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A slab breakoff model for the Neogene thermal evolution of South Karakorum and South Tibet

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Abstract

On the South Karakorum margin, Neogene high-temperature–medium-pressure (HT–MP) gneisses define an east–west trending thermal anomaly. These rocks have been heated from 600 to 750°C during a slight pressure drop from 0.7 to 0.5 GPa. Their retrogressive path cross-cuts the relaxed geotherm of tectonically thickened crust. Such a *P–T* evolution occurs only if an advective source of heat is involved. Involvement of an advective heat source is also implied by the occurrence of Neogene granitoids and lamprophyres within the HT–MP gneiss area. These rocks are strongly enriched in large ion lithophile elements relative to primitive mantle and show negative high field strength element anomalies. We interpret these geochemical characteristics to be the result of melting of metasomatized Asian lithospheric mantle. The Nd and Sr isotopic compositions of the South Karakorum Neogene magmatic rocks ($\varepsilon_{Nd} = -12$ to -7 and $^{87}Sr/^{86}Sr = 0.705$–0.725) further suggest they could have originated from mixing between Asian variously metasomatized mantle and Precambrian crust. By contrast, the origin of the youngest magmatic rocks (< 10 Myr), here exemplified by the Hemasil syenite and associated lamprophyres, requires involvement of a depleted mantle. The combined ε_{Hf}–ε_{Nd} signature of these rocks ($\varepsilon_{Hf} = +10.4$–$+11.5$ and $\varepsilon_{Nd} = +3.4$–$+4.3$) suggests that the source of the Hemasil syenite could have been depleted mantle contaminated by oceanic sediments, likely during the earlier subduction of the Tethyan ocean. Neogene magmatic rocks with the same geochemical characteristics and evolution as those of South Karakorum have previously been described in South Tibet. Based on their location and the geochemical evolution of their source region, we here propose that the Neogene magmatic and metamorphic evolution of the South Asian margin was controlled by slab breakoff of the subducting Indian continental margin starting at about 25 Ma. This model is supported by available geophysical data from South Karakorum and South Tibet.

Keywords: Karakorum; Xizang china; high temperature; medium pressure; gneisses; Neogene; magmas; slabs

1. Introduction

Understanding the origin of high-temperature–medium-pressure (HT–MP) gneisses associated with migmatites and mantle-derived magmatic rocks in orogenic areas may help provide insight

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into thermal and mechanical relationships between continental crust and upper mantle in a convergent tectonic context. Synchronous occurrence of high-temperature metamorphism, migmatization, and mantle-derived magmatism in an orogenic domain, long after the final emplacement of subduction-related magmas, may be explained in a number of ways: (a) upwelling asthenospheric mantle due to lithospheric thinning during late orogenic extension [1], (b) localized heat advection within lithospheric strike-slip shear [2], (c) convective thinning of the lithospheric root [3] or (d) slab breakoff affecting the subducting continental lithosphere [4]. One way to distinguish between these different scenarios is to integrate the geographic location of the magmatic rocks with their geochemical evolution and available geophysical data.

In South Karakorum (NE Pakistan), the recent discovery of Neogene granulitic rocks associated with migmatites and numerous mantle-derived magmatic rocks in a setting of global north–south shortening [5] strongly suggests that interaction between the thickened Asian crust and the underlying mantle occurred during the India–Asia convergence. Eastward, in South Tibet, potassic Neogene magmatism has also been observed [6–9]. The standard interpretation of this magmatism

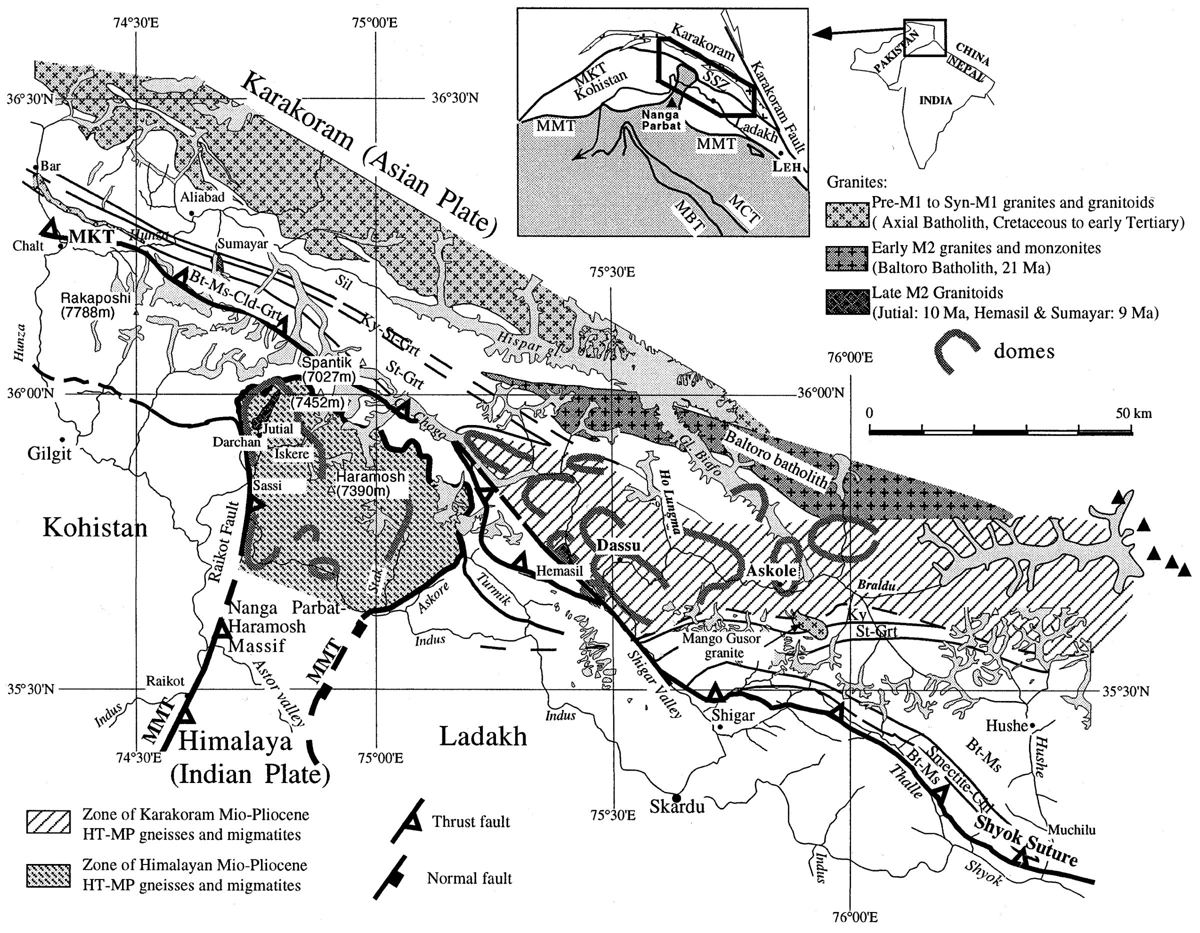

Fig. 1. Geological and metamorphic sketch map of the South Karakorum margin after [5]. Main tectonic contacts are the Main Boundary Thrust (MBT), the Main Central Thrust (MCT), Main Mantle Thrust (MMT), the Shyok Suture Zone (SSZ), and the Main Karakorum Thrust (MKT).

has been in terms of convective thinning of the lithospheric root beneath the Tibetan plateau. In this context, asthenosphere upwelling induced melting of enriched and hydrated portions of the thinned lithospheric mantle [7,8,10]. Recently, however, Miller et al. [7] tentatively invoked slab breakoff in SW Tibet.

In this paper, the origin of the South Karakorum HT–MP gneisses and the associated Neogene magmatism will be discussed in the light of slab breakoff of the subducting Indian slab. Based on the *P–T–t* path evolution of the HT–MP gneisses and the geochemical characteristics of the Neogene magmatic rocks and their magmatic evolution, we further suggest that the proposed model of slab breakoff for South Karakorum can be extended to encompass the entire south Tibetan margin.

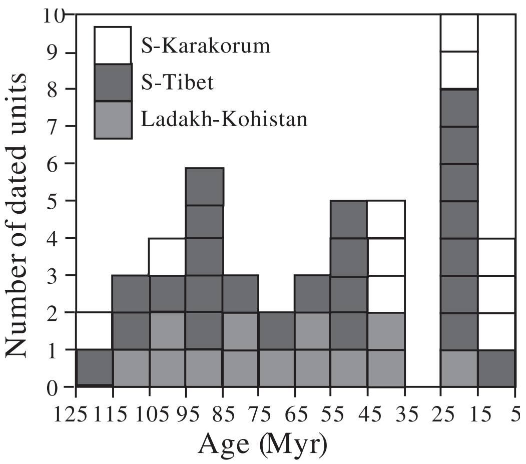

Fig. 2. Distribution of the crystallization ages of the South Karakorum, Ladakh–Kohistan, and South Tibet magmatic rocks. Data from [6,7,9,11,12,20–22,56].

2. Geological and structural setting

In the NW part of the India–Asia collision zone, the south Karakorum orogenic domain constitutes the SW part of the so-called Asian margin (Fig. 1). The south Karakorum margin is separated from the Indian margin by the middle Cretaceous Kohistan–Ladakh arc, accreted during Upper Cretaceous times [11]. During the northward drift of the Indian plate, between 125 and 37 Ma [12], numerous subduction-related calc-alkaline plutons were emplaced on the south Karakorum margin [13]. Contemporaneously, nappe stacking occurred in an overall SW–NE direction of shortening. The nappe stacking was associated with the development of the M1 Barrovian metamorphism [5,12,14], an event marked by a NW–SE-trending zonation from smectite–chlorite schists in the SW to sillimanite- and K-feldspar-bearing migmatites in the NW [5,12,14]. This magmatic and metamorphic event is post-dated by the emplacement of the calc-alkaline Mango Gussor pluton at 37 Ma [15].

The M1 zonation is cross-cut by an E–W-trending M2 metamorphic zone, 120 km long by 20 km wide. This zone is underlain by granulitic and migmatitic domes (hereafter referred to as the domes area) associated with plutonic and syenitic plutons (Fig. 1). The northern edge of this metamorphic zone is bound by the E–W-elongated Baltoro granite with U/Pb zircon ages between 25 and 21 Ma [16] and is temporally and spatially associated with the Hunza leucogranitic dikes emplaced between 25 and 4 Ma [14]. Lamprophyre and shoshonite dikes also cross-cut the Baltoro granite, as well as the K2 gneisses [17,18], and are associated with the 8 Ma Hemasil syenitic pluton (Ar/Ar age on amphiboles [19]), which is the object of our investigation here. It is important to note that this Neogene magmatic event occurred 10 Myr after the period of subduction-related magmatism (Fig. 2) and is therefore a distinct event.

Ages for the metamorphic rocks from the domes area range from 10 to 3 Ma (U/Pb ages, see [5] for a review). Migmatitic domes form kilometer-sized, roughly conical folds marked by HT sillimanite+biotite foliation and migmatitic foliation. Bending of migmatitic segregation and tilting of granitic dikes imply that melting occurred before doming [5].

3. The Neogene granulitic metamorphism

A complete description of the Neogene HT metamorphism is given by Rolland et al. [5] and will not be repeated here. For this paper, it is important to stress only the following features. The domes area can be separated into two main zones: (1) the Transition Zone, which is characterized by relicts of the nappe-stacking event (kyanite+staurolite+muscovite+garnet 1+K-feldspar) overprinted by late HT assemblages (biotite+sillimanite+garnet 2), and (2) the High Grade Zone (HGZ), where previous metamorphic events are completely overprinted by HT events. Metapelites are partially melted and composed of HT parageneses (sillimanite+biotite+K-feldspar ± garnet). In the HGZ, the estimated *P–T* path is characterized by strong heating associated with a slight pressure decrease under HT–MP facies conditions from 625°C to 775°C at 0.7 ± 0.1 to 0.5 ± 0.1 GPa (Fig. 3). This heating event is associated with anatexis characterized by muscovite and biotite breakdown reactions. As demonstrated by Rolland et al. [5], the bending of the migmatitic segregation implies that subsequently to the heating event, the partly molten mid-crustal rocks were exhumed rapidly (up to 5 mm/yr) by crustal-scale fold amplification during N–S shortening. This rapid exhumation was associated with a high cooling rate (70–100°C/Myr, [19]).

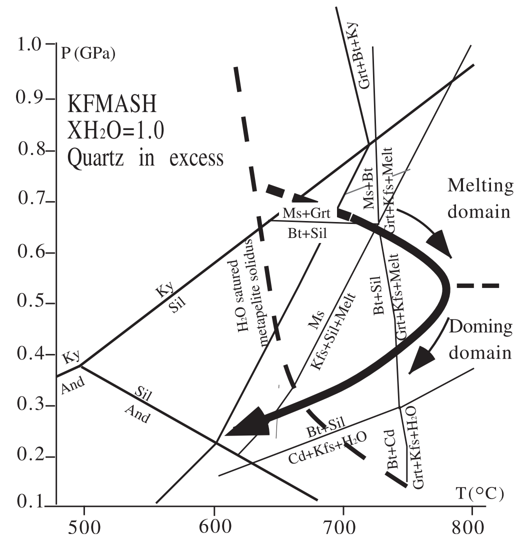

Fig. 3. *P–T* path of the Neogene South Karakorum HT–MP gneisses in the core of the domes area (after [5]). Petrogenetic grid after Spear et al. [23], Le Breton and Thompson [24], and Vielzeuf [25].

To explain such a strong temperature increase prior to the period of rapid exhumation, an additional heat input must have taken place. Because extensional tectonics are not recorded in South Karakorum, a widespread heat flux increase, typical of extensional settings [26], cannot be advocated. By contrast, the doming in this area is compatible with a model of a fold amplification of previously molten rocks [27] related to the N–S shortening of the South Karakorum. The occurrence of numerous pegmatitic dikes cross-cutting the earlier M2 foliation that were tilted before doming, and the presence of granitic and syenitic plutons exhumed to the present-day surface level in the domes area, suggest that the potential heat source needed to explain such a high thermal gradient could be pluton emplacement beneath and around the domes [5].

4. Neogene magmatism in South Karakorum and South Tibet

4.1. Geochemistry

We present here a re-interpretation of geochemical data from the Baltoro area [28], the Hunza leucogranitic dikes [29], the K2 lamprophyres and shoshonites [17], and the Hemasil syenite and associated lamprophyres [17]. The geochemical signatures of these magmatic rocks have been interpreted in various ways: Searle et al. [28] and Crawford and Searle [29] considered the granitic rocks from Baltoro and Hunza to be of continental crustal origin, whereas the Hemasil syenite, the lamprophyres, and the shoshonites were assigned to be of mantle origin [12,17,28]. However, the Neogene granitic rocks show key geochemical features that are similar to the associated lamprophyres and shoshonites (Fig. 4). Both rock types are enriched in large ion lithophile elements (LILE) relative to primitive mantle (PM) and have negative anomalies for high field strength elements (HFSE). The youngest of these lamprophyres, which cross-cuts the 8 Ma old Hemasil syenite, is also the least enriched of the mafic rocks in LILE and the most depleted in HFSE. The granites have incompatible element abundan-

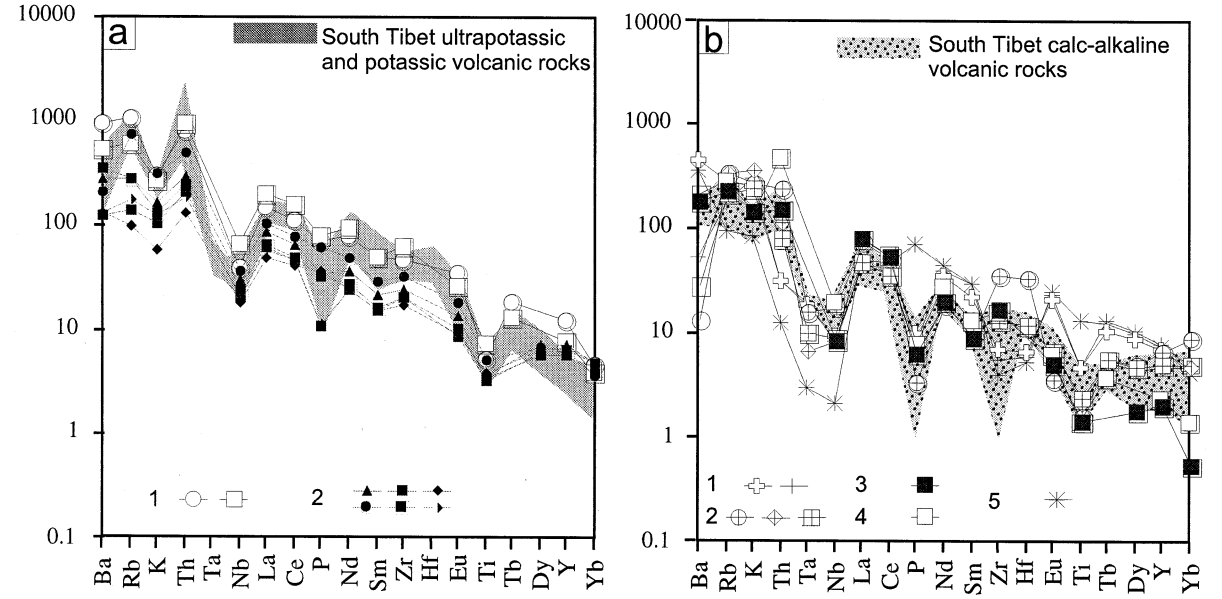

Fig. 4. Primitive mantle-normalized incompatible element diagram for the Neogene Karakorum magmatic rocks. (a) Lamprophyres from the (1) Baltoro area [28] and (2) K2 [17] compared with the field of south Tibetan calc-alkaline volcanic rocks [6–8]. (b) (1) The Hemasil syenite, primary epidote-bearing [12], (2) the Hemasil syenite, primary epidote-absent [12], (3) average Baltoro monzogranites ($n = 5$, [28], (4) average Hunza monzogranites ($n = 20$ [29]), and (5) a Hemasil lamprophyre [12] compared with the field of South Tibetan ultra-potassic and potassic volcanic rocks [7]. Normalization factors from [30].

ces higher than generally observed for the continental crust [31]. Consequently, their geochemical characteristics cannot be explained solely by a continental crust origin. A mantle source similar to that invoked for the lamprophyres, the shoshonites, and the Hemasil syenite should therefore be considered. The strong enrichment in LILE relative to PM and the negative HFSE anomalies suggest metasomatism of this mantle source prior to the magmatic activity that gave rise to the Neogene plutonic rocks. Based on the location of the South Karakorum magmatism, the involved mantle source is inferred to be the Asian lithospheric mantle previously metasomatized by processes related to the Tethyan oceanic lithosphere subduction.

Neogene volcanic rocks have been observed all along the South Tibetan margin and in North Tibet (Fig. 5). As in South Karakorum, these rocks were formed during a distinct Neogene magmatic event (Fig. 2). This event occurred 5–10 Myr after the emplacement of the last subduction-related magmas. The North Tibet magmatism shows no clear geochemical differences with respect to the South Tibet magmatism but nevertheless corresponds to a distinct magmatic event for the following reasons. First, the magmatism in North Tibet is significantly younger, between 16 and 0.07 Ma [8], than the magmatism in South Tibet and South Karakorum, which are both between 25 and 10 Ma [6,7]. Second, there is no spatial continuity between South Tibet and North Tibet as no Neogene magmatic rocks have been found in Central Tibet. Third, the South Tibet and South Karakorum Neogene magmatic rocks are localized along a narrow belt following the southern boundary of the Asian margin, whereas in North Tibet the Neogene magmatism is far more diffuse. We therefore consider that South Tibet and North Tibet represent two distinct Neogene magmatic provinces. For this reason we will in the following compare the South Karakorum Neogene magmatic rocks only to those from South Tibet. The origin of the North Tibet magmatic rocks will be discussed separately in the last section.

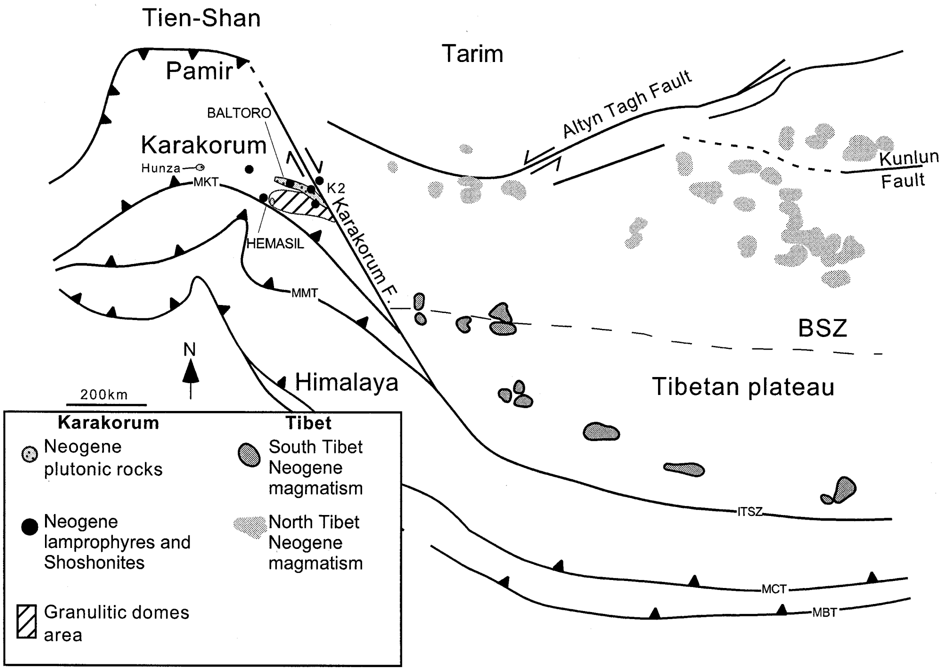

Fig. 5. Location map of the main Neogene magmatic rocks in South Karakorum and South Tibet.

In South Tibet, Neogene magmatic rocks have been divided into two main groups, the ultra-potassic and potassic volcanic rocks (UPV and PVR), erupted between 23 and 14 Ma, and the highly potassic calc-alkaline volcanic rocks (CAV), erupted between 20 and 10 Ma [6–9]. The main geochemical characteristics of the South Tibet volcanics have likewise been interpreted, as argued above for South Karakorum, as resulting from melting of the Asian subcontinental mantle previously metasomatized during subduction of the Tethyan ocean [7,8].

The comparison between the South Tibet and the South Karakorum magmatism on a primitive mantle-normalized spider diagram (Fig. 4) shows that the K2 and Baltoro lamprophyres have the same characteristics as the UPV and PVR, and that the granitic and syenitic rocks are very similar to the CAV. The lower concentration in heavy rare earth elements (HREE) in the garnet-bearing Baltoro and Hunza granites suggests fractional crystallization of garnet. By contrast, both the Hemasil syenite and the associated lamprophyres show enrichments in HREE relative to CAV. The fact that both of these lithologies share the same signature suggests this signature is inherited from their source region rather than being the result of fractional crystallization.

4.2.. Sr–Nd isotope systematics of the South Karakorum and South Tibet magmatic rocks

4.2.1. 25–17 Ma magmatism

A mantle derivation of the South Karakorum and South Tibet magmatism is also indicated by mixing models calculated from initial Sr and Nd isotopic compositions of whole rocks using the simple mixing mass balance relationship of DePaolo [32] (Fig. 6; recalculated from [7–9] for South Tibet and [12,28,29] for South Karakorum). The isotopic signatures of the Hunza and Baltoro granitic rocks can be accounted for by mixing between the Precambrian crust of the Gondwana continent [34] and the metasomatized Asian lithospheric mantle as represented by the most primitive magmatic rocks from the Hunza unit [13]. This unit corresponds to the magmatic activity on the Cretaceous Asian active margin [13]. It is therefore likely that these Cretaceous magmas were contaminated by Asian crust. This

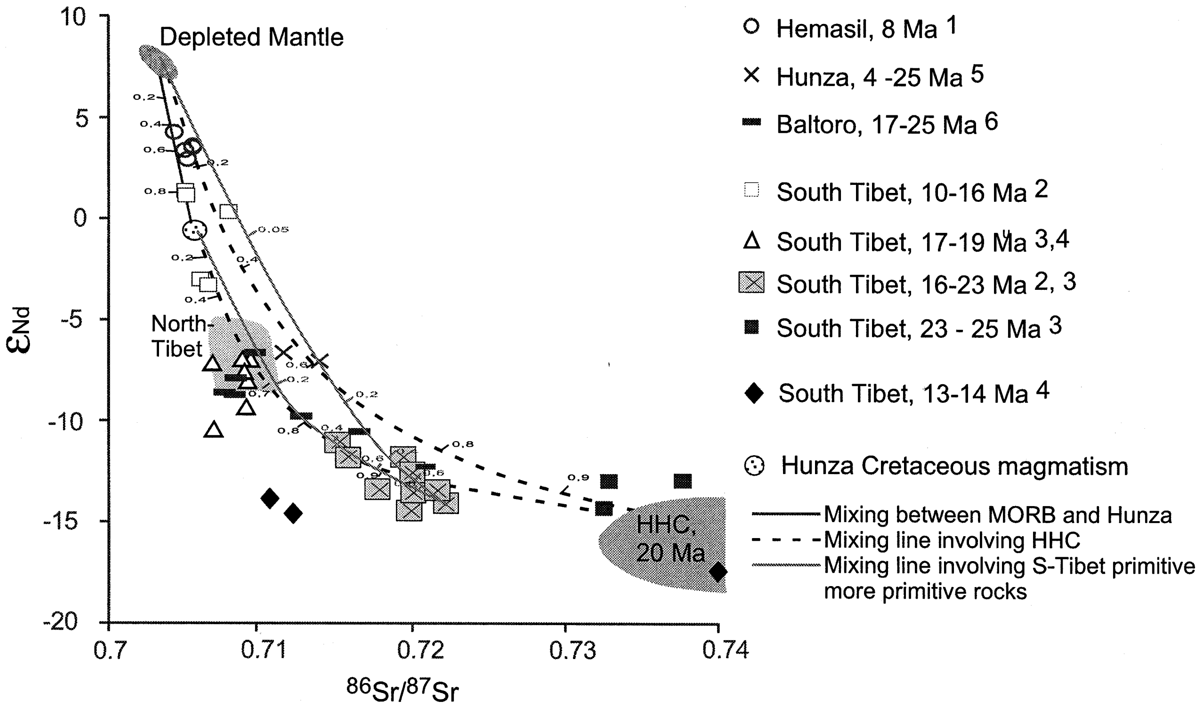

Fig. 6. Initial ε_{Nd} and $^{87}Sr/^{86}Sr$ of the South Tibetan and Karakorum Neogene magmatic rocks. Data recalculated from (1) [12]; (2) [8]; (3) [7]; (4) [29]; (5) [28]. Hunza Cretaceous granites are from [13], High Himalayan Crystallines (HHC) data from [33,34] and North Tibet ultra-potassic rocks from [8].

in turn implies that a more accurate end-member for the Asian metasomatized lithospheric mantle should have slightly higher initial ε_{Nd} and lower $^{87}Sr/^{86}Sr$. However, no isotopic data of the contemporaneous mafic rocks are available to test this hypothesis. Nevertheless, the oldest South Tibetan volcanic rocks (13–25 Ma) plot on the same mixing trend as the 20–25 Ma Baltoro and Hunza magmatic rocks. Miller et al. [7] demonstrated that the most primitive South Tibetan rocks that are of mantle origin with minor crustal contamination, have the most radiogenic Sr and unradiogenic Nd isotopic compositions. Thus the mixing line defined by the Hunza and Baltoro magmatism and the oldest South Tibetan magmatic rocks (13–25 Ma) could also represent the magmatic signature of melting of variously metasomatized lithospheric mantle (Fig. 6).

In order to discriminate between these two hypotheses, we plotted all the available data from the South Tibet and South Karakorum Neogene magmatism on a Rb/Sr versus La/Ce diagram (Fig. 7). In this diagram UPV, CAV, Baltoro lamprophyres, K2 lamprophyres, and some Baltoro and Hunza granites define a mixing line between the most primitive UPV, as defined by Miller et al. [7], and the Cretaceous Hunza magmatic rocks which have the highest La/Ce ratios. This trend is very different from that expected if crustal contamination was involved but can be explained by the melting of variously metasomatized mantle. Nevertheless, the PVR and some Baltoro and Hunza granites are clearly shifted toward a crustal end-member, thus confirming the crustal contamination of the PVR proposed by Miller et al. [7]. To summarize, Fig. 7 demonstrates that most of the South Tibet and South Karakorum Neogene magmatic rocks can be explained by the melting of a variously metasomatized mantle source. Crustal contamination seems to be minor except for the PVR and some Hunza and Baltoro granitic rocks.

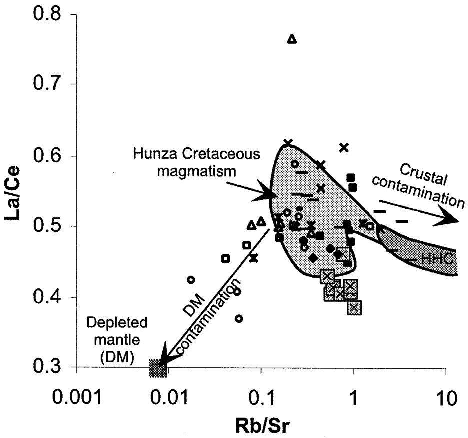

Fig. 7. La/Ce versus Rb/Sr diagram for the South Karakorum and South Tibet Neogene magmatic rocks. Hunza Cretaceous magmatism from [13] and HHC data from [35]. *K2 lamprophyres and shoshonites [17], other symbols and data sources as in Fig. 6.

4.2.2. Post-16 Ma magmatism

According to the Sr–Nd isotopic data (Fig. 6) and the La/Ce versus Rb/Sr relationship (Fig. 7), the Hemasil syenite and the youngest CAV (the Maquiang rocks [6]) plot on a trend distinct from those defined by the other South Tibet and South Karakorum Neogene magmatic rocks (Figs. 6 and 7). These rocks are shifted toward a mid-ocean ridge basalt (MORB)-like end-member implying the involvement of a depleted mantle source. Since these rocks were emplaced exclusively after 16 Ma, this further suggests that the depleted source was involved only in the latest stages of the magmatic activity. We emphasize that at the same time CAV and UPV production continued uninterrupted (Figs. 6 and 7).

4.3. Magmatic evolution

In South Tibet and South Karakorum the oldest volcanic rocks (UPV and PRV) were extracted from the most enriched mantle (Figs. 6 and 7). In South Tibet, this first melting event was followed by melting of a less depleted mantle producing the CAV between 17 and 19 Ma (Figs. 6 and 7). Magmatic rocks originating from the less enriched mantle only appear after 16 Ma in South Tibet and close to 8 Ma in South Karakorum with the emplacement of the Hemasil syenite (Figs. 6 and 7). During the same period, magmatic rocks similar to the UPV, PVR, and CAV appear in South Tibet (Figs. 6 and 7).

In summary, it appears that the South Tibetan and the South Karakorum magmatic Neogene rocks were extracted from variously metasomatized mantle contaminated by Precambrian crust as seen in the PVR, the Hunza, and the Baltoro granites. Through time, however, the mantle involved in the magmatic production appears to have shifted from being strongly to less metasomatized and some of the last magmatic rocks have Nd and Sr isotopic compositions and incompatible versus incompatible element ratios close to those of MORB.

4.4. Hf isotope systematics of the Hemasil syenite

In order to better constrain the depleted mantle component observed in the youngest South Karakorum magmatic rocks, and by inference the South Tibetan magmatic rocks, we measured the Hf isotopic composition of four samples from the Hemasil syenite taken to be representative of this suite of rocks. The Hf separation chemistry and mass spectrometry followed the method described in Blichert-Toft et al. [36] and Blichert-Toft [37]. The Hf isotope measurements were done by multi-collector inductively coupled plasma mass spec-

Table 1
Hf isotopic compositions of syenites from the Hemasil syenite

Sample	$^{176}Hf/^{177}Hf$	ε_{Hf}	ε_{Nd}	Source of Nd isotope data
TK835	0.283065 ± 23	10.4	3.4	[12]
TK839	0.283092 ± 10	11.3	4.3	[12]
TK841	0.283091 ± 11	11.3	3.6	[12]
TK845	0.283087 ± 16	11.1	3.5	[12]
	0.283098 ± 19	11.5	3.5	[12]

Hf isotopic compositions measured by MC–ICP–MS (VG Plasma 54). $^{176}Hf/^{177}Hf$ normalized for mass fractionation to $^{179}Hf/^{177}Hf = 0.7325$. $^{176}Hf/^{177}Hf$ of JMC-475 Hf standard = 0.28216 ± 0.00001. Hf standard run alternately with samples. Uncertainties reported on Hf measured isotope ratios are in-run $2\sigma/\sqrt{n}$ analytical errors in last decimal place, where n is the number of measured isotopic ratios.

trometry (MC–ICP–MS) using the VG Plasma 54 in Lyon.

The four samples are isotopically identical within error and show rather radiogenic Hf isotopic compositions (ranging from ε_{Hf} +10.4 to +11.5) compared to their Nd isotopic compositions (ranging from ε_{Nd} +3.4 to +4.3) (Table 1). The mantle array as defined by published and unpublished Hf and Nd isotopic data for some 1500 ocean island basalts (OIBs) and MORBs is described by the equation $\varepsilon_{Hf} = 1.39\varepsilon_{Nd}+2.75$ [38]. Given the ε_{Nd} signature of +3.5 on average for the Hemasil syenite (Table 1), the corresponding ε_{Hf} value calculated from the equation of the Hf–Nd mantle array should be about +7.6. Instead we measure ε_{Hf} of +10–11 (Table 1). Not only is this about 30% higher than predicted by the equation for the mantle array but this value also falls at the extreme outskirts of the relatively large scatter about the mantle array regression line (Fig. 8).

Very few terrestrial materials have highly radiogenic Hf relative to Nd, but oceanic sediments do. This is believed to be due to their anomalously high (Lu/Hf)/(Sm/Nd) ratios caused by the 'zircon effect' [42,43]. Mantle-derived samples deviating from the Hf-Nd mantle array towards radiogenic Hf isotopic compositions therefore may testify to the presence in their source of oceanic sediments

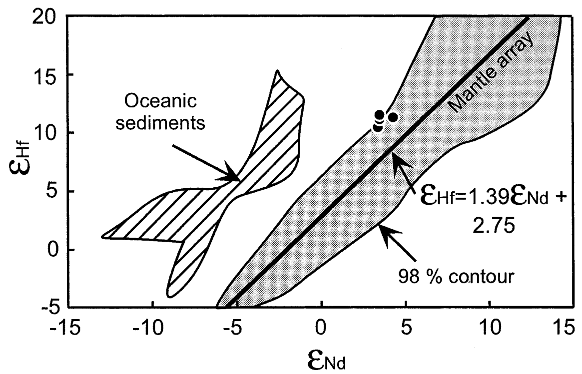

Fig. 8. Plot of ε_{Hf} versus ε_{Nd} for the Hemasil syenite. Mantle array based on numerous published (references too many to cite here) and unpublished [38] Hf and Nd isotope data for ca. 1500 OIBs and MORBs. Error bars for the Hemasil data are smaller than the symbols. See text for explanation. Oceanic sediment field from [39–41].

supposedly brought there by subduction zone processes. Since the geographic region discussed in this paper has been the venue of massive subduction during the Cretaceous to Paleocene subduction of the Tethyan oceanic lithosphere below the Asian continental lithosphere, we do not consider it farfetched to suggest that the unusual radiogenic Hf isotopic signature of the Hemasil syenite could reflect the introduction and incorporation of substantial amounts of oceanic sediment into the Asian depleted mantle beneath South Karakorum. Currently, however, very little is known quantitatively about how widespread or volumetrically significant the anomalous Hf–Nd isotopic signature is in oceanic sediments. Furthermore, the overall mass balance for sediment fluxes into the mantle through subduction zones is also poorly constrained and, in addition, probably varies from one subduction zone to the next. Not surprisingly, no Hf–Nd isotopic data exists for local sediments from the Indian margin that we are concerned with in this study. We therefore cannot quantify further our proposition that the radiogenic Hf characterizing the Hemasil syenite derives from oceanic sediments in its mantle source. We simply note that the Hf isotopic composition of the Hemasil syenite is consistent with our previous conclusion based on other geochemical evidence that this magma was derived from the depleted Asian mantle that had been previously polluted by the subduction of the Tethyan oceanic lithosphere. We also note that Pb isotopes in the Neogene volcanic rocks of South Tibet led Miller et al. [7] to suggest contamination of the Asian mantle by oceanic sediments.

5. Discussion

5.1. Model for the origin of the South Tibet and South Karakorum ultra-potassic magmatism

The South Karakorum and South Tibet Neogene magmatism and associated HT–MP gneisses define a new thermal event distinct from the subduction-related magmatism that terminated 5–10 Myr prior. The Neogene South Karakorum and South Tibet magmatic rocks are located within a belt about 100 km wide and 2000 km long oblique to the Karakorum Fault. Because of this cross-cutting relationship, the narrow Neogene magmatic zone cannot be the result solely of the presence of this lithospheric-scale strike-slip fault despite its obvious ability to help focus magma ascent and favor HT–MP gneiss exhumation in a transpressive setting. Rather, the belt-like shape of the 'thermal anomaly' could be related to the existence of a narrow, linear, deeply rooted hot zone. Such a geometry is typically, if not exclusively, produced by either subduction-related magmatism or slab breakoff processes [4]. In contrast, convective thinning produces a far more diffuse and widespread magmatic activity [3].

The magmatic evolution of South Tibet and South Karakorum is also a good indicator of the operation of slab breakoff rather than convective thinning. In the case of convective thinning, as pointed out by Turner et al. [44] in the Betic, the oldest magmatism is associated with decompressional melting of the asthenosphere resulting from its upwelling to replace the convectively removed lithosphere. Decompressional melting of the asthenosphere does not occur until the asthenosphere is within 50 km of the surface [45], implying a not very thickened continental crust. The upwelling asthenosphere heats the remaining lithospheric mantle, first causing melting of the lower boundary layer of the mechanical lithosphere and then of the shallower lithospheric mantle [44]. As the lithosphere is progressively heated from below, its different levels thus melt one after the other, but, importantly, never at the same time.

In South Tibet and South Karakorum, where the crust is thick, about 70 km [46], decompressional melting of the asthenosphere cannot occur. The most interesting specificity of the South Karakorum and South Tibet Neogene magmatism is that its successive mantle sources evolve from being strongly to less metasomatized. The less metasomatized source appears exclusively in the youngest magmatic rocks, whereas mantle significantly more metasomatized is involved throughout the entire Neogene magmatic activity. When mantle is heated from below, as in the case of convective thinning, the various mantle sources (corresponding to different levels in the mantle) melt one at the time [44]. By contrast, during slab breakoff, a detached part of the lithosphere sinks into the mantle and pulls the resulting gap downwards with it. The hot asthenosphere filling this gap will heat those progressively deeper parts of the mantle localized directly above the descending gap as the plate sinks deeper and the gap stretches downward. The mantle sources involved in the magmatic activity observed on the surface will thus be of progressively deeper origin as the rocks get younger. Because the depleted isotopic signature in South Karakorum and South Tibet is observed at the late, rather than the earlier stages of magmatic activity, slab breakoff as opposed to convective thinning more accurately accounts for the magmatic evolution of this region.

Breakoff of the Indian continental lithosphere starting at 25 Ma could explain both the renewal of the magmatic activity 10 Myr after the end of the subduction-related magmatism in South Karakorum and South Tibet (Fig. 2) and the observed geochemical evolution of the Neogene magmatism. We propose the following scenario to explain the Neogene magmatic evolution. 25 Myr ago, slab breakoff of the Indian continental lithosphere was initiated at a depth of about 50–70 km (Fig. 9a) according to the model of Davies and Van Blanckenburg [4]. The hot Indian asthenosphere rose through the window created between the detached lithosphere and the leftover slab, and then induced the melting of the metasomatized Asian lithospheric mantle (Fig. 9b). The resulting mantle-derived magmas migrated throughout the Karakorum thickened crust, thus advecting heat and giving rise to the mid-crustal granulitization [5]. While the Indian continental subduction was still active and the detached Indian lithosphere fell into the asthenosphere, the slab window gradually migrated downwards (Fig. 9c). Consequently, the hot Indian asthenosphere rose through a progressively deeper window and could heat and partially melt progressively deeper-seated Asian mantle at successively later stages. Since metasomatism in subduction zones is believed to affect the supra-subductive mantle down to a maximum depth of about

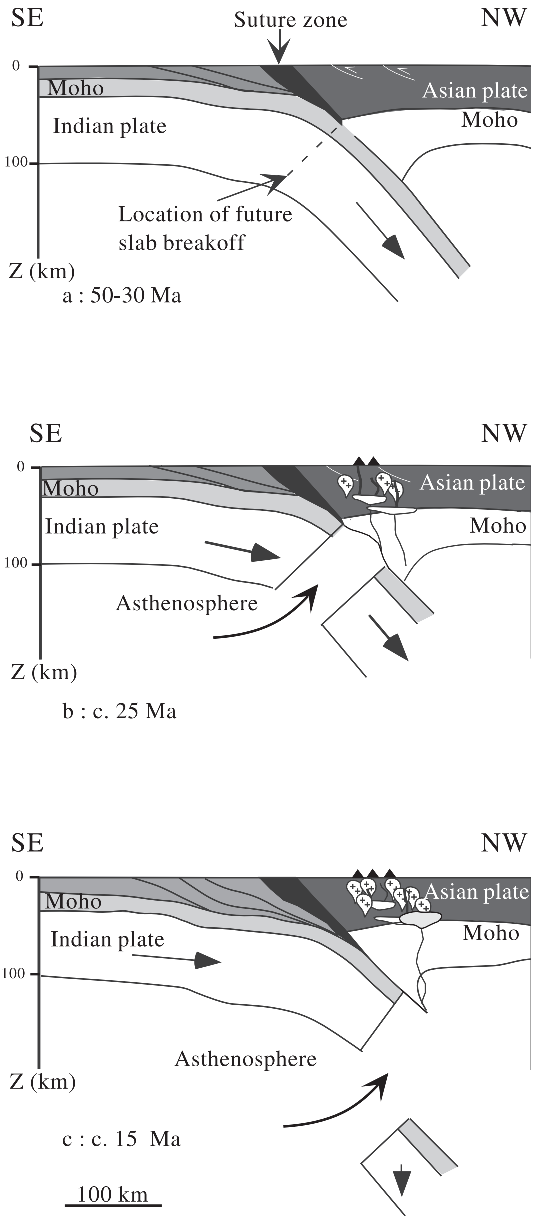

Fig. 9. Evolution of the India–Asia convergent zone during Tertiary times. (a) Southward subduction of the Indian continental lithosphere. The slab breakoff occurs at about 70 km depth according to the model of [4]. (b) Asthenosphere rising in the gap produced by the slab breakoff induces melting of the metasomatized Asian lithospheric mantle. (c) As the detached Indian continental lithosphere continues to descend the uprising hot asthenosphere triggers melting of the metasomatized Asian asthenosphere.

150–200 km [47], the window created beneath South Karakorum and South Tibet was sufficiently deep for the Asian metasomatized asthenospheric mantle to be heated and melted in addition to the Asian metasomatized lithospheric mantle.

This gradual increase in the depth of the plate window through time readily explains the progressive evolution of the geochemical characteristics of the Neogene magmatism in South Karakorum and South Tibet in that the melting of progressively more depleted mantle would account for the more depleted character of the youngest South Karakorum and South Tibetan rocks. A late involvement of a depleted mantle source is also observed in numerous other areas where slab breakoff has been proposed to take place (Central Italy [48]; western Anatolia [49]). The similarity of the geochemical signature of slab breakoff in all of these cases can be explained by the fact that the overlying mantle was previously metasomatized by subduction of oceanic lithosphere. The only difference between the Mediterranean and the Indian scenarios lies in the amount of subducted continental crust involved. The most substantial amount has been subducted in the latter case, which represents a mature continent/continent collision zone as opposed to the former case, which represents a less mature collision zone. This particular characteristic of the Indian setting is related to the fact that a large amount (500–1500 km) of Indian continental lithosphere has been subducted since the Paleocene [50] and consequently the gradual increase in density by ecologitization of the subducting Indian plate produced a negative buoyancy that facilitated slab breakoff [51,52]. It appears, therefore, that upon subduction of continental material to depths of 100–250 km, slab breakoff is a very common process [52].

Tomographic data throughout the India–Asia convergent zone suggest that gradual slab breakoff occurred during Mesozoic and Tertiary times [53]. According to analog modeling compared with these tomographic data, Chemenda et al. [51] associated the shallower tomographic positive anomaly with a 25 Ma old breakoff of the Indian continental lithosphere. Breakoff of the subducting Indian lithosphere is also clearly evidenced in NW Kohistan based on historic seismicity compiled by Chatelain et al. [54] and by Kosarev et al. [55] in South Tibet according to P to S conversion of teleseismic waves.

5.2. Comparison between North Tibet and South Tibet ultra-potassic Neogene magmatism

Ultra-potassic Neogene magmatism was also described in North Tibet [8]. As discussed above, we consider that this magmatism is distinct from the Neogene magmatism of South Tibet and South Karakorum. First, the North Tibet magmatism is localized in a diffuse zone (Fig. 5) from the Altyn-Tag fault zone to Central Tibet and there is no continuity with the South Tibet and South Karakorum magmatism (Fig. 5). Second, the North Tibet magmatism has a very homogeneous geochemical signature similar to that of the CAV and only occurs between 16 Ma and 0.07 Ma [8]. As first proposed by [8], we think that the North Tibet ultra-potassic magmatism could be associated with convective thinning of the northern Tibetan lithospheric mantle. The homogeneity of this ultra-potassic magmatism is consistent with a single stage of melting of a lithospheric mantle induced by upwelling of the asthenosphere. The thickness of the crust (>50 km [46]) could explain why there is no evidence of decompressional melting of the asthenosphere.

6. Conclusion

The South Karakorum margin is characterized by Neogene granulitic metamorphism and potassic magmatism with mantle-like geochemical signatures. This magmatism is also observed along the South Tibet margin. These features reflect a vast thermal anomaly related to the breakoff of the Indian continental lithosphere below Asia. The present study confirms conclusions reached previously for the Apennines, the western Anatolia, and the Austro-Italian Alps by showing the importance of slab breakoff in the mature evolution of mountain belts.

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