GR Letter

When and why the continental crust is subducted: Examples of Hindu Kush and Burma

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A B S T R A C T

The Indian subcontinent has been colliding against Asia along the Himalayas. Hindu Kush and Burma in this collision zone have intermediate-depth seismicities beneath them, with most of the continental crust subducted into a few hundred km depth. The subduction, not collision, in these regions is an enigma long time. We show that the continental lithosphere subducted beneath Hindu Kush and Burma traveled over the Reunion and Kerguelen hotspots from 100 Ma to 126 Ma and is likely to have been metasomatized by upwelling plumes beneath those hotspots. The devolatilization of the metasomatized lithosphere impinging on the collision boundary would have provided a high pore fluid pressure ratio at the thrust zones and made the subduction of the continental lithosphere in these regions possible. The subducted lithosphere could give intermediate-depth seismicities by devolatilization embrittlement. Such subduction of hotspot-affected lithosphere without accompanying any oceanic plate would be one candidate for producing ultrahigh-pressure metamorphic rocks by deep subduction of the continental crust.

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1. Introduction

When two continental plates converge, smooth subduction is hard to operate, and collision occurs (McKenzie, 1969; Dewey and Bird, 1970). In such collision zones, offscraping of the upper crust from underthrusting continental lithosphere at shallow depths (e.g., Molnar, 1984; Butler, 1986; Mattauer, 1986) and indentation and severe deformation of the upper plate (Tapponnier et al., 1982) are seen. The rest of the lithospheric slab with lower crust is often recognized as subducing in the mantle by tomographic studies (e.g., Van der Voo et al., 1999; Bijwaard and Spackman, 2000; Replumaz et al., 2004). Capitanio et al. (2010) showed by numerical modeling that such continental lithosphere, without upper crust, is dense enough to be subducted into the upper mantle.

More strictly saying, however, offscraping of the upper crust does not always happen in collision zones. For example, coesite (a high-pressure polymorph of SiO2) and diamond in eclogite blocks or layers or as inclusions in zircons in ultrahigh-pressure (UHP) metamorphic rocks are found in the sialic crust subducted to a more than 100 km depth and exhumed up to the surface (Coleman and Wang, 1995; Ernst and Liou, 1999; Chopin, 2003; Zhang et al., 2009). Although some of them might be accompanied with subduction of a continental plate dragged down by a foregoing oceanic plate, in other cases no oceanic plate is accompanied. Which extent of the continental crust can be subducted is, then, an important issue to understand the mechanism of formation of geological structures. Searle et al. (2001) listed Hindu Kush as a type locality of UHP formation, not associated with any oceanic plate. He attributed the subductability of the continental crust beneath Hindu Kush to the eclogitization of the subducted lower crust of the Indian continental margin. In this study, we will treat Hindu Kush and Burma and present a different hypothesis on the subductability of the crust in these regions, by paying attention to the fact that they have intermediate-depth seismicities.

Seno (2008) showed that the pore fluid pressure ratio λ (= Pw/σ_n, where Pw is the pore fluid pressure and σ_n is the normal stress at the thrust) is a controlling factor for offscraping/subductability of the underthrusting upper continental crust in collision zones. The value of λ determines the shear stress along the roof of a continental crustal block embedded in the slab. It is assumed that for small enough λ, offscraping of the upper crustal block occurs by cutting the faults bounding the block (See also Seno, 2008). He showed that the buoyancy of the crust is not important, contrary to previous studies (e.g., van den Beukel, 1992). He showed that the buoyancy of the crust is not important, contrary to previous studies (e.g., van den Beukel, 1992), and offscraping of the upper crust occurs for λ less than ~0.4. On the contrary, traditional geodynamic and laboratory models treating subductability of the continental crust do not pay much attention to the role of the shear resistance at the subduction zone thrust (Chemenda et al., 2000; Capitanio et al., 2010).

The value of λ could be related to intermediate-depth seismicity as described below. Intermediate-depth earthquakes are usually not observed in collision zones (Seno, 2007). When they are seen, they are...
mostly representing relict subduction of an oceanic plate trailing a continent prior to the collision (e.g., McCaffrey et al., 1985; Wang et al., 2006). Hindu Kush and Burma in the Himalayas, although continental crust is converging there, accompany intermediate-depth seismicities apparently without any oceanic plate. Why they accompany intermediate-depth seismicities has been an enigma long time.

High lithostatic pressure makes the occurrence of intraslab earthquakes improbable even if the rheology is predicted to be in the brittle regime (Griggs and Handin, 1960). Although Negredo et al. (2007), for example, showed that the slab beneath Hindu Kush could be in the brittle regime, it does not suffice to explain the observed seismicity. Similarly, Lister et al. (2002) explained the intraslab seismicity beneath Hindu Kush by the deformation associated with boudinage. Even if earthquake faulting is associated with boudinage, this itself does not explain why faulting can occur under such a high lithostatic pressure.

In recent years, dehydration embrittlement hypothesis has been proposed for occurrence of intermediate-depth earthquakes (Raleigh and Paterson, 1965; Kirby et al., 1996; Seno and Yamanaka, 1996; Peacock and Wang, 1999; Omori et al., 2002). In this hypothesis, hydrous metamorphic minerals like amphibole and serpenitine within the oceanic plate dehydrate as the temperature and pressure rise when it is subducted. This raises the pore fluid pressure and reduces the effective stress, making earthquakes possible to occur (Raleigh and Paterson, 1965). It has been shown that the observed intraslab seismicity is well explained by the dehydration locus expected from phase diagrams of hydrous minerals (e.g., Peacock and Wang, 1999; Omori et al., 2002; Hacker et al., 2003; Yamasaki and Seno, 2003). Because dehydrating from the sediments and pore spaces in the crust of the subducting slab finishes at shallow depths (Fyfe et al., 1978; Jarrard, 2003; Hacker, 2008), dehydration from the altered crust and/or serpenitized slab mantle would be a major source of the pore fluids brought to the thrust. For example, the values of $\lambda$ in subduction zone thrusts are more than 0.9, as estimated from the force balance between the shear stress at the thrust and the differential stress in the wedge (Seno, 2009). These high values of $\lambda$ must represent pore fluids released from the deeper part of the slab. Therefore intermediate-depth earthquakes could be a proxy for the level of dehydration, and thus, for $\lambda$ in the thrust. This would be also true for subducting continental lithosphere. Dehydration embrittlement can be extended to devolatilization embrittlement, if we include CO$_2$ and other volatiles as pore fluids fed from the metasomatized lithosphere (Kirby, 1995), and we will use this general term.

The intermediate-depth seismicities in Hindu Kush and Burma, therefore, suggest that devolatilization is occurring in the slab beneath these regions to a similar extent in subduction zones. Although it is difficult to determine the exact value of $\lambda$ in these regions at present, we guess that it is close to the values in subduction zones. If so, it would suffice to prevent offscraping and promote subduction of the upper crust. On the contrary, the general absence of intermediate-depth seismicity in collision zones implies absence of devolatilization from the subducting continental lithosphere (See Seno and Yamasaki, 2003; Seno, 2007). This can be attributed to greater breakdown depths of white mica and biotites contained in the granite or granulate in the continental crust (Ernst et al., 1998; See also Seno, 2007). This would cause a low value of $\lambda$ and result in decoupling between the upper and lower crusts, possibly along detachment faults with horst-graben structures (Guillot et al., 2000), and offscraping of the upper crust in collision zones.

If we admit devolatilization in the slab to operate in Hindu Kush and Burma, volatilization in the lithosphere prior to subduction must have occurred. This would be the most difficult problem to solve on the existence of the intermediate-depth seismicities in Hindu Kush and Burma. We will propose in this paper that this could happen because the Indian lithosphere had passed over the Reunion and Kerguelen hotspots in the Cretaceous and was metasomatized by the upwelling plumes beneath these hotspots. When the metasomatized lithosphere has impinged on Hindu Kush and Burma, it would have been devolatilized to lubricate the mega-thrust and produce intermediate-depth seismicities.

2. Tectonic settings

We first present tectonic settings of Hindu Kush and Burma (Fig. 1), in order to show that a continental plate is converging beneath both of these regions, and yet features of collision are weak. Hindu Kush is located within the Asian plate, southwest of Pamir and west of Karakorum. To the south, there is the Mesozoic Kohistan-Ladakh arc (Fig. 1A), which was welded to Asia at ~115-75 Ma (Pettersson and Windley, 1985; Mikoshiba et al., 1999). India later collided with this arc at ~55 Ma (e.g., de Sigoyer et al., 2000; Guillot et al., 2003; Leech et al., 2005). The geological terranes, the High Himalaya, the Lesser Himalaya, and the Siwaliks, associated with the collision between India and Kohistan, are similar to those in other Himalayan regions where India and Asia collided. However, the widths of the High and Lesser Himalayas are less than ~1/2 of those in the central and eastern Himalayas to the east (Coward et al., 1987; Guillot et al., 2008). This indicates that offscraping and accretion of the upper crust of the underthrusting Indian continental margin have been in a lesser extent than in other Himalayan regions and a considerable amount of the crust is subducted south of Kohistan.

South of Kohistan, the plate boundary where the Indian plate is currently underthrusting is likely to be located from the Main Frontal Thrust to the Main Boundary Thrust (Fig. 1A, Searle et al., 2001). To the north, there is an intermediate-depth seismicity dipping steeply northward to a depth of ~300 km beneath Hindu Kush and dipping southward to a depth of ~150 km beneath Pamir (yellow colored in Fig. 1A, Billington et al., 1977; See also Searle et al., 2001). Studies of these seismicities using focal mechanisms and seismic tomography (e.g., Pogger and Das, 1998; Van der Voo et al., 1999; Pavlis and Das, 2000; Koulakov and Sovolev, 2006) show that the seismic zone beneath Hindu Kush is continuous to that beneath Pamir. Because Kohistan collided against Asia during the late Mesozoic and India against Kohistan during the early Tertiary, no oceanic plate is recently subducting in this region as pointed out by Searle et al. (2001), Negredo et al. (2007) also showed that the subducting slab is continental lithosphere by comparing the seismicity with the reconstruction of the Indian plate geometry. One the other hand, the intermediate-depth earthquakes are the phenomena occurring within only past several Ma, provided with the depth of the seismicity of 300 km and the convergence rate of ~4 cm/yr (DeMets et al., 1990). (See also Negredo et al., 2007; Replumaz et al., 2010). Thus it is difficult to relate the intermediate-depth seismicity beneath Hindu Kush with subduction of an oceanic plate, contrary to some previous authors (Billington et al., 1977; Chatelain et al., 1980; Roecker, 1982; Pavlis and Das, 2000; Seno, 2007) and thus continental lithosphere is subducting here.

Burma is a microplate (blue-colored in Fig. 1B) decoupled from the Sunda plate (pink-colored in Fig. 1B; See Stein and Okal, 2007). In western Burma, there is a belt of high-grade metamorphic rocks with Mesozoic ophiolites (green colored in Fig. 1B, Maurin and Rangin, 2009). This ophiolite belt was regarded as an eastward continuation of the Indus-Zango suture zone by Mitchell (1984). In Tibet, south of the ophiolite belt, the Tethys and High Himalayas, i.e., the Mesozoic and Paleozoic rocks offscraped from the Indian continental margin, characterize collision. However, they are absent in Burma. Instead, west of the ophiolite belt, there is the Indo-Burman Wedge representing a Tertiary accretionary complex growing to the southwest (dark-blue colored in Fig. 1B, Maurin and Rangin, 2009). East of the ophiolite belt, there are Miocene-Quaternary calcalkaline volcanics (v-marks in Fig. 1B, Mitchell, 1984). These suggest that, in the Burman arc, collision did not occur, unlike the Himalayas, but subduction of the crust has been occurring during the late Cenozoic (Mitchell, 1984; Maurin and Rangin, 2009).

There is an intermediate-depth seismicity beneath Burma down to a depth of 200 km (yellow-colored in Fig. 1B, Le Dain et al., 1984; Biswas and Gupta, 1986; Ni et al., 1989; Vanek et al., 1990; Satyabala,
1998). Although some workers (Ni et al., 1989; Guzman-Speziale and Ni, 1996; Rao and Kumar, 1999) argued that subduction has stopped and the intermediate-depth seismicity represents relict subduction or that the Indian-Burman relative motion is along the arc, the geological structures off and on the Burman coast (Mitchell, 1984; Maurin and Rangin, 2009; Nielsen et al., 2004) and the reconstruction of the relative motion on the basis of the global and local plate motion data (Nielsen et al., 2004; Stein and Okal, 2007) demonstrate that the Bay of Bengal has a significant component of convergence to the Burma plate (Fig. 1B). Seismic tomography studies show that a high P-velocity anomaly dips from the Bengal Basin eastward to a depth of 400 km along with the shallow - intermediate-depth seismicity (Li et al., 2008; Replumaz et al., 2010), suggesting that the Indian lithosphere is subducting eastward beneath the Burma plate. The Bay of Bengal and the Bengal Basin on land have a crustal thickness of 32–40 km (Brune and Singh, 1986; Kaila et al., 1992). These indicate that Burma is a continent-continent convergence zone, where most of the upper crust is subducting with an intermediate-depth seismicity, similarly to Hindu Kush.

3. Reunion and Kerguelen hotspot traces

The intermediate-depth seismicities to depths of a few 100 km beneath Hindu Kush and Burma and the tectonic settings described above suggest that the subducted lithosphere is continental and yet devolatilized to produce the intraslab seismicities. The subducted lithosphere is different from that in ordinary collision zone in a sense that it has much of the upper crust. However, dehydration is not expected from the upper crust as mentioned before. The problem now concerns why and where the continental lithosphere in these regions was volatilized. This would not seem an easy problem to solve.

We invoke a volatilization mechanism in relation to metasomatization of the lithosphere by plumes beneath hotspots. We first show that this part of the lithosphere could be located over hotspots during the Cretaceous. Western India had traveled over the Reunion hotspot, and eastern India over the Kerguelen hotspot. In Fig. 2, we plot the volcanics that are related to these hotspots, and hotspot traces. For the Reunion hotspot, we plot the Deccan Traps, the alkali intrusions ∼3 m.y. older than the Deccan (Basu et al., 1993), and the South Tethyan suture zone volcanics (∼80 Ma, Mahoney et al., 2002), by the dark brown colors. Geochemical and isotope data (Mahoney et al., 1983; Storey et al., 1989; Kent et al., 2002) suggest that their source is the Reunion hotspot. The age distributions of these volcanics indicate that the Reunion and Kerguelen hotspots were active at least back to ∼80 Ma and ∼120 Ma, respectively.

In Fig. 2, we also plot the traces of the Reunion and Kerguelen hotspots on the Indian plate younger than 100 Ma (blue lines with ages), based on the Muller et al.’s (1993) finite rotations of India with respect to hotspots by assuming that these hotspots have been fixed at their present locations.
The trace of the Reunion hotspot indicates that, if it were active back to ~100 Ma, the Indian continental lithosphere over the hotspot at 100 Ma reaches now the southwestern edge of the intermediate-depth seismicity beneath Hindu Kush (Fig. 2). The lithosphere over the Kerguelen hotspot at 100 Ma is north of the Andaman Islands and does not reach the intermediate-depth seismicity beneath Burma. However, the older location estimated by Kent et al. (2002) (115-126 Ma, the large blue star in Fig. 2) and that by Storey et al. (1989) (110 Ma, the secondary large blue star in Fig. 2) overlap with the intermediate-depth seismicity beneath Burma (Fig. 2).

4. Metasomatization and devolatilization

The above reconstruction of the hotspot traces suggests a possibility that the Indian lithosphere in the vicinity of the intermediate-depth seismicities beneath Hindu Kush and Burma had traveled over the Reunion and Kerguelen hotspots during the mid-Cretaceous. We note here that a double-planed structure is seen in the intermediate-depth seismicity in some of the slabs in circum-Pacific subduction zones (e.g., Hasegawa et al., 2009; See also Seno and Yamanaka, 1996). Although the upper plane is explained by the dehydration of altered basalt (Kirby et al., 1996; Peacock and Wang, 1999; Hacker et al., 2003; Yamasaki and Seno, 2003), it is difficult to explain the lower plane because it is located in the lower part of the oceanic lithosphere. Kirby (1995) and Seno and Yamanaka (1996) proposed that it is caused by the devolatilization embrittlement in the subducting oceanic lithosphere, of which lower part is metasomatized by hotspots in the Pacific Ocean.

We imagine that the Indian continental lithosphere was similarly metasomatized in its lower portion by the plume activities beneath the Reunion and Kerguelen hotspots when it traveled over them. Wyllie (1988) proposed the processes of metasomatization of the continental lithosphere by plumes as follows; uprising plumes beneath hotspots contain partial melts dissolving C-H-O, and release its vapor from magmas accumulated below the solidus in the lithosphere. This hydrofractures and metasomatizes the lithosphere (Fig. 3A, See also Wilshire and Kirby, 1989).

The minerals in the lower portion of the lithosphere metasomatized by H2O and CO2 may enter a collision zone and underthrust to a depth of a few tens of km along the interplate megathrust (Fig. 3B). As the temperature and pressure rise, fluid is released from the slab and migrates along the thrusts, lubricating them and making it possible for the continental lithosphere to be subducted with the upper crust, producing feeble features of collision. As the slab subducts deeper, devolatilization embrittlement occurs in the slab, producing an intermediate-depth seismicity.

5. Discussion

Although direct evidence for the metasomatization of the Indian lithosphere by hotspots and its succeeding devolatilization beneath Hindu Kush.
Kush and Burma presented in this paper is lacking, the coincidence of the hotspot traces with the intermediate-depth seismicities suggests that it is likely, and, without such a causal link, it remains difficult to understand the intermediate-depth seismicities beneath these places. Because the fundamental ideas presented in this paper are simple, geological, geophysical, and geochemical facts should be more quantitatively examined in details in the future to test them. However, we feel that the insights that we have obtained have already important implications for interpreting geological histories of the Earth, some of which we show below.

Vrancea in southeast Carpathians in middle eastern Europe is a unique place with an intermediate-depth seismicity down to a depth of 220 km. A high seismic velocity slab is associated with this seismicity (Fan et al., 1998). Under Europe, seismic tomography and geochemical studies (Granet et al., 1995; Wilson and Patterson, 2001) suggest a few to several plumes upwelling from the 670 km discontinuity. Because there has been convergence between Europe and Alps since the early Tertiary, it is possible for a portion of the lithosphere affected by the upwelling plumes to have been subducted beneath E. Europe and to produce an intermediate-depth seismicity beneath Vrancea like Hindu Kush.

Although there are more than a dozen of locations where UHP rocks are exhumed (Chopin, 2003), mechanisms how continental crust can be brought to such a great depth have not been easy to understand. In some cases, a leading oceanic plate drags down the continental plate and the continental crust might be subducted to a such a great depth. The formation of UHP in the Himalayas around 55-47 Ma (Kaneko et al., 2003; Guillot et al., 2008) might be such a case when the Tethys ocean dragged down the Indian continent. Formation of UHP in W. Alps may also be due to intermittent subduction of oceanic plates, succeeded by continental plates (Platt, 1986; Seno, 2008). Searle et al. (2001) listed Hindu Kush as one of type localities of formation of UHP, not accompanied by oceanic plates, as we already mentioned. They proposed that the leading edge of the lower continental crust of the Indian plate has been subducted during recent several Ma, with the upper crust pealed off making the Pakistan Himalaya. However, their model requires complex deformation of the

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**Fig. 3.** (A) Metasomatization of the continental lithosphere (adapted from Wyllie, 1988). Lines 2 and 3 represent crossing points between the geotherm and the solidus for peridotite-CO₂-H₂O. Line 1 represents the lithosphere-asthenosphere boundary, above which partial melts accumulate and form magmas. From the cooling magmas, vapors of CO₂ and H₂O are released and metasomatize the lower portion of the lithosphere by hydrofracturing (green-colored). (B) Devolatilization of the metasomatized continental lithosphere in a continent convergent zone. When the continental lithosphere converges and the lower portion of the lithosphere is metasomatized by a plume (green-colored), devolatilization from the lithosphere makes volatiles (blue-colored) to migrate upward and lubricate the thrust zone above. The whole continental lithosphere could be subducted (black arrow) and produce intermediate-depth seismicity by devolatilization embrittlement.
subducted lower crust to mimic the shape of the intermediate-depth seismicity. Furthermore the predicted volume of the offscraped upper crust amounting to 300 km × 15 km is not observed south of the Main Mantle Thrust (Coward et al., 1987).

We propose that subduction of hotspot-affected lithosphere would be a likely candidate for the formation of UHP rocks without accompanying leading oceanic plates or thin marginal lower crust. In this case, intraslab earthquakes are located in the slab mantle. The geometry of intraslab seismicity need not be simple because the area of metamatization in the lithosphere might not be simple. Complex deformation of the lithosphere to explain the geometry of the intraslab seismicity is thus not required. Other areas of UHP exhumation in the world deserve to be examined from this viewpoint. Recently, Sumino and Dobzhanietskaya (2009) analyzed noble gases contained in the metamorphic diamonds exhumed from the UHP belt in Kokchetav massif, Kazakhstan, and found that their 4He/3He ratios are close to that observed in OIBs, significantly higher than that of MORB. This indicates a possibility that metasomatism by plumes might be related to the formation of the UHP in Kokchetav and subduction of the continental crust to a large depth might have occurred there similarly to Hindu Kush and Burma. This kind of geochemical analyses would become important to elucidate the causes of the subductability of continental crust.

A thick crust covered the surface of the early Earth (Sleep and Windley, 1982; Bickle, 1986), which has made subduction of the subductability of continental crust.

Analyses would become important to elucidate the causes of the subduction of the continental crust to a large depth might have occurred higher than that of MORB. This indicates a possibility that metasomatism mechanism of initiation of continental lithosphere convergence in to operate on the Earth, as on the Venus. The fact that it had started beneath these regions traveled over the Reunion and Kerguelen hotspots during the middle Cretaceous and were possibly metasomatized by upwelling plumes beneath those hotspots. We propose that the intermediate-depth seismicities beneath these regions occur due to devolatilization embrittlement of the metasomatized Indian continental lithosphere. The devolatilization would also have lubricated the thrust zones and made the subduction of the continental lithosphere with the upper crust in these regions possible. This type of the continental crust subduction would provide one important case for UHP rock formation in the geological past.

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