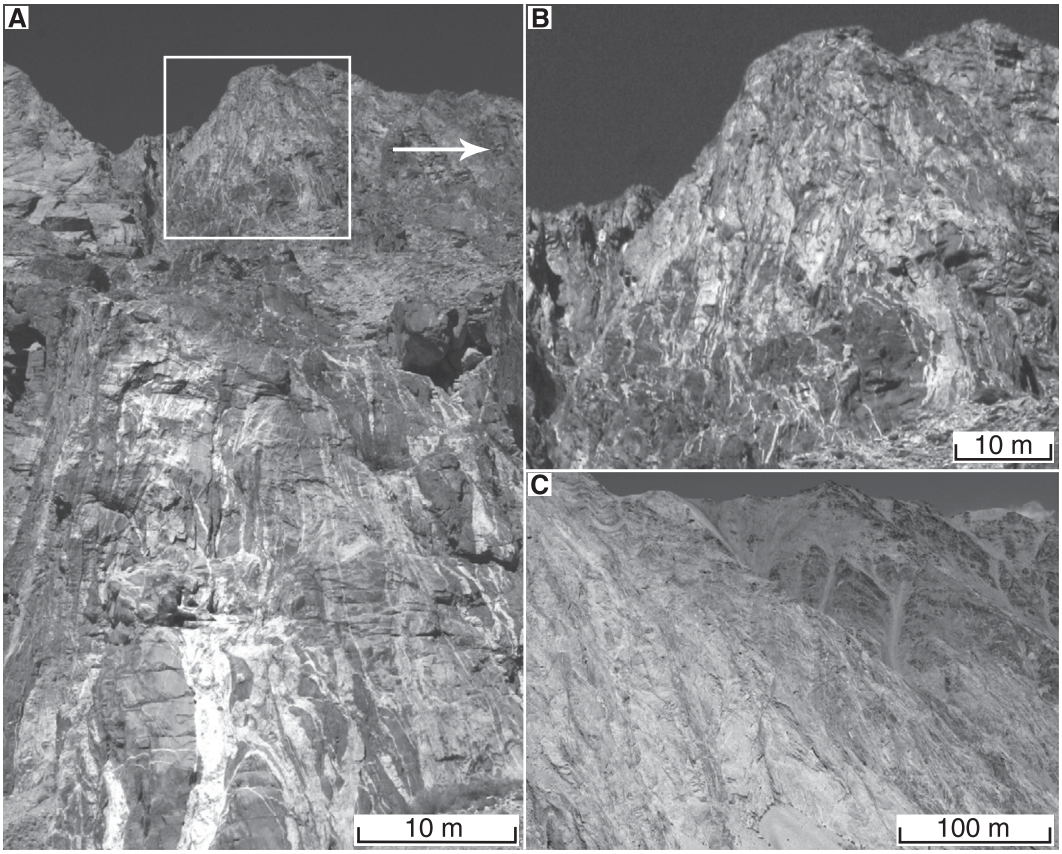

Figure 15. (A) Leucogranite dikes intruding calc-alkaline diorites of Muglib Batholith at SW end of Darbuk-Shyok gorge. (B) Enlargement of A, showing merging of dikes and link to leucogranitic Darbuk Pluton at the top of the ~100-m-high exposure. (C) Darbuk Pluton looking NE into the Darbuk-Shyok gorge. Note that dikes on right (NE) side of pluton merge in an anastomosing network. Note also feature of dikes merging with pluton close to the top right side of pluton.

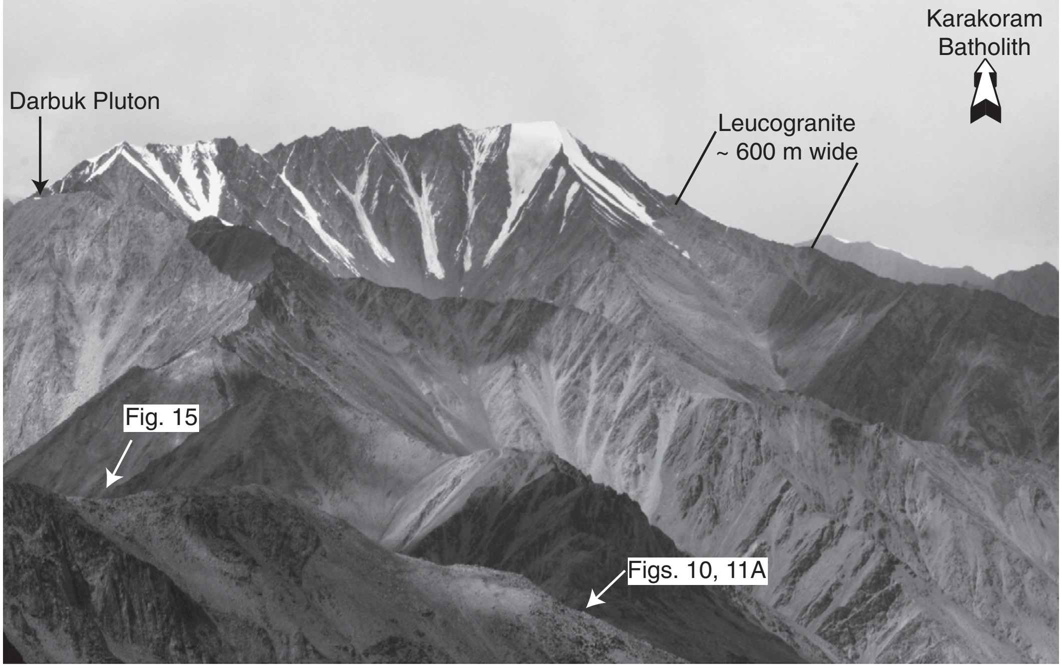

Figure 16. Pangong Range looking NW toward the Karakoram Batholith, showing an elongated leucogranite body ~600 m wide (light band). View from Horlam Pass in Pangong Range above (NW) Tangtse Pluton. Band can be followed into Darbuk-Shyok gorge (closer to viewer), where dike networks in Figure 10, 11A, and 15 are exposed. The far ridge of the leucogranite band is ~15 km along strike from viewpoint.

megacrysts and high amounts of the accessory minerals titanite, apatite, and allanite. These are interpreted to be a combination of early formed magmatic minerals, peritectic minerals, and residual assemblages of minerals that have been left behind (Reichardt et al., 2010).

In migmatites, melt was extracted through axial-planar channels (Weinberg and Mark, 2008). Here, schlieren entrained from the melanosome, large hornblende, and early crystallized feldspars may have clogged narrow pathways and were filtered out of the flowing magma. In diatexites, other mechanisms of filtering must have been active for separation of melt from residue. We envisage that the en masse flow of the diatexite gave rise to preferential channelways linking melt-rich zones that migrated faster and drained the melt-poor, less mobile regions of the diatexite. This process could have been combined with clogging of preferential channels and filter pressing of solids (Wickham, 1987).

Magma Transfer at High Angle to Shortening Direction

The geometry of dike swarms suggests that a significant component of magma transfer took place in sheets parallel to the Karakoram shear zone, at high angles to the axis of maximum compression. In ductilely deforming anatectic rocks, melt migration along anisotropies such as foliation planes may occur because the tensile strength normal to the fabric is low (Brown and Solar, 1998a; Wickham, 1987).

In metatexite and diatexite migmatites, magma channels developed in axial-planar orientation of open to isoclinal folds. Weinberg and Mark (2008) used this feature to argue that magma migration on planes parallel to the axial plane, together with block rotation and transposition of layering, allowed for enhanced mass transfer and shortening perpendicular to the axial plane. In this way, the orientation of magma channels is a net result of the interaction between shortening direction, anisotropies, and volume loss from the folded mass.

The shear fabric dike swarm described above is interpreted to have intruded and migrated parallel to the shear zone fabric, exploiting and interacting with both shear planes and maximum shortening planes (McFadden et al., 2010), equivalent to C-S fabric of mylonites (Fig. 10). In fact, most dikes in the Karakoram shear zone have orientations between those of the axial plane of folds and the strike of the shear zone itself (Fig. 8A). These orientations contrast with magma sheets formed at low angles or parallel to the maximum shortening direction found in ductile shear experiments in incompressible material lacking internal anisotropies (Holtzman and Kohlstedt, 2007; Katz et al., 2006; Kohlstedt and Holtzman, 2009; van der Molen and Paterson, 1979). The possibility that current dike orientations resulted from rotation toward the dominant shear plane is not entirely excluded here, but the delicate features recording magma extraction along axial-planar orientations (Weinberg and Mark, 2008) and the well-defined dike patterns described previously suggest negligible rotation after solidification.

Ductile Fractures

Ductile fractures can provide efficient pathways for magma transport through ductile rocks, and we suggest that the dike network in the calc-silicate layer in the Darbuk-Shyok gorge (Fig. 10) is an example of this mechanism (Weinberg and Regenauer-Lieb, 2010). This network type is only found in this lithology, and, in contrast to other network styles, anisotropies in the host rock appear to have negligible influence as the dikes cut across both bedding and axial-planar foliation. Here, dikes bifurcate, forming conjugate sets with acute angles of ~60°. Unlike brittle-elastic failure, ductile fractures develop along shear planes (Weinberg and Regenauer-Lieb, 2010). Like the chaotic network, the conjugate dikes lack signs of crosscutting relationships and are in general petrographically continuous.

It is not entirely clear why ductile fracturing only occurred in calc-silicate rocks. We note that dikes tend to be wider here than in other rocks, and that unlike the other main rock types in the region, calc-silicate rocks did not melt. We infer that these several-hundred-meter-wide calc-silicate layers formed relatively competent blocks surrounded by anatectic rocks, and they were prone to ductile fracturing, which then acted as efficient transfer zones.

Implications for Magma Transfer

Figure 17 summarizes the main features of the dike swarm exposed within the Karakoram shear zone and exemplifies interconnection at all scales from in situ leucosomes feeding into a hierarchy of magma channels linked to dike networks, injection complexes, stocks, and plutons. We have described a variety of dike network styles, controlled by stresses related to dextral transpressional deformation (Weinberg et al., 2009). The magma network in the metatexites, the transposition of layering in diatexites into parallelism with the axial plane of folds, the development of dike networks relating to structural features, such as lineation, shear planes, and maximum shortening planes, and the accumulation of magmas in the strain shadow of more competent bodies (Weinberg et al., 2009) all point to contemporaneity of deformation and magmatism.

Water-fluxed melting is generally not considered to play a major role in crustal differentiation (Clemens, 2006; Clemens and Vielzeuf, 1987). This is because water-rich magmas tend to crystallize due to decompression (Clemens and Droop, 1998). Here, we describe a complete magmatic system, driven by water infiltration within an active shear zone, that was capable of transferring large volumes of magma into a batholith. We argue therefore that water-present melting should not be discarded a priori as a potential driver of batholith formation and crustal differentiation.

A possible source for these fluids is the metasedimentary rocks of the Karakoram metamorphic complex, which were underthrusted during oblique movement of the shear zone (McCarthy and Weinberg, 2010). The shear zone most likely created local and regional pressure gradients driving water migration into it, and then played an active role in driving magma migration, forming the complex and interconnected magma network. The geometric variety of network styles suggests varied responses to local and regional changes in stresses and rheology. The resulting crustal-scale system provided paths that allowed for net volume decrease in the source, and concomitant volume increase at batholith level, allowing for differences in strain rate and total strain in different crustal sections.

CONCLUSIONS

Mechanisms of felsic magma transport have long been debated. The Karakoram shear zone hosts a complex network of leucogranites that link the roots of the system through a transfer zone, to the Karakoram Batholith. Syndeformational melting related to water influx produced a magma network in migmatites characterized by layer-parallel leucosomes linked to axial-planar leucosomes, which together provided magma extraction pathways and assisted in rock disaggregation and transposition of preexisting layering. Drainage of magma from migmatites is linked to development of a transfer zone dominated by a dike swarm having varying styles as a function of rock type, strain distribution, and deformation history. The typical features of the magma transfer zone are: (1) dikes form an anastomosing system linked continuously with only rare crosscutting relationships, and (2) dike intersection is dominantly parallel to the mineral elongation lineation. The dike swarm is linked to numerous irregular sills, stocks, and plutons,

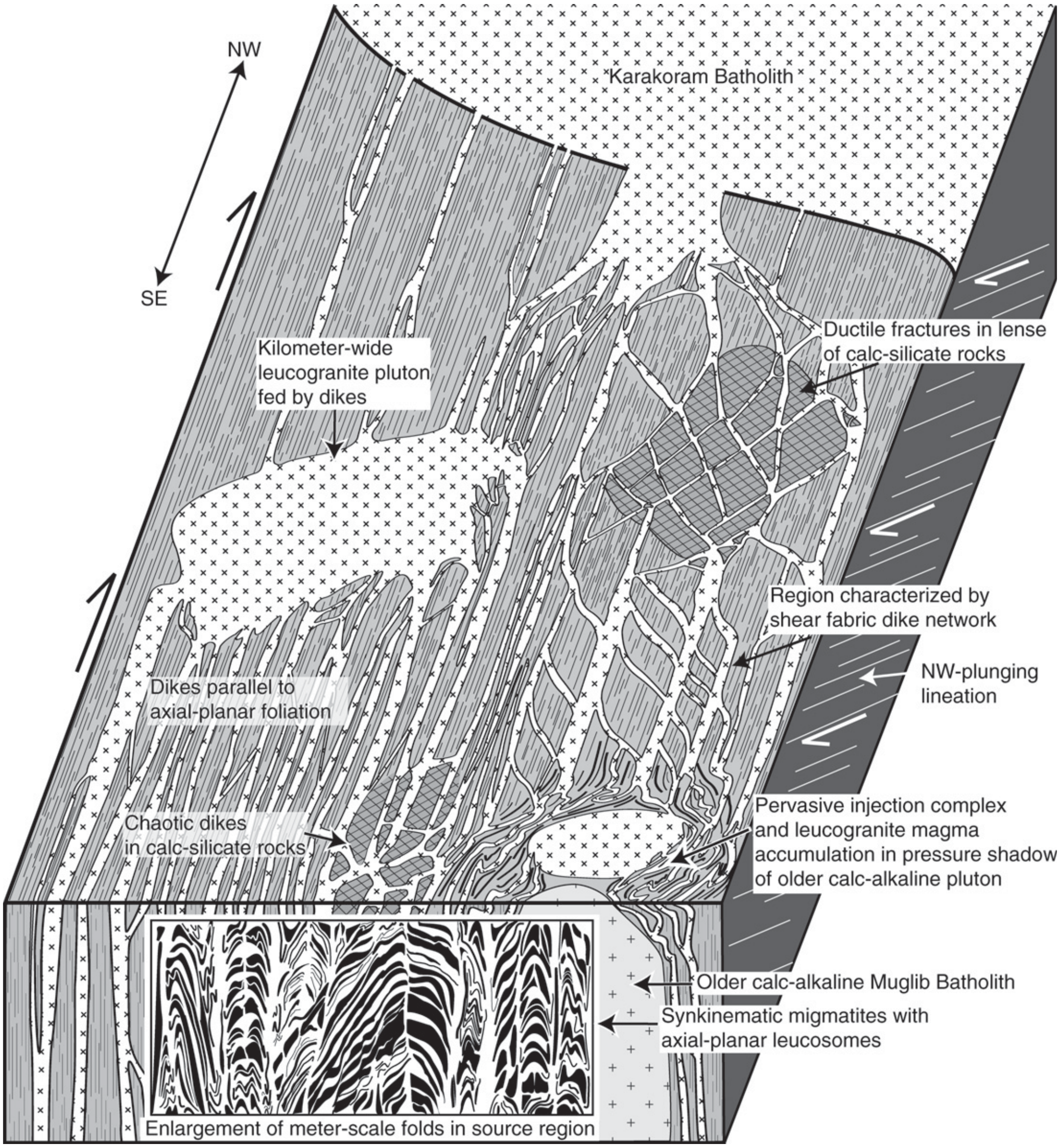

Figure 17. Interpretational block diagram of Karakoram shear zone dike swarm. Note varying scale to better demonstrate features. Horizontal plane corresponds to width of the Karakoram shear zone (~10 km). Top side covers ~70 km in the horizontal from source at Tangtse (closer to the viewer) to Karakoram Batholith tip at Agham (farther from viewer). On the front panel's right-hand side, there is a pervasive injection complex of irregular magma sheets in viscously deforming migmatite associated with a leucogranite pluton formed in the strain shadow of the older (ca. 70 Ma) calc-alkaline Muglib Batholith. Inset box on front panel shows folds in metatexites and transposition of layers into axial-planar orientation, and leucosomes in axial-planar orientation developed during shortening. Note transposed zones between folds occupied by diatexite. On top panel, on left side, dikes are parallel to main regional foliation and Karakoram shear zone, and they feed a kilometer-sized leucogranite pluton (see also Fig. 15). Lenses of calc-silicate rock (diamond pattern) host a chaotic, but interconnected dike network (front center) and conjugate dike pair network (ductile fractures; center right). Dikes link also to a wide leucogranite band (top center, see also Fig. 16). Karakoram Batholith occupies a width similar to that of Karakoram shear zone and its dike swarm. The ubiquitous NW-plunging lineation is indicated on right-hand-side panel of block diagram.

and to the Karakoram Batholith. Unlike general laboratory predictions, dikes developed at high angles to the maximum shortening axis during deformation and resulted from anisotropy control on diking, ductile fracturing, and three-dimensional effects related to volume transfer across the system. In summary, the leucogranitic Karakoram Batholith exposed in India is an example of a large granitic body originating from water-fluxed melting of a heterogeneous source. Thus, we conclude that the Karakoram shear zone created conditions for water release and focused water migration, which triggered water-fluxed melting, and the formation of an interconnected magma channel network linking migmatites to a batholith.

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