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Exhumation of Neogene gneiss domes between oblique crustal boundaries in south Karakorum (northwest Himalaya, Pakistan)

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ABSTRACT

In southeast Karakorum (northwest Himalaya, Pakistan), kilometric size migmatitic domes were exhumed in a context of north-south shortening during Neogene times. The domes are characterized by a conical shape, and ductile deformation criteria indicate both radial expansion and extrusion of the migmatitic core relative to the surrounding gneisses. Most of the domes are aligned along the dextral, strike-slip Shigar fault that is parallel to the N130°E Karakorum fault. Along the Shigar fault, exhumation of the domes is mainly vertical with a slight dextral component.

We propose that the high temperature exhumation of the domes is due to diapiric ascent of the molten mid-crust helped by the compressive regime. The localization of the initial diapir was controlled by crustal-scale vertical structures parallel to the Karakorum fault. The later stage of exhumation in mid to low temperature conditions was related to the uplift and erosion of the whole southeastern Karakorum by crustal-scale east-west folding. In south Tibet, the westward prolongation of south Karakorum, Neogene crustal melting is also supported by geophysical data and volcanism, but mid-crustal rocks have not been exhumed. This difference between the amount of exhumation in south Karakorum and south Tibet could be related to the transpressive context of south Karakorum inducing a strain partitioning between the N130°E faults and east-west folding. Such partitioning produces heterogeneous uplift

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in this area. Moreover, zones of rapid uplift rate are associated with erosion due to the high incision rate of the large Shyok and Braldu rivers and the large Biafo-Hispar and Concordia glaciers in south Karakorum.

Keywords: Karakorum, Tibet, Himalaya, gneiss domes, migmatites, diapirism, crustal scale folding.

INTRODUCTION

In convergent zones, partly melted, mid- to lower crustal rocks (high temperature–mid pressure gneisses) are formed and exhumed during syn- or post-collisional evolution. The formation of these rocks is generally due to thermal equilibration and subsequent partial melting of previously thickened crust (England and Thompson, 1984; Dewey et al., 1988). Additional heat can also be provided by magma advection (Gardien et al., 1997) or shear heating along major faults (Leloup et al., 1999). Exhumation mechanisms of these mid to lower partly melted crustal rocks are still debated. For some authors, the generalized extension affecting the whole orogen during post-collisional evolution is the main cause for exhumation of mid-crustal rocks (Vanderhaeghe, 1999). In this case, rocks are exhumed as metamorphic core complexes whose formation is controlled by extensional ductile shear zones (Lister and Davis, 1989; Brun et al., 1994). In contrast, exhumation of crustal rocks during syn-collisional processes is controlled by compressive tectonics and related to three main types of structures: (1) the core of crustal-scale antiforms, (2) major thrust faults, (3) and major strike-slip faults.

1. Outcrops of mid-crustal rocks in crustal-scale antiforms are observed at both edges of the Himalayan belt, in the Nanga Parbat and Namche Barwa syntaxes (Burg et al., 1998; Zeitler et al., 1989, 1993). The main model proposed for the generation of such folds is a buckling of the whole thickened lithosphere after a thermal perturbation (Burg and Podladchikov, 1999). At the smallest scale, crustal rock exhumation can be localized in the core of ramp anticlines, as proposed for the Kangmar dome in Himalaya (Lee et al., 2000).

2. Along major thrust faults, crustal rocks can either be exhumed as slices, delimited by a basal thrust fault and an upper normal fault, which is the case for the Higher Himalayan Crystallines (Le Fort, 1975; Pêcher and Le Fort, 1986; Vannay and Hodges, 1996). Numerous models were proposed to depict and explain exhumation in this context (see Guillot, 1999, and Hodges, 2000, for reviews). More recently, it has been proposed that exhumation results from the competition between the shear force and the buoyancy force acting on the exhumed slices (Grujic et al., 2002; Guillot and Allemand, 2002). When the buried rocks are partly melted during thermal equilibration, the volume forces are then higher than the shear strength at the boundaries and exhumation occurs.

3. Exhumation of crustal rocks along major strike-slip faults only occurs where significant obliquity exists between the plate motion vector and the fault direction (Teyssier et al., 1995). In Asia, this mechanism accounts for exhumation of granulites along the Red River Fault (Leloup et al., 1999) or the Karakorum Fault (Rolland and Pêcher, 2001).

In southeast Karakorum (northwest Himalaya, Pakistan; Fig. 1), Neogene partly melted mid-crustal rocks are exhumed in kilometric metamorphic domes (Bertrand et al., 1988; Searle et al., 1989; Allen and Chamberlain, 1991; Lemennicier et al., 1996; Rolland et al., 2001). Typically, these rocks have the same petrological characteristics and pressure-temperature evolution as the post-collisional high temperature gneisses observed in an extension context in the Canadian Cordillera and French Variscides (Vanderhaeghe and Teyssier, 2001). However, the south Karakorum migmatites are set in a global north-south shortening context. In south Tibet, the eastward extension of south Karakorum, the mid and lower crust is also probably partly melted, according to geophysical data and observation of Neogene volcanism (Brown et al., 1996; Makovsky et al., 1996; Nelson et al., 1996; Kola-Ojo and Meissner, 2001; Wei et al., 2001; Mahéo et al., 2002). In a previous paper, we have attributed the formation of such rocks as a consequence of mantle upwelling following the breakoff of the Indian continental lithosphere around 25 Ma (Mahéo et al., 2002). The aim of this paper is, in the context of the India-Asia active convergence, to propose a model for the exhumation and the localization of high temperature gneisses in south Karakorum. Such gneisses are absent at the surface in south Tibet.

SOUTHEAST KARAKORUM GEOLOGICAL SETTING

The south Asian margin is divided into two blocks, south Karakorum in the west and south Tibet in the central and eastern parts. The boundary between these two blocks is the N130°E Karakorum dextral strike-slip fault. South Karakorum is separated from the Indian passive margin by the Middle Cretaceous Kohistan-Ladakh arc (Fig. 1). The backbone of south Karakorum is the large NW-SE elongated composite Axial batholith (Fig. 1). The core of this batholith is dated between 120 and 80 Ma and has a calc-alkaline signature related to the Tethyan northward subduction (Debon et al., 1987; Searle et al., 1989). The subduction event was followed by the accretion of the Middle Cretaceous Kohistan-Ladakh volcanic arc to the Karakorum margin during the Upper Cretaceous (Petterson and Windley, 1985; Rolland et al., 2000; Weinberg et al., 2000). The boundary between the Kohistan-Ladakh arc and the Karakorum active margin is the Shyok Suture Zone that was reactivated later as a sharply northward dipping reverse fault, the Main Karakorum Thrust (Coward et al., 1986). Since the India-

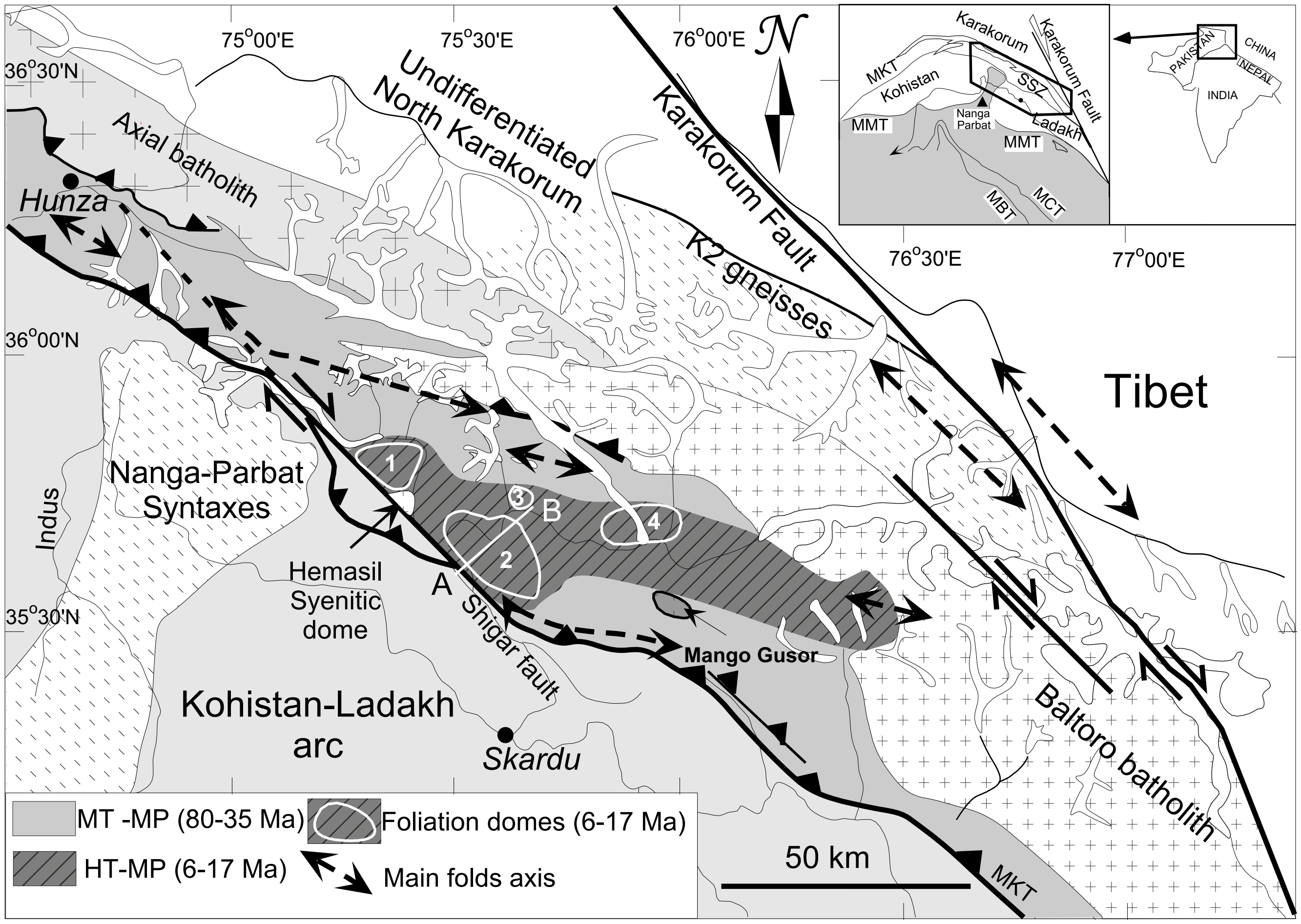

Figure 1. Simplified geological map of south Karakorum (after Pêcher and Le Fort, 1999). Numbers referred to the gneissic domes. 1—Mangol; 2—Dassu; 3—Ho Lungma; 4—Askole-Panhma. ITSZ—Indus-Tsangpo Suture Zone; MKT—Main Karakorum Thrust; MMT—Main Mantle Thrust; SSZ—Shyok Suture Zone.

Asia collision 50 Ma ago, the Kohistan-Ladakh arc is pinched out between the Asian (Karakorum) and Indian blocks and obducted onto the Indian margin along the Main Mantle Thrust, the western extension of the Indus-Tsangpo Suture Zone. Following the collision, a portion of the Indian crust was folded in a large pop-up anticline (Schneider et al., 1999), the Nanga-Parbat spur, possibly the surface expression of lithospheric scale folding (Burg and Podladchikov, 1999).

The deformation of the south Karakorum margin is dominated by continuous south- to southwest-verging folding and nappe stacking, suggesting an overall north-south to northeast-southwest direction of shortening (Searle and Tirrul, 1991; Fraser et al., 2001; Rolland et al., 2001). This nappe-stacking event is associated with the emplacement of numerous metamorphic units of various metamorphic degrees (Bertrand et al., 1988; Hanson, 1989; Searle et al., 1989; Searle and Tirrul, 1991; Lemennicier et al., 1996; Fraser et al., 2001; Rolland et al., 2001). On the basis of geochronologic data, crosscutting relationships, and differences in metamorphic degrees, several tectono-metamorphic events are distinguished (Searle et al., 1989; Searle and Tirrul, 1991; Fraser et al., 2001). However, all the metamorphic units formed before 28 Ma belong to the same Barrovian evolution and are associated with the same north-south to northeast-southwest direction of shortening. Thus, for clarity and following Lemennicier et al. (1996) and Rolland et al. (2001), we will refer to this tectono-metamorphic phase as a single M1 event. This event is first related to the whole collision of the Karakorum block with the Ladakh-Kohistan arc and then with the Indian plate (Searle and Tirrul, 1991; Fraser et al., 2001; Rolland et al., 2001). According to Searle et al. (1989) and Fraser et al. (2001), the Barrovian tectono-metamorphic event ended with the emplacement of the Mango Gusor pluton as early as 26.4 Ma (Fraser et al., 2001). Although the exact relationship between the Mango Gusor granite and the M1 tectonic fabric is not obvious, the main M1 foliation is clearly crosscut by younger granites dated between 7 and 25 Ma, such as the Baltoro batholith (Parrish and Tirrul, 1989). Nevertheless, shortening, with top to the south thrusting, is still active after 26.4 Ma. The best example is the thrusting of the 21–25 Ma Baltoro batholith over the M1 metamorphic units, with syn-magmatic internal fabric in the granite also indicating top to south motion (Bertrand et al., 1988; Searle et al., 1992; this study). In the Hunza area, Searle et al. (1999) proposed that southward thrusting still occurred along the Main Karakorum Thrust during Miocene-Pliocene times. Thus, the north-south shortening recorded by the Karakorum margin should have been a continuous phenomenon from 80 Ma to almost the Pliocene, in direct relation with the northward motion of India relative to Eurasia.

North of Skardu, in southeast Karakorum, the M1 metamorphism is overprinted by a high temperature metamorphic event, M2, associated with the formation of gneissic domes (Bertrand et al., 1988; Lemennicier, 1996; Rolland et al., 2001). The M2 metamorphism is characterized by the occurrence of partly melted high temperature–mid-pressure gneisses (migmatites) exhumed in the core of the domes and surrounded by unmelted sillimanite gneisses preserving relicts of the M1 metamorphic event (Rolland et al., 2001). The migmatites are map-scale mixed diatexites or metatexites. The leucosomes proportion varies from 10% to 45% at outcrop scale. The *P-T* evolution of the migmatites implies a period of heating from 600 °C to >750 °C during a slight pressure decrease, from 0.7 to 0.5 GPa, inducing the partial melting of the mid-crustal rocks (Rolland et al., 2001). Such high temperature–mid-pressure conditions would result from heat advection by mantle magmas intruding the previously thickened crust (Rolland et al., 2001; Mahéo et al., 2002). At a regional scale, imprint of the M2 metamorphism defined an east-west–trending zone, limited to the east by the Baltoro batholith and bounded to the west by a zone of N130°E sub vertical foliation (Fig. 1, Hanson, 1989; this study). The eastern contact between the Baltoro batholith and the M2 metamorphic zone is not a tectonic contact (Bertrand and Debon, 1986; Searle et al., 1992) but an intrusive contact of the batholith within the M1 gneisses, reheated by the M2 metamorphism. The western contact, previously described as the Shigar lineament (Cronin, 1989), shows some evidences of ductile and brittle dextral strike-slip motion and clearly offset the Main Karakorum Thrust by more than 40 km. This zone is also the southward prolongation of a narrow lineament, the south Karakorum fault (Pêcher and Le Fort, 1999), in which the gneiss foliation is vertical and where syn- to post-M1 fold axes plunge sharply (Coward et al., 1986; Pêcher and Le Fort, 1999), probably in relation to diffuse ductile strike-slip movements. In the following, this lineament will be referred as the Shigar fault. Large shifting of the Main Karakorum Thrust, as well as the injection of the 8 Ma Hemasil syenite (Villa et al., 1996), with mantle affinities (Mahéo et al., 2002), along this fault, indicates that it could be almost a crustal scale fault. Field observations as well as interpretation of satellite images indicate that this fault is now inactive.

MORPHOLOGY AND STRUCTURE OF THE SOUTHEAST KARAKORUM DOMES

The shape of the southeast Karakorum domes is drawn by the foliation pattern, viz. gneiss foliation in the external part of the domes and migmatitic intrafolial segregations in their core (Fig. 2). Fuzzy migmatitic intrafolial segregations, as well as better individualized melt segregations, probably formed sub-horizontally during early heating of the mid crust, and have been folded and tilted during the doming phase (Rolland et al., 2001). Measurements of foliation and migmatitic layering collected during our field investigations have been completed by previous data from F. Debon (1999, personal commun.), Lemennicier (1996), and interpretation of satellite images (Landsat and Spot). Several distinct domes are observed (Fig. 3). The first group of gneissic domes is localized along the Shigar fault, with the Dassu and Mangol domes. In between the two domes, the Hemasil syenitic intrusion also presents a domal structure defined by its internal magmatic foliation and the metamorphic foliation of the surrounding contact aureole. They form a nearly continuous N130°E elongated zone lying along the Shigar fault. According to the metamorphic foliation pattern (Fig. 3) the Hemasil intrusion and Mangol dome have a conical shape with a sub-circular section, whereas the Dassu dome displays an elliptical section with a large axis of about 30 km long, parallel to the Shigar fault (Fig. 3). In cross section, the Dassu dome is asymmetric with a vertical SW limb along the Shigar fault. Between the Dassu dome and the Baltoro batholith, the Ho Lungma and the Panhma-Askole domes form a second group. The Ho Lungma dome is poorly studied and will not be discussed here. The Askole-Panhma dome has an

Figure 2. The Askole-Panhma dome.

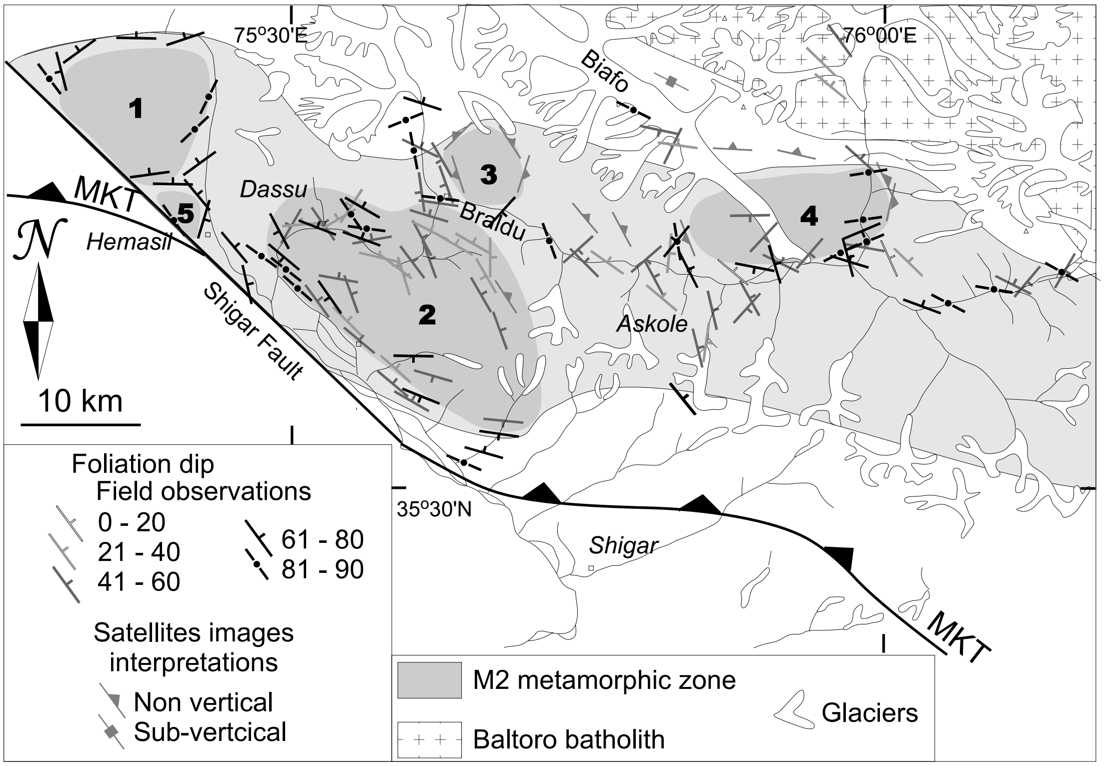

Figure 3. Map of the foliation pattern in the Skardu area (this study, Lemennicier, 1996; F. Debon, 1999, personal commun.). 1—Mangol; 2—Dassu; 3—Ho Lungma; 4—Askole-Panhma; 5—Hemasil syenitic dome; MKT—Main Karakorum Thrust.

elliptical section with an east-west–trending long axis of about 20 km long and a north-south–trending short axis of about 10 km. Flanks of the Askole-Panhma dome are symmetric and plunge radially at about 60°. Inter-dome basin structures are difficult to observe; they are restricted to narrow synforms squeezed between the domes (Fig. 4).

DUCTILE DEFORMATION OF THE SOUTHEAST KARAKORUM DOMES

In order to understand the mechanism that controlled the exhumation of the Karakorum domes, we focused our study on the well-defined Dassu dome. Two zones can be distinguished: the migmatitic core of the dome and the gneissic rim. In the migmatitic core, high temperature mineral lineation (biot + sil) is generally down-dip in the foliation plane (Fig. 5). This fabric is associated with both normal and reverse sense of shear (Figs. 5 and 6), the former being much more frequently observed. The southwestern part of the migmatitic core of Dassu dome has not been reached, however, and we have no data on normal fault type motions in this area. Such motions were observed at the edges as well as inside the migmatitic core of the Dassu dome. It suggests both radial expansion and extrusion of the migmatitic core with respect to the surrounding gneisses (Fig. 6), with dominant flattening at the top of the outer part of the migmatitic core. Drag folds affecting the migmatitic segrega-

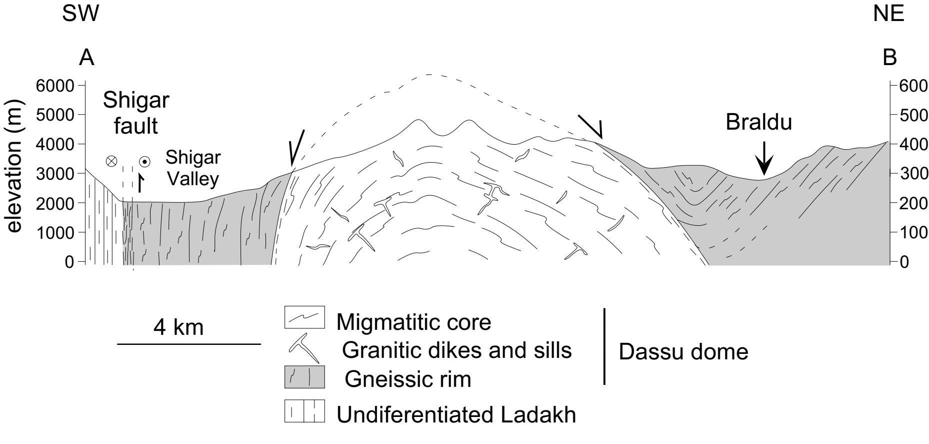

Figure 4. Schematic geological cross section of the Dassu dome. See Fig. 1 for location.

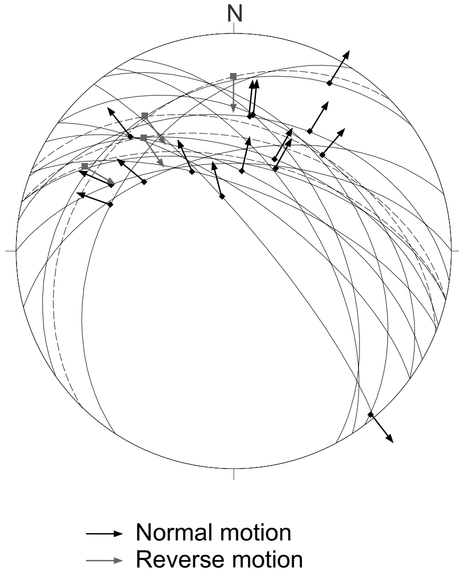

Figure 5. Foliation plane and associated stretching lineation for the Dassu dome migmatites. Arrowhead indicates motion of the upper block. Equal area projection, lower hemisphere.

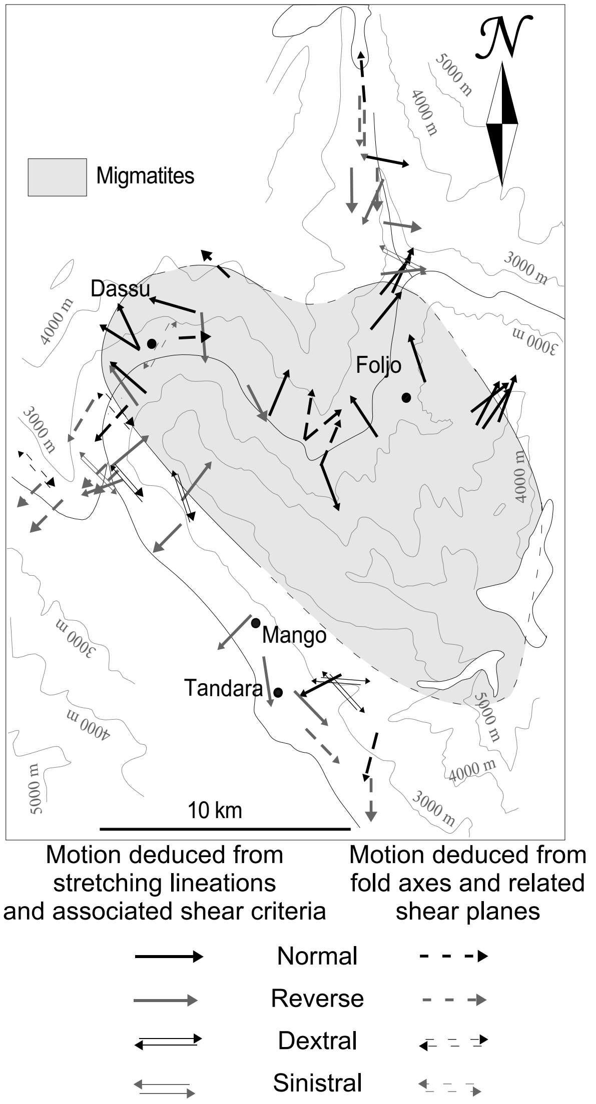

Figure 6. Map of the ductile deformation in the Dassu dome area. Arrowhead indicates the motion of the upper block.

tions also show the extrusion of the migmatitic core (Fig. 7). Extrusion of the migmatitic core was previously observed by Bertrand et al. (1988) and Allen and Chamberlain (1991). It is also evidenced by the highest amount of exhumation recorded by the migmatite as compare to the surrounding gneisses since the M2 peak (Rolland et al., 2001). Locally, the fabric (N0° to N30°E stretching lineations associated with C-S structures and syn- to post-migmatitic drag folds) indicates that south to southwestward thrusting was still active during and after the M2 migmatization (Figs. 5, 6, and 8).

In the gneisses of the western rim of the Dassu and Mangol domes, along the Shigar fault, the deformation is quite different than elsewhere in the domes. The foliation planes are very steep, and associated mineral and stretching lineation lie parallel to the Shigar fault (N120°E to N160°E) and plunge steeply (70 to 90°) toward the NW. Shear criteria as drag folds indicate a top to SE displacement with a slight dextral strike-slip component.

In the northern gneissic rim of the Dassu dome, outside of the migmatitic core, southward thrusting is predominant. However, in this area, the M1 metamorphic fabric and associated minerals have not been totally overprinted by the M2 fabric, and it is often difficult to say if the top to the south shearing deformation is either associated with the M1 event or with the M2 one. In south Karakorum, the M1 event is generally associated with southwestward thrusting, suggesting that the southward structures observed in the southern limbs of the domes could actually be earlier southwestward structures reoriented in the dome area. Similar rotation of the M1 structures is also evidenced at map scale between the Shigar and the Karakorum faults by the reorientation of calcareous beds and of the main M1 folds axes (Fig. 1).

Far from the Shigar fault, in the Askole-Panhma dome area, the late- or post-migmatitic deformation of the core of the dome also shows extrusion of the migmatitic zone relative to the surrounding unmelted gneisses. In this area, asymmetric folds striking N90°E to N120°E are compatible with a top to the south bulk motion. In the Panhma area, local southward thrusting of the Baltoro granite over the M1 tectono-metamorphic units show evidence of N-S shortening. Moreover, the shape of the dome is characterized by an east-west elongated large axis (Fig. 3) compatible with late north-south shortening.

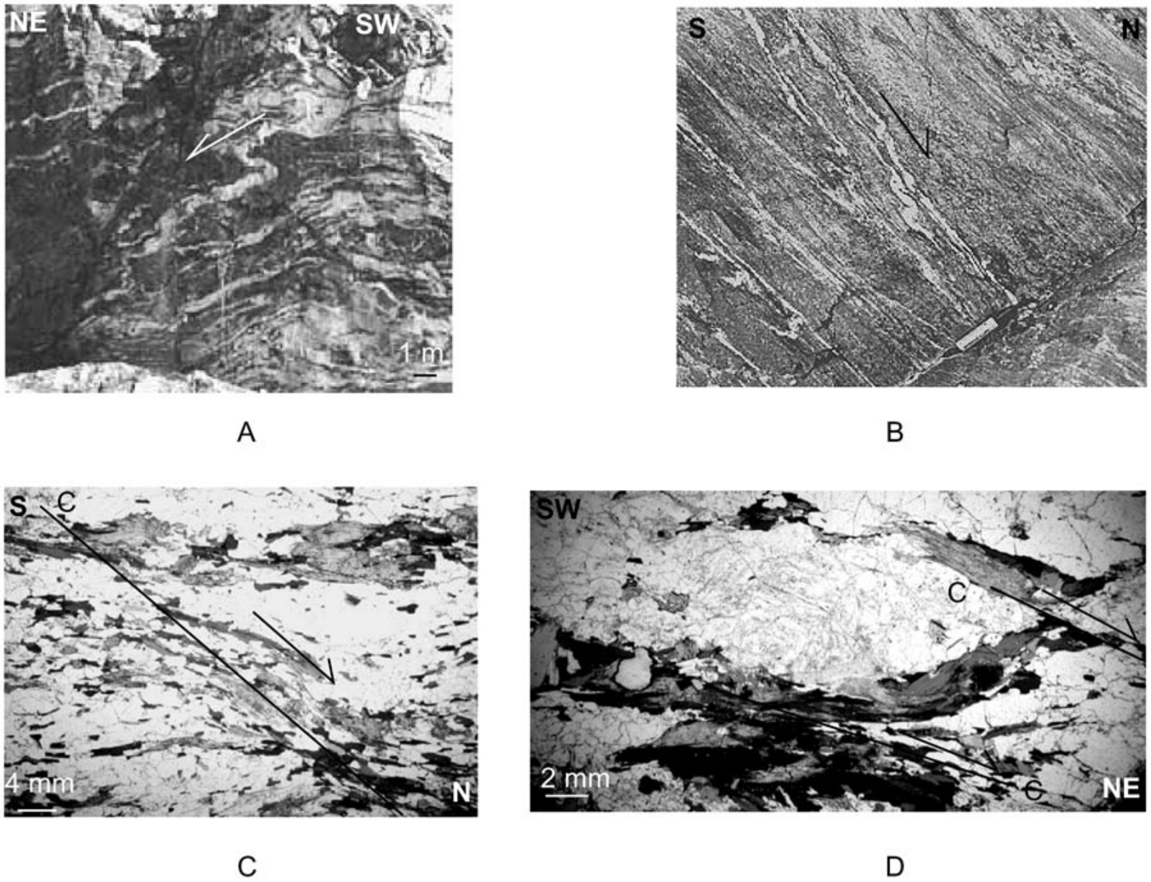

Figure 7. Asymmetric folds in the NE limb of the Askole dome (A) and in the N limb of the Dassu dome (B). Thin section scale shear plane in N (C) and NE (D) limbs of the Dassu dome.

DICUSSION

Model for the Exhumation of the Southeast Karakorum Domes

A classical interpretation of doming is the formation of metamorphic core complexes (Davis and Coney, 1979). Such domes are formed during generalized extension and associated with the reactivation of older compressive structures (Coney and Harms, 1984). In the southeast Karakorum domes, normal motions are only observed in the migmatitic core, precluding a general extensional context. The observed extension is radial, while in metamorphic core complexes it is localized along a main fault, guiding the total exhumation. Moreover, in southeast Karakorum, southward to southeastward thrusting was still active during and after the dome formation, which clearly indicates that the Karakorum domes do not correspond to extensional metamorphic core complexes.

Shortening can also produce dome structures, either during polyphase deformation leading to an interference pattern or due

Figure 8. Inverse ductile structure in the core of the Dasu dome (syn- to post-migmatitic sheared fold).

to heterogeneous deformation during a single tectonic phase. In south Karakorum, previous structural studies mainly focused on the deformation of the gneiss surrounding the migmatitic core (Bertrand and Debon, 1986; Bertrand et al., 1988; Hanson, 1989; Searle et al., 1989; Allen and Chamberlain, 1991; Lemennicier et al., 1996). As previously discussed, the deformation of these gneisses is related to a north-south to northeast-southwest shortening, leading to models in which doming is controlled by shortening. The main south-southwest–north-northeast shortening direction is roughly constant since 80 Ma and no superimposition of other shortening directions is observed; consequently, models invoking heterogeneous deformation associated with a single stage of south-southwest–north-northeast compressive deformation have been favored (Lemennicier et al., 1996; Searle and Tirrul, 1991). Based on the model developed by Merle and Guillier (1989), Lemennicier et al. (1996) proposed that the south Karakorum domes resulted from vertical extrusion along the Main Karakorum Thrust, associated with a dextral strike-slip motion. In this model, the exhumation of the gneiss is controlled by the compressive tectonic regime. In this case, as observed in the Nanga-Parbat and Namche-Barwa syntaxes or the Kangmar dome, the high temperature (HT) deformation is mainly—if not exclusively—compressive (Burg et al., 1997, 1998; Lee et al., 2000; Schneider et al., 2001). Thus, if compressive models could explain the deformation pattern observed in the gneiss surrounding the migmatitic core, they cannot explain the HT deformation of the migmatites, dominated by normal structures, indicating both radial expansion and extrusion of the migmatitic core relative to the surrounding rocks. Although, compressive deformation in the rim of the domes underlines the bulk shortening context, shortening alone cannot explain all the structures observed in the domes, especially in the migmatitic cores.

Diapirism has been mainly studied and strongly debated in the case of ascent and emplacement of granitic magmas (see Clemens, 1998, and Miller and Paterson, 1999). In the case of gneissic domes, the partial melting of deep-seated rocks may have produced an inversion of the density between deep and shallow rocks (Teyssier and Whitney, 2002). This inversion of density, coupled with the decrease of the viscosity of the partly melted rocks, allows the development of gravitational instabilities (Teyssier and Whitney, 2002). In gneissic domes showing similar *P-T* conditions and evolution to those of the south Karakorum domes, Calvert et al. (1999) and Soula et al. (2001) estimated that at peak temperature, both the density difference (>200 kg m^{-3}) and the viscosity ratio (10^{-1} to 10^{-3}) between the molten gneisses and the overlying gneiss or metasedimentary schist was sufficient to initiate diapiric ascent. Diapiric ascent could also explain the radial extension observed in the migmatitic core of the domes (Fig. 6). However, it appears that ascent of liquid granitic magmas must stop at an approximate depth of 15 to 10 km (Weinberg and Podladchikov, 1994; Guillot et al., 1993). This is mainly due to magma crystallization as the temperature decreases, increasing its viscosity drastically. Nevertheless, Weinberg and Podladchikov (1995) modeled that solidified granitic magmas still could rise after crystallization, the amount of rise depending of the geothermal gradient.

Structural and modeling studies of salt diapirism and granitic ascent emphasize the role of tectonic shortening or extension as an overwhelming factor (Guillot et al., 1993; Scaillet et al., 1995; Waltham, 1997; Ismail-Zadeh and Birger, 2001). A strong relationship between diapirism and shortening was also observed in the Archean domes and basin structures (Bouhallier et al., 1995). In southeast Karakorum, evidence of syn- to post-migmatitic shortening has been observed. Thus some syn-diapiric shortening could have amplified the diapiric

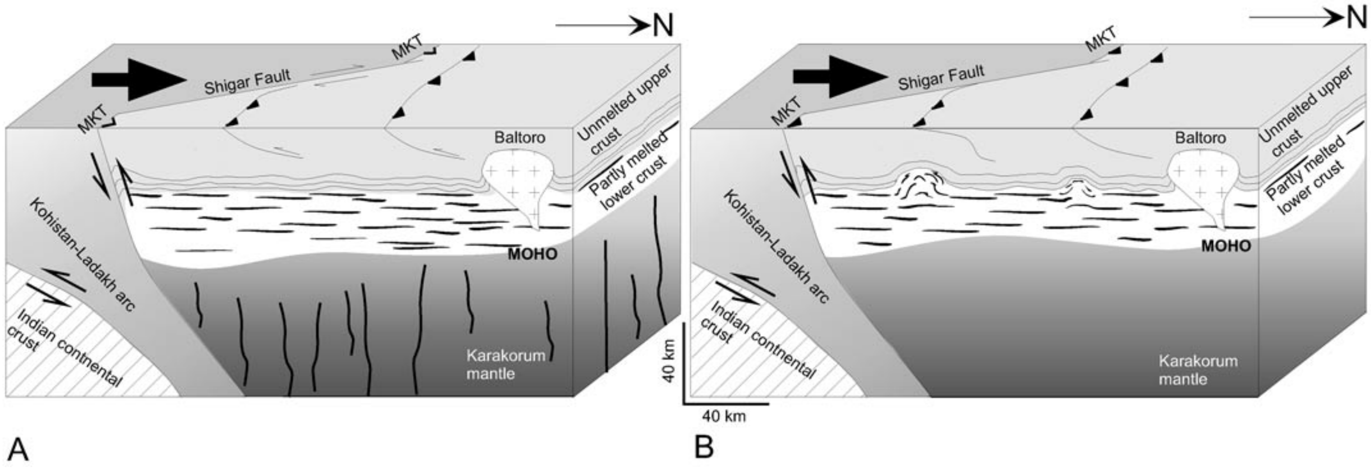

Figure 9. Model for the high-*T* evolution of the south Karakorum Neogene migmatites. A. Heating and partial melting of the lower crust, induced by heat advection from mantle magmas (black lines) and crustal magmas. B. Development of diapiric ascent of the partly melted lower crust.

ascent previously initiated and could have helped the extrusion of the ductile migmatitic core through the unmelted surrounding rocks (Fig. 9). Nevertheless, diapiric ascent even amplified by compressive tectonics cannot explain all the exhumation from 15 km depth to the surface of the southeast Karakorum migmatites. The difference in amount of exhumation since the M2 peak between the migmatites and the surrounding gneisses is 2–3 km (Rolland et al., 2001), indicating that the extrusion of the migmatite is limited. Therefore, as previously proposed by Allen and Chamberlain (1991), the diapirism model could explain the high temperature exhumation of the southeast Karakorum domes, but an additional mechanism must be invoked to explain the medium and low temperature exhumation.

Late Exhumation of the Southeast Karakorum Domes

In the context of the active India-Asia convergent zone, the Karakorum and the Main Karakorum Thrust faults bounding southeast Karakorum are still active today (Fig. 10; Cronin, 1989; Fan et al., 1994; Pegler and Das, 1998), while between these two faults, southeast Karakorum appears as an aseismic zone (Fig. 10). Nevertheless, this zone appears as relatively high compared to the Ladakh block and the axial batholith with a sharp increase of the elevation east of the Shigar fault (Fig. 11), and all of southeast Karakorum seems to be a zone of active uplift. A study of the Pleistocene Indus fan suggests that Karakorum was also an active uplift zone during the entire Pleistocene (1.8–0.01 Ma) (Clift et al., 2002). Accordingly, we propose that the late exhumation of the southeast Karakorum domes from 5 km depth to the surface can be related to the regional uplift of the southeast Karakorum, coupled with erosion. This uplift can correspond to two mechanisms, either “en bloc” vertical motion or crustal scale folding. The high relief (>7000 m) is not widespread within all of south Karakorum, but defines a roughly east-west–trending zone (Fig. 11), comprised between the Karakorum fault (K2 area) and a zone of vertical foliation, oriented N130–N140°E in southward continuity with the Shigar fault (Pêcher and Le Fort, 1999). This localized elevated area within the Karakorum block is also evidenced by a NW-SE topographic profile across the whole block (Fig. 11). Thus, the recently uplifted zone seems to be a rather narrow zone of ~150 km in the N-S direction and ~100 km in the E-W direction including the M2 metamorphic zone (Fig. 11). Lack of relative motion and thermal contrast between the gneiss affected by the M2 metamorphism and the Baltoro batholith implies that both the dome area and the granite have been exhumed together as a single block, and the actual exhumation zone thus extends from the Shigar fault to the Karakorum fault. The map-view shape of the 21–25 Ma Baltoro batholith (E-W far from the Karakorum fault, and NW-SE close to it), as well as the rotation of the magmatic foliation (Bertrand and Debon, 1986; Searle et al., 1992), indicate syn-magmatic dextral shearing of the batholith, and in turn implies that the dextral Karakorum fault was active 21 to 25 Ma. On the western side of the exhumed zone, the Shigar fault is parallel to the Karakorum fault and also had a dextral strike-slip component (Fig. 1). Thus, the exhumed area (Fig. 11) appears as a crustal scale fold due to north-south shortening between two NW-SE dextral shear zones (Fig 12). It suggests a heterogeneous kinematic and strain field, viz. dextral strike-slip motion along the Karakorum fault, north-south shortening, and vertical motion between the Shigar fault and the Karakorum fault and transpressive shortening along the Shigar fault (Fig. 12). The location of most of the migmatitic domes along the crustal-scale Shigar fault is a noticeable feature. According to the obliquity of the fault relative to the global north-south direction of shortening at the boundary of southeast Karakorum, transpressive dextral motion should be induced. However, along the Shigar fault, the high temperature lineation plunges steeply (70–90º) toward the NW, implying that most of the high temperature motion is vertical, with little along-strike movement. It seems that along the Shigar valley, the early dextral strike-slip indicators have later been obliterated, the Shigar fault playing the role of a major structural boundary guiding the exhumation of the previously molten mid-crust. In this context, the Shigar fault would have acted as a boundary between a rigid block, the Kohistan-Ladakh, where no recent heating is observed, and a thermally softened one, south Karakorum heated by magma advection.

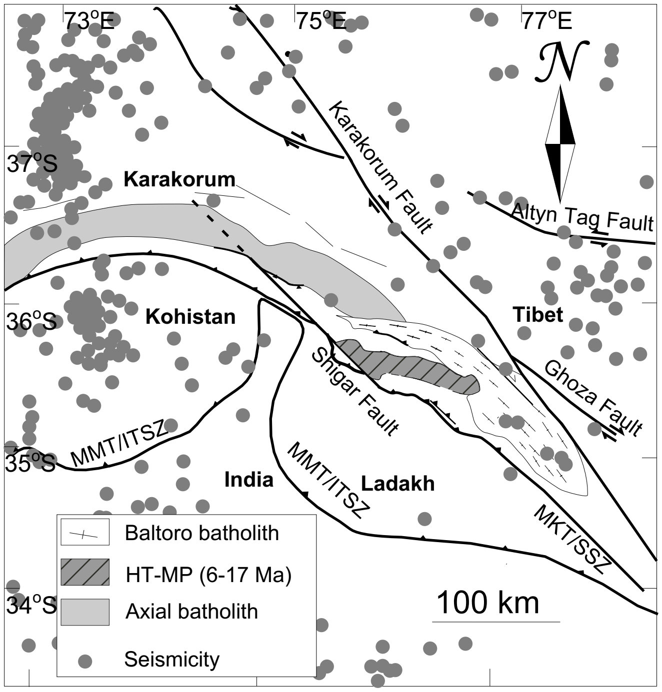

Figure 10. Seismicity map (between 01 January 1964 and 31 December 1992) of west Himalaya, Karakorum and Pamir (after Pegler and Das, 1998)

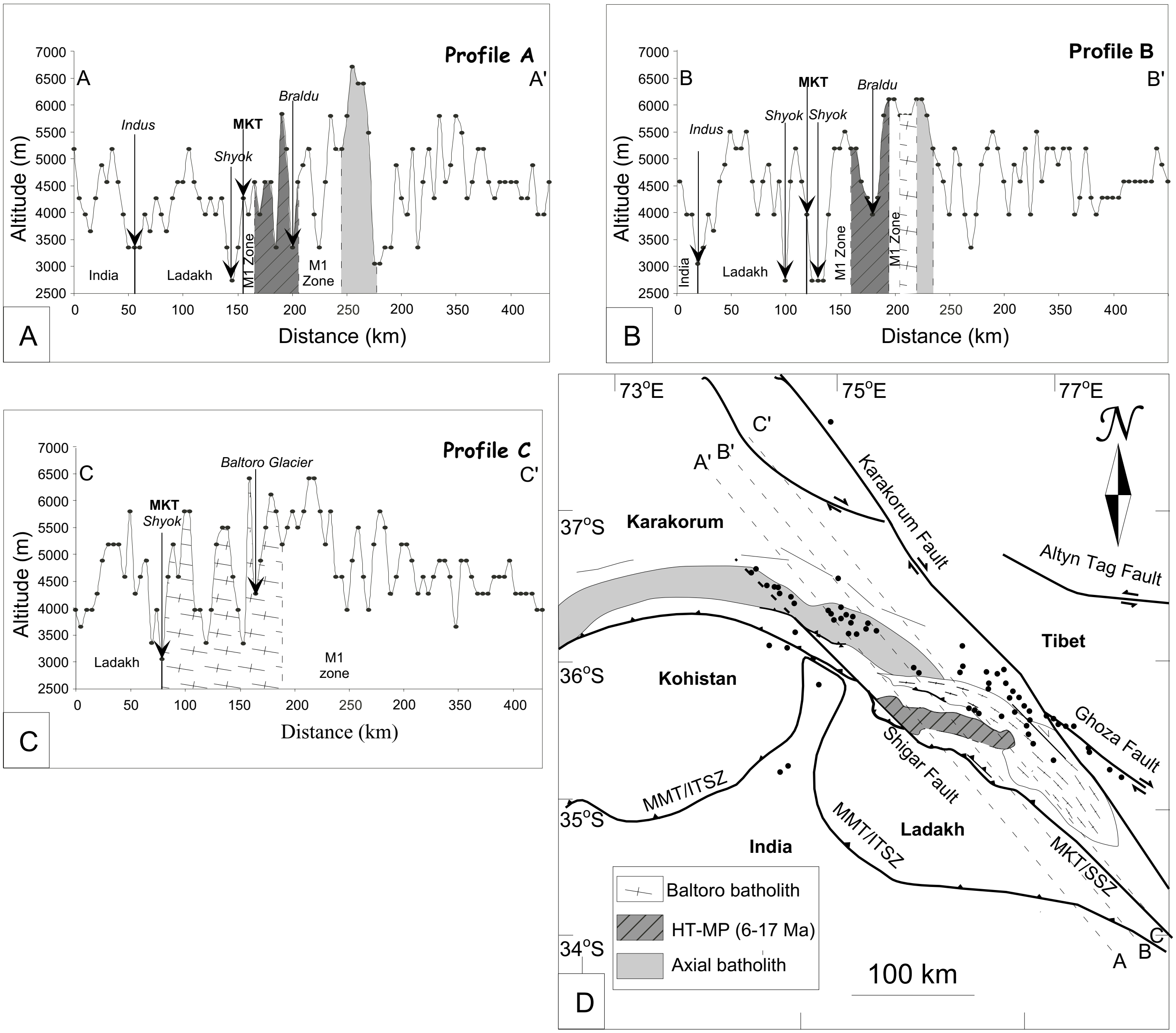

Figure 11. Karakorum topography deduced from the 1:1,000,000 ONC topographic map G-7 (Afghanistan, China, India, Pakistan, Soviet Union). A, B, C: Topographic profiles across the Karakorum block. D. Structural map of west Himalaya, Karakorum and Pamir with location of relief over 7000 m in south Karakorum (black dots). ITSZ—Indus-Tsangpo Suture Zone; MMT—Main Mantle Thrust.

Far from the Shigar fault, dome exhumation is less clearly linked to major block boundaries, even if numerous N130°E lineaments, parallel to the Shigar and Karakorum faults, have been recognized in the dome area (Bertrand et al., 1988; Cronin, 1989; Cronin et al., 1993; Lemennicier, 1996), the N130 direction also being emphasized by the direction of the glaciers located between the Shigar and the Karakorum faults (Fig. 13). As for the Shigar fault, very few along strike motions have been evidenced along these lineaments (Bertrand et al., 1988; Cronin, 1989). Nevertheless, we propose that the structures observed in southeast Karakorum could have been strongly controlled by NW-SE faults such as the Karakorum and Shigar faults at the boundaries of the block and also other similar faults in between. In this context, localization of diapiric ascent of a partially melted middle crust can be controlled by the N130°E inherited structures. Localization of the Askole-Panhma dome on the Biafo glacier, one of the main N130°E lineaments of southeast Karakorum, can probably be explained by this hypothesis. The crustal-scale folding could be responsible for the uplift of the high relief-part of southeast Karakorum (Fig. 11). Coupled with

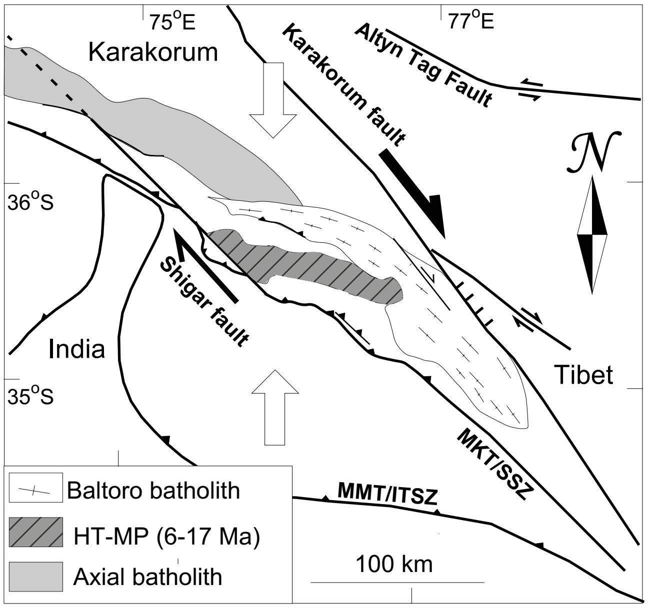

Figure 12. Structural setting of south Karakorum. Strain is partitioned in dextral strike-slip motion along the N130 Karakorum and Shigar faults, and N-S shortening between the two faults. ITSZ—Indus-Tsangpo Suture Zone; MMT—Main Mantle Thrust.

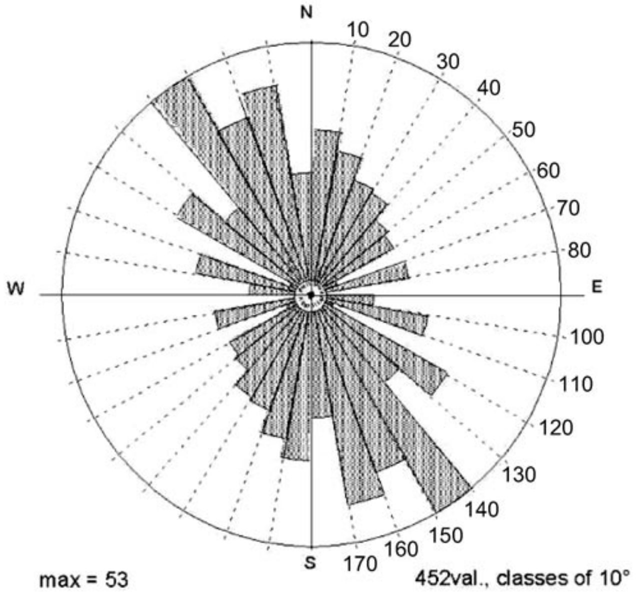

Figure 13. Compilation of glacier orientation in the southeast Karakorum. The study zone is delimited by the Shigar and Karakorum fault, the Main Karakorum Thrust, and the Hispar glacier. Each glacier orientation has been measured using 1.5 km segments on satellite images.

erosion, it allows exhumation of the M2 metamorphic zone. This secondary exhumation process would explain the medium to low temperature exhumation following the high temperature vertical motion associated with diapiric processes.

CONCLUSION

Thermo-Mechanical Evolution of the South Asian Active Margin

From 80 Ma to Pleistocene times, south Karakorum was a compressive domain with a global N-S direction of shortening. The strong spatial and temporal relationships between the domes and Neogene magmatism suggest that prior to dome formation, a thermal change occurred in south Karakorum. It was proposed that the origin of this magmatism and HT metamorphism was related to the breakoff of the Indian subducting continental lithosphere around 25 Ma (Mahéo et al., 2002). Following the model developed by Davis and von Blanckenburg (1995), the supra-subductive Karakorum plate was heated by the hot asthenospheric mantle rising up in the window opened by the breakoff. The Karakorum lithospheric mantle melted and produced magma, which intruded the crust. It produced HT metamorphism and partial melting of the continental crust by heat advection (Rolland et al., 2001). As a consequence, mid-crustal rocks would have been softened, allowing rapid exhumation by diapirism

The same thermal evolution has been proposed for south Tibet, the eastern extension of south Karakorum (Mahéo et al., 2002). Although numerous geophysical data suggest partial melting of the mid and lower crust of south Tibet (Brown et al., 1996; Makovsky et al., 1996; Nelson et al., 1996; Kola-Ojo and Meissner, 2001; Wei et al., 2001), there is no evidence in this area of mid-crust exhumation.

As crustal thickness is rather similar between south Tibet and south Karakorum (Pegler and Das, 1998), we cannot invoke a difference of buoyancy to explain the non-diapiric ascent in Tibet. An additional point in the bulk forces balance is the erosion rate. With no significant differences in rainfall between south Karakorum and south Tibet (World Meteorological Organization, 1981), it can be observed that the Tibetan plateau erosion products are not evacuated by the rivers (Tapponnier et al., 2001), while in south Karakorum numerous rivers and glaciers crosscut this area and reach the Indus River. Consequently, river incision is much more important in southeast Karakorum than in Tibet. The geometrical boundary conditions are also different between Tibet and Karakorum and could account for different uplift rates, even if the India-Asia convergence rate is similar in both areas (~4.5 cm/yr, Besse et al., 1984; Patriat and Achache, 1984; Holt et al., 2000). The eastward expulsion of north Tibet, at high angle to the shortening direction (Avouac and Tapponnier, 1993), has accommodated an important part of the India-Asia convergence, while in the Karakorum area, the orientation of the main faults bounding Karakorum, viz.

the Chaman and Karakorum faults, precludes any east-west lateral expulsion. Consequently, for a similar convergence rate, a higher proportion of the convergence is accommodated by vertical motions in south Karakorum. Structural analysis shows that the ductile deformation is partitioned between folding and associated uplift of the dome area and the Baltoro batholith and dextral strike-slip motion along the Karakorum fault. The combination of high erosion rate with strong uplift controlled by strain partitioning in an oblique convergent setting, together with the lack of lateral expulsion in south Karakorum, could explain why high temperature rocks from the mid-crust only outcrop in southeast Karakorum and not in south Tibet.

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