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Initial geometry of western Himalaya and ultrahigh-pressure metamorphic evolution

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Abstract

Ultrahigh-pressure metamorphic rocks on both sides of the western Himalayan syntaxis show different P–T–t paths. The Kaghan unit was metamorphosed under the UHP conditions significantly later (∼46 Ma) than the Tso Morari unit (∼53 Ma), implying that the Tso Morari was subducted earlier (∼57 Ma) than the Kaghan unit (∼52 Ma). The age difference likely reflects the initial shape of Greater India, with the Kaghan unit located greater than 300 km south of the Tso Morari before the collision of two continents. We calculate the dip of the subducting plate using two independent methods. The results show gentle dipping subduction east of the western syntaxis, and steep subduction west of the syntaxis since the time of India–Eurasia collision to the present time. We propose that the steep subduction in the western part is likely related to the proto-Chaman and Karakorum faults along which the Indian plate moved northward. In the eastern part, the overlying Eurasian plate extruded to east, which allowed gentle dipping subduction of the Indian continent. Although the main period of eastward extrusion of the Eurasian continent occurred between 30 and 15 Ma, our results suggest that this was likely taking place since the early India–Asia collision. Using those geometrical constraints, a 3D image of the slab is reconstructed in the western part, showing the sharp bending of the western syntaxis along the proto-Chaman fault. This bending resulted in the warping of the slab surface to form a conical fold with a north-dipping axis located near the western syntaxis.

Keywords: Subduction geometry; UHP metamorphism; Himalaya; Tectonics

1. Introduction

One of the crucial questions in the India–Eurasia collision concerns the geometry of the Indian plate prior to continental subduction, particularly on its western part (e.g., Ali and Aitchinson, 2005 for review). P–T–t evolution of ultrahigh-pressure (UHP) metamorphic rocks have provided such information related to the geometry of many convergent margins (Ernst, 2001). Northwestern Himalaya has two major UHP units; the Kaghan unit in northern Pakistan and the Tso Morari unit in northern India. The two are considered to have developed contemporaneously during the early subduction of the Indian continent in Paleocene-Eocene time (O'Brien et al., 2001; Kaneko et al., 2003) but recent age determinations show different PTt evolution of the two units. We estimated the dip of the subducting Indian continent for the two areas between 55 and 40 Ma using two different methods. One is based on the trigonometric calculations using the horizontal displacement of the Indian continent and the depth of the UHP units during their subduction and subsequent exhumation (Guillot et al., 2004) and the second method uses the bending of the Indian plate during the same period as has recently carried out by Leech et al. (2005). This paper presents the results, and discusses the initial geometry of the Greater India and the collision between the India and Eurasia continents during the Paleogene.

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2. Geological setting

Along the Himalayan belt, two units of UHP rocks have been recognized (Fig. 1). The occurrence of HP rocks were reported in the Kaghan valley southwest of the Nanga Parbat spur in northern Pakistan by Pognante and Spencer (1991) and they are now considered to be UHP rocks based on the discovery of coesite in this unit by O'Brien et al. (2001). The second occurrence is in the Tso Morari unit in eastern Ladakh, NW India (Guillot et al., 1995, 1997; de Sigoyer et al., 1997). It is now recognized as a UHP unit based on the discovery of coesite by Sachan et al. (2004). Both units represent distal parts of the NW Indian continental margin that were subducted to a depth of 100 km for the Kaghan unit (O'Brien et al., 2001) and most likely 130 km for the Tso Morari unit (Mukherjee and Sachan, 2003). The third and fourth occurrences of an eclogitic unit is reported by Le Fort et al. (1997) in the Indus suture zone, east of the western syntaxis and by Lombardo and Rolfo (2000) in the MCT zone, Central Nepal. The rocks in these units are extensively retrograded at unknown age, and are therefore, not included in the following discussion (Fig. 2).

2.1. Tso Morari unit

The Tso Morari unit in eastern Ladakh is separated from the higher Himalayan crystallines by the Zanskar synclinorium (Guillot et al., 1997). The unit contains hectometric lenses of eclogites in Cambro–Ordovician gneisses overlain by upper Carboniferous to Permian metasedimentary rocks (Colchen et al., 1994; de Sigoyer et al., 2004). The metamorphic condition of the eclogites is estimated up to 3.9 GPa and 750–850 °C (Mukherjee and Sachan, 2003) and dated at ~55 Ma by isotope methods (de Sigoyer et al., 2000; Table 1). Although the age of ~55 Ma is significantly different from the peak metamorphism age of ~46 Ma for the Kaghan unit (Kaneko et al., 2003), the onset of the subduction was considered synchronous both west and east of the western syntaxis probably because of large uncertainty in the peak metamorphic age of the Tso Morari unit. However, recent geochronological studies confirm the age difference of metamorphism between the two units. First, Schlup et al. (2003) obtained a $^{40}Ar/^{39}Ar$ phengite age of 53.8 ± 0.2 Ma from a Tso Morari gneiss which is interpreted as a cooling age. Second, Leech et al. (2005) obtained the UHP metamorphic age of 53.3 ± 0.7 Ma based on a U–Pb zircon SCHRIMP age from a quar-

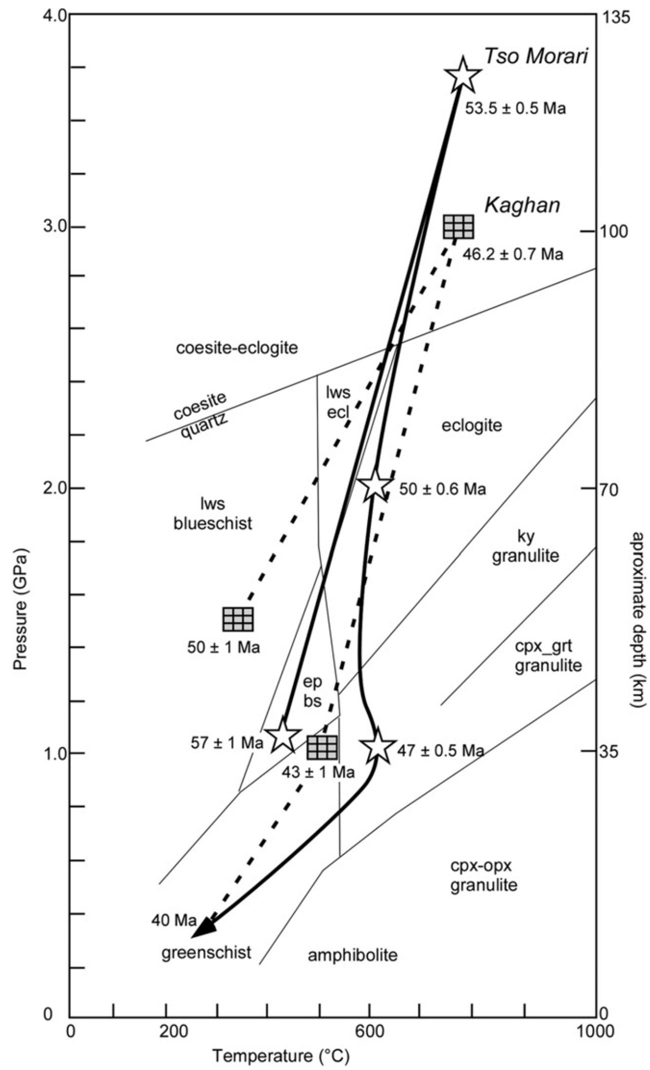

Fig. 2. Pressure–Temperature–time path of the UHP Tso Morari (open stars) and Kaghan units (meshed squares). (see Table 1 for references). Note lower dP/dT gradients and higher peak temperature for the Kaghan unit, probably related to the slower subduction rate. *Abbreviations*: bs, blueschists; cpx, clinopyroxene; ep, epidote; grt, garnet; ky, kyanite; lws, lawsonite; opx, orthopyroxene.

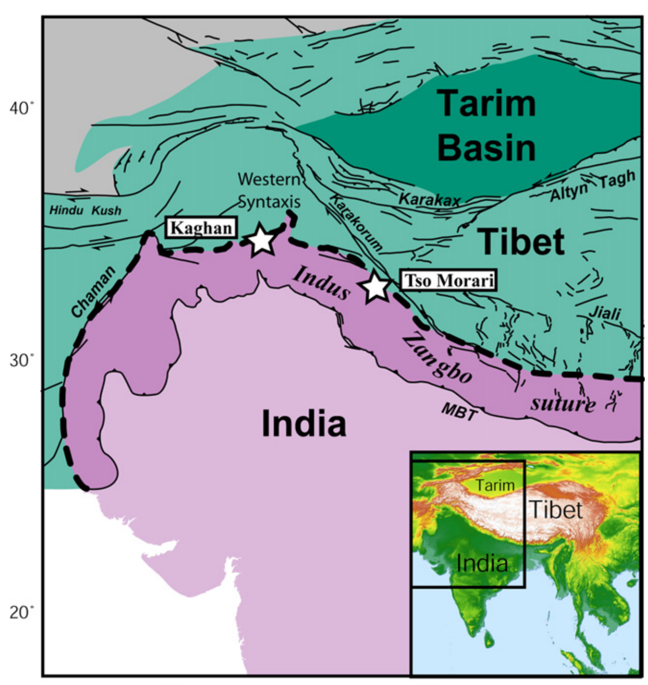

Fig. 1. Schematic map of the NW Himalaya showing the locations of the two UHP units (open stars), Kaghan and Tso Morari (modified after Replumaz and Tapponnier (2003)).

Table 1
Geochronological data of the Tso Morari and Kaghan ultrahigh-pressure units

Unit	Stage	Pressure (GPa)	Temperature (°C)	Age (Ma)	Methods[a]	References
Tso Morari	Prograde HP	~1.0	300–400	57 ± 1	Indirect estimate	Leech et al. (2005); this study
	UHP	2.7–3.9	759–800			Mukherjee and Sachan (2003)
				55 ± 6	Lu–Hf (Grt–Cpx–WR)	de Sigoyer et al. (2000)
				55 ± 9	U–Pb (Aln)	de Sigoyer et al. (2000)
				55 ± 4	Sm–Nd (Grt–Gln–WR)	de Sigoyer et al. (2000)
				53.8 ± 0.2	$^{40}Ar/^{39}Ar$ Phe	Schlup et al. (2003)
				53.3 ± 0.7	U–Pb zircon SCHRIMP	Leech et al. (2005)
	Retrograde HP	2.0 ± 0.2	580 ± 60			Guillot et al. (1997), de Sigoyer et al. (1997)
				50.0 ± 0.6	U–Pb zircon SCHRIMP	Leech et al. (2005)
	Amphibolitic	1.1 ± 0.2	630 ± 50			Guillot et al. (1997); de Sigoyer et al., 1997
				48 ± 2	$^{40}Ar/^{39}Ar$ Phe	de Sigoyer et al. (2000)
				47 ± 6	Sm–Nd (Grt–Amp–WR)	de Sigoyer et al. (2000)
				45 ± 2	Rb–Sr (Phe–Ap–WR)	de Sigoyer et al. (2000)
				47.5 ± 0.5	U–Pb zircon SCHRIMP	Leech et al. (2005)
	Greenschist	0.3 ± 0.1	200–300			Guillot et al. (1997), de Sigoyer et al. (1997)
				45 ± 2	FT (Ap)	Schlup et al. (2003)
				38 ± 2	FT (Ap)	Schlup et al. (2003)
				34 ± 2	FT (Ap)	Schlup et al. (2003)
				36 ± 2	FT (Ap)	Schlup et al. (2003)
				37 ± 3	FT (Ap)	Schlup et al. (2003)
				40 ± 2	FT (Ap)	Schlup et al. (2003)
				35 ± 2	FT (Ap)	Schlup et al. (2003)
Kaghan	Prograde HP	~1.5	300–400	50 ± 1	U–Pb zircon SCHRIMP	Kaneko et al. (2003)
	UHP	3.0 ± 0.2	770 ± 50			O'Brien et al. (2001), Kaneko et al. (2003)
				49 ± 6	Sm–Nd (Grt–Cpx–WR)	Tonarini et al. (1993)
				46.2 ± 0.7	U–Pb zircon SCHRIMP	Kaneko et al. (2003)
				46.3 ± 0.2	U–Pb zircon	Parrish et al. (2003)
	Retrograde HP	2.4 ± 0.2	610 ± 30			Lombardo et al. (2000)
				44 ± 3	U–Pb zircon SCHRIMP	Spencer and Gebauer (1996)
				44.1 ± 1	U–Pb zircon	Treloar et al. (2003)
	Amphibolitic	~1.0	~500	43 ± 1	Rb–Sr Phe	Tonarini et al. (1993)
				42.6 ± 1.6	Ar–Ar Hbl	Chamberlain et al. (1991)

[a] Aln, allanite; Ap, apatite; Amp, amphibole; Cpx, clinopyroxene; FT, fission track; Gln, glaucophane; Grt, garnet; Hbl, hornblende; Phe, phengite; WR, whole rock. Errors at 1σ uncertainty.

tzo–feldspathic gneiss (Table 1). Leech et al. (2005) also obtained a SCHRIMP zircon age of 50.0 ± 0.6 Ma as a retrograde HP metamorphism (2 ± 0.2 GPa, 580 ± 60 °C; Guillot et al., 1997; de Sigoyer et al., 1997). The amphibolite facies conditions (1.1 ± 0.2 GPa, 630 ± 50 °C; ibid.) is dated at 47 ± 0.5 Ma by a variety of methods by de Sigoyer et al. (2000) and Leech et al. (2005) (Table 1). The retrograde greenschist-facies conditions at the depth of ~10 km is dated between 34 ± 2 and 45 ± 2 Ma (average 38 ± 4 Ma, $n = 7$) based on fission track analyses of zircon (Schlup et al., 2003) (Table 1).

2.2. Kaghan unit

A wide zone of high-grade metamorphic rocks is exposed north of the Main Central Thrust (MCT) in the upper Kaghan valley in Pakistan. The higher Himalaya is divided into three units (Spencer et al., 1990; Kaneko et al., 2003): the lowest unit, which contains pelitic gneisses with minor amphibolite lenses, equivalent to the higher Himalayan crystalline rocks farther east (Guillot et al., 1999; Hodges, 2000), is bounded to the south by the MCT. The upper unit is composed of marbles and granitic gneisses, and is in contact with the Kohistan arc along the Main Karakorum Thrust (MKT). An intermediate UHP unit is comprised of felsic and granitic gneisses and marbles containing boudins and layers of eclogites (Lombardo et al., 2000) and the entire rocks are considered to have originated from the Indian continental margin of Permian age with Panjal trap affinity (Spencer and Gebauer, 1996).

Kaneko et al. (2003) obtained an age of 50 ± 1 Ma from a quartz–eclogite as the age of the prograde metamorphism (1.5 GPa and 350 °C) and the peak UHP metamorphism of the same rocks is estimated to be 3.0 ± 0.2 GPa and 770 ± 50 °C (O'Brien et al., 2001) and dated at 46.2 ± 0.7 Ma and 46.3 ± 0.2 (Kaneko et al., 2003; Parrish et al., 2003). Retrograde HP conditions is reported at 2.4 ± 0.2 GPa (Lombardo et al., 2000) and 770 ± 50 °C, which likely occurred at ~44 Ma based on SCHRIMP zircon age of 44 ± 3 Ma from a coesite-free eclogite (Spencer and Gebauer, 1996) and a U–Pb rutile age of 44.1 ± 1 Ma from a coesite-bearing eclogite (Treloar et al., 2003). The unit cooled below 500 °C by 40 Ma (Treloar and Rex, 1990) based on a Rb–Sr phengite age of 43 ± 1 Ma from an eclogite (Tonarini et al., 1993), and ^{40}Ar–^{39}Ar hornblende age of 42.6 ± 1.6 Ma from surrounding amphibolitic rocks (Chamberlain et al., 1991).

3. Subduction dip

The two UHP units, which have similar protoliths of Indian continental margin, show different P–T–t paths. The Tso Morari unit reached UHP conditions significantly earlier (~53 Ma) than the Kaghan unit (~46 Ma). When the Kaghan unit was at peak UHP conditions, the Tso Morari unit had already been exhumed and retrograded to amphibolite-facies conditions at the base of the crust (de Sigoyer et al., 2004). The different P–T–t paths between the two units may be related to (1) a different dip angle of the subduction plane, (2) different timing for the onset of subduction, (3) the subduction rate, and/or (4) the initial shape of the northwestern Indian margin.

As both UHP units record high pressure low temperature metamorphic evolution, it is reasonable to assume they were part of the subduction plate. The dip angle (α) of a subduction plane may be calculated using the age data and geometry of the subduction zone (Fig. 3). We use two independent sets of data for the calculation: the method A (Fig. 3A) combines the amount of vertical displacement of the UHP unit (ΔD) during an interval of time Δt, and the length of subducted Indian plate (ΔH) during the same time interval Δt (Fig. 3A).

The length of subducted Indian continent (H) is estimated as the sum of the shortening of the Indian continent plus the contraction of the Asian continent, including the loss of continental mass due to the eastward extrusion of Tibet. The shortening of the Indian plate is equal to the amount of subducted Indian continent and corresponds to the displacement of India relative to the Indus Suture Zone. By fixing the boundary conditions (present-day and initial rate, total shortening), Guillot et al. (2003) calculated the movement of the Indian continent respect to Eurasia based on paleomagnetic data. The movement of the Indian continent is used as the value of ΔH (Table 2). The length of vertical displacement (ΔD) is obtained from the pressure estimate of the UHP units (Table 1).

During the burial of the UHP unit, the angle of the subduction plate is given by the equation:

$$\sin(\alpha)_t = (D_t - D_{t-1})/(H_t - -H_{t-1})$$

The method B assumes that the lithosphere has a finite bending radius and that the angle of subduction at a selected depth is mainly dependent on the bending parameter (Fig. 3B). This method is essentially identical to that described in Leech et al. (2005) and the parameters used for the calculation are listed in Table 3. The thickness of sedimentary rocks overlying the UHP rocks is assumed to be 5 km (Z_1) at the onset of subduction at 57 Ma for the Tso Morari and 50 Ma for the Kaghan units. Z_2 (the depth of trench below or above the sea level) is set −1 km for Tso Morari and +1 km for the Kaghan unit (Guillot et al., 2003). Z_3 (depth of the UHP unit) is fixed at 100 km for Kaghan and 130 km for Tso Morari. Z_4, Asian topography, is fixed at 1 km).

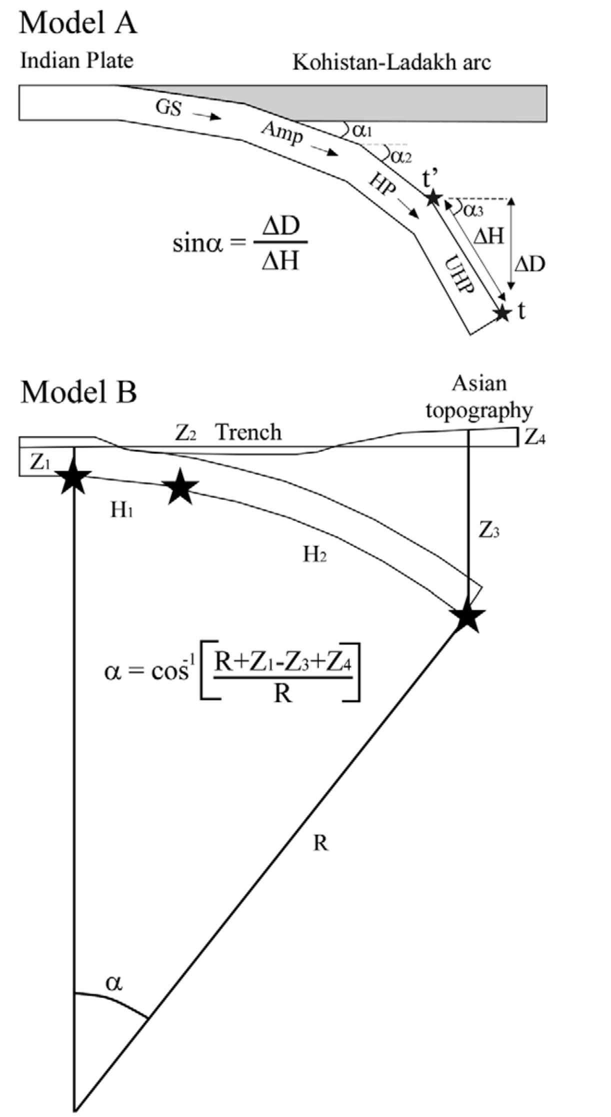

Fig. 3. Simplified geometry used for the calculation of subduction angle in the western Himalaya. Model A presented by Guillot et al. (2004). ΔH, length of subducted continent. ΔD, vertical displacement of the UHP unit estimated from the barometric data of metamorphic assemblages (Table 2). Stars corresponds to the metamorphic condition of the UHP unit at time t' and t. α, dip angle of subducting plate. *Abbreviations*: GS, greenschist-facies; Amp, amphibolite facies; HP, eclogite-facies; UHP, coesite eclogite-facies. Model B: Bending model of Leech et al. (2005) with the parameters used for the dip angle estimates. L_1, distance to trench; L_2, length of subducted Indian plate; R, radius of curvature; Z_1, depth of the unit in the Indian crust; Z_2, trench depth; Z_3, depth of metamorphic stages; Z_4, Asian topography; α, subduction angle.

Leech et al. (2005) used an average subduction velocity of 6.9 cm/year between 57 and 50 Ma, but it is known that the velocity substantially decreased during this period

Table 2
Dip angle of the subducted Indian continent estimated by Method A

	Age[a] (Ma)	Velocity (mm/yr)	Distance (km)		Dip angle
			Vertical ΔD	Horizontal[a] ΔH	
Tso Morari					
HP to UHP	57 to 53	21 ± 10	84 ± 20	400 ± 120	12 ± 5
HP to UHP	55 to 53	42 ± 15	84 ± 20	200 ± 60	24 ± 5
HP to UHP	54 to 53	84 ± 20	84 ± 20	100 ± 30	57 ± 5
Kaghan					
HP to UHP	50 to 46	14 ± 2	56 ± 8	84 ± 28	41 ± 14

[a] Calculated by Guillot et al. (2003) using the paleomagnetic data of Patriat and Achache (1984), Besse et al. (1984), Acton (1999), De Mets et al. (1990) and Klootwijk et al. (1992).

Table 3
Dip angle calculated by the bending model of Leech et al. (2005) (Fig. 3B)

	Stage	Age (Ma)	R (km)	Z_1 (km)	Z_2 (km)	Z_3 (m)	Z_4 (km)	d_1	angle at Z_3
Tso Morari									
	UHP	53	350	5	−1	130	0	6	50
Kaghan									
	UHP	46	350	5	1	100	1	6	43

R, radius of curvature; Z_1, thickness of sediments overlying the UHP units; Z_2, trench depth; Z_3, depth of the UHP metamorphism; Z_4, Asian topography (1 km); d_1, dip of the subduction slab at trench.

(Guillot et al., 2003). Thus, we employed the rate of 10 cm/year between 57 and 53 Ma and 4 cm/year between 53 and 50 Ma to reach the present day value of 2 cm/year since 50 Ma (ibid.).

Each of the two methods has advantages and disadvantages. The method A requires the age of the initial India–Asia contact, but yields precise subduction angle for an interval of given times. This method also yields the uncertainty associated with the estimates. The method B (Fig. 3B) may provide the well-defined age of the initial India–Asia contact (at 57 ± 1 Ma) but must assume the bending angle of the Indian subduction plane. Furthermore, the angle is progressively greater at deeper depth and reaches near-vertical at the depth of 200 km. Comparison of the results obtained by the two methods allows us to better constrain the geometry of the subduction zone at the time of initial contact between the two continents and subsequent subduction of the Indian continent.

Assuming the initial India–Asia contact at 57 Ma, method A predicts shallow angle of about 12° based on the data of Tso Morari unit. The angle may be up to 57° if the initial contact was later at 54 Ma (Table 2). Using the same set of data, method B yields a steep angle of about 50° with an intial contact at 57 Ma. For the Kaghan unit, both methods predict similar steep angle of about 40–45° (Table 3).

4. Discussion

4.1. Initial India–Asia contact

The dip angles estimated by the two methods for the Kaghan unit are remarkably similar during the burial of the UHP unit. This validates the two methods of calculations and selected parameters for the calculations. Dip angle of the subducted plate was less than 50° at 100 km depth, suggesting that the geometry of the subducting plate beneath the Hindu Kush during the Paleocene was similar to the present-day configuration with a bending curvature of about 350 km (Burtman and Molnar, 1993). In contrast, the two methods of calculation yielded different values for the Tso Morari unit, when the UHP unit reached the maximum depth of about 130 km. The method B yielded a much steeper subduction angle than method A; this discrepancy is explained by uncertainties in the P–T–t data used for method A or errors in the estimated bending of the Indian plate east of the western syntaxis. The P–T–t path, is well constrained for the Tso Morari unit with age uncertainties less than 1 Ma and pressure uncertainties less than 0.2 GPa (Table 1). Leech et al. (2005) demonstrated that the method B yielded well-defined age of 57 ± 1 Ma as the onset of the subduction of the Indian continent in the Tso Morari area; this age agrees well with 57 and 55 Ma proposed by DeCelles et al. (2002) and Guillot et al. (2003) based on stratigraphic, thermal, geochronologic and tectonic data of the area. The evidence suggests that the parameters used for method A is most likely correct and that the subduction was shallow (<25°; Table 2) as observed at present east of the western syntaxis by tomography imaging (Van der Voo et al., 1999) and seismic data (Nelson et al., 1996).

The burial of the Kaghan unit was estimated using the available P-t data and the bending of the subducting plate. Assuming that the dip of the subduction plane before 50 Ma is about 40° (Table 3), the length of subducted

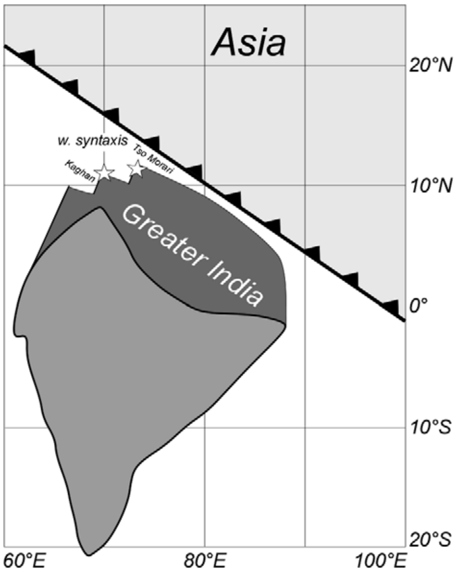

Fig. 4. Proposed Greater India geometry (after Ali and Aitchinson, 2005) and at its western syntaxis with the initial location of the Kaghan and Tso Morari units. The position of the Indian craton and the Eurasian margin at ~55 Ma using paleomagnetic data of Acton (1999) and works of Tapponnier et al. (1986) and Guillot et al. (1999).

Indian continent is calculated to be 60 to 220 km. With an average velocity of 6.9 cm/year, this implies that the Kaghan unit reached the depth of 50 km (~1.5 GPa HP event) between 1 and 3 Ma. Thus, the Kaghan unit (west of the western syntaxis) was buried later than the Tso Morari, between 51 and 53 Ma along a steeper subduction plane (>40°) as observed at present day (Burtman and Molnar, 1993; Van der Voo et al., 1999).

4.2. Tectonic evolution of the early stage of the collision

Diachronic evolution of the two UHP units suggests that the western part of Greater Indian had a shorter north–south length than the central part as recently proposed by Ali and Aitchinson (Ali and Aitchinson, 2005; Fig. 4). We estimate that the Kaghan was located 340 ± 140 km south of the Tso Morari (Fig. 4). This value is similar to the 350 km estimated by Ali and Aitchinson (2005) based on paleogeographic arguments.

4.3. Tomographic evidence

Our proposed interpretations are evaluated using the available tomographic imaging of the mantle underlying the western syntaxis area documented by Kárason and Van der Hilst (2001). The images show the cold subducted Indian slab as a high *P* velocity zone. The Indian slab in its western part under the Hindu Kush region plunges nearly vertical to the north at the depth below 600 km and it laterally extends to a narrow finger-like E–W seismic zone below the Hindu Kush (Replumaz et al., 2006). This unusual geometry is attributed by Replumaz et al. (2006) to the proto-Chaman fault and the proto-Karakorum fault cutting the Indian slab west and east, respectively. Farther east towards the Tso Morari unit, the Indian slab gentle dips beneath South Tibet (Van der Voo et al., 1999) as the indentation of Asia (horizontal motion) during the extrusion of Indochina between 30 and 15 Ma. In summary, the tomographic images suggest that the Indian subduction west of the western syntaxis was steep since 45 Ma (Table 2) and that this steep subduction along a NNW–SSE direction, perpendicular to the subduction zone, is likely related to the proto-Chaman and Karakorum faults. The present-day subduction zone shows steep angle (>30°), particularly west of the western syntaxis (Roecker, 1982; Van der Voo et al., 1999). Farther east, the Indian plate is not constraint by faults or plate boundaries, and the eastward extrusion of the overlying Asian continent allowed gentle dipping subduction of the Indian continent. Although the main period of eastward extrusion of the Asian continent occurred between 30 and 15 Ma (Leloup et al., 1995), the gentle dipping subduction plane recorded by our estimates suggests that this eastward extrusion probably existed since the early India–Eurasia collision.

The reconstructed 3D image of the slab in the western part shows the dip change of the Indian continent and a sharp bending of the western syntaxis along the proto-Cha-

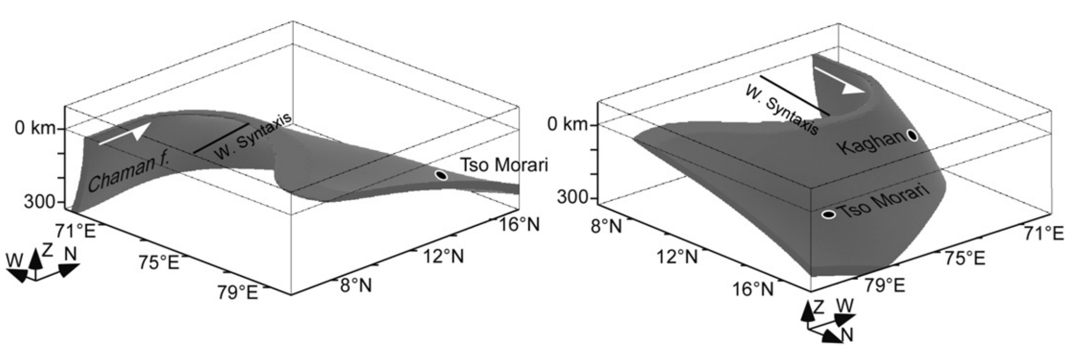

Fig. 5. Geometry of the northwestern Himalaya showing the warped Indian plane between 55 and 50 Ma. The initial India–Eurasia contact is located at ~10°N (Guillot et al., 1999). At this time, the Tso Morari unit reached a depth of about 130 km, following the subduction of the Neothethys whereas the Kaghan unit was not yet subducted. Note that the intersection of the two curved parts of the subduction plane corresponds to a north-dipping axis, defining the western syntaxis.

man fault (Fig. 5). This bending of the subducted Indian continent resulted in the warped slab surface, and formed a conical fold with a north-dipping axis near the western syntaxis (Fig. 5).

5. Conclusion

The P–T–t paths of the UHP units in the western part of the Himalayan belt allow us to constrain the timing of the initial contact between two continents and the geometry of the subducting Indian continent during the Paleogene. The results confirmed the age for the initial contact between India and Eurasia continents between 55 and 57 Ma east of the western syntaxis and a shallow (<25°) angle of subducting Indian plate. The data from the Kaghan unit, located west of the western syntaxis, show the start of the subduction at later time, ~50 Ma, along a steeper subducting plate (>40°). Moreover, the westernmost part of the Greater Indian margin is 350 km shorter in latitude than the rest of the Greater Indian margin (Fig. 4). The tomographic images of the mantle underlying the area illustrate that the northern Indian margin was linear at the initial stage of the continental subduction, but that the eastern part remained to have shallow subduction angle and this was compensated by the eastward extrusion of the overlying Eurasian continent. On the other hand, the western part of the subducted Indian continent maintained a steep subduction angle due to the proto-Chaman and Karakorum faults.

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