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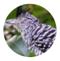

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The Hindu Kush Seismic Zone as a Paradigm for the Creation of Ultrahigh-Pressure Diamond- and Coesite-Bearing Continental Rocks

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ABSTRACT

Coesite eclogites and diamond-bearing ultrahigh-pressure (UHP) metamorphic rocks along ancient plate boundaries were mostly derived from quartz- and carbonate-bearing rocks originally formed close to the earth's surface. Their mineral assemblages and *PT* conditions require that they were subducted to depths of 90–130 km (27–40 kbar) and then brought back to the surface, still retaining evidence of their UHP formation. The geological record shows that continental-derived UHP rocks can be formed by subduction of thinned continental-margin crust beneath ophiolites (e.g., Oman ophiolite, west Himalayan ophiolites) or beneath island arcs (e.g., Kohistan Arc, Pakistan) as well as in continent-continent collision zones (e.g., Dabie Shan–Sulu Belt, Kazakhstan, western Norway, Alps). We present a model, based on the geometry of the seismically active Hindu Kush continental subduction zone and its restoration, assuming present-day plate motions, which explains how surficial graphite-rich shales and carbonates deposited along the northwest Indian plate margin were dragged down to these depths, anchored by the eclogitized leading edge of the thinned Indian plate crust. We suggest that coesite eclogite and diamond-bearing UHP metamorphism is occurring today at depth along the Hindu Kush seismic continental subduction zone.

Introduction

Continental crust (density ~2.8 g cm^{-3}) resists subduction into the earth's mantle (~3.3 g cm^{-3}) because of buoyancy forces. However, ultrahigh-pressure (UHP) terrains demonstrate that not only is continental crust subducted to depths as great as 130 km but also that it is sometimes subsequently exhumed to the earth's surface (Chopin 1987; Coleman and Wang 1995*b*; Hacker et al. 1995). Ultrahigh-pressure terrains are typically composed of mainly continental crustal rocks that contain minerals, such as coesite or diamond, indicative of pressures >2.5 GPa (fig. 1). Coesite is known from at least 10 genetically distinct orogenic belts (Liou et al. 1998). It is most often found in eclogite blocks or layers within the continental rocks, as inclusions within other minerals, or as a rare intergranular phase, but it also occurs as inclusions in zircons within the continental rocks themselves. Diamond occurs as included phases in graphitic biotite schists and dolomitic marbles in four orogenic belts including the Kokchetav terrain in Kazakhstan (Sobolev and Shatsky 1990; Zhang et al. 1997), Dabie Shan–Sulu UHP terrain, China (Xu et al. 1992; Xu and Su 1997), and the Western Gneiss region of Norway (Dobrzhinetskaya et al. 1995; Larsen et al. 1998). The continental crustal rocks vary from dominantly metasedimentary, as in the Dabie Shan, to dominantly metaigneous, as in western Norway. In Norway and China, rocks containing coesite or diamond crop out over areas of at least 5000 km^2, and contiguous high-pressure (HP) rocks crop out over areas >20,000–30,000 km^2 (Coleman and Wang 1995*a*; Wain 1997; Hacker et al. 2000). Temperatures of eclogites during UHP metamorphism, assessed mostly via Fe-Mg exchange between garnet and clinopyroxene or phengite, range from ~700° to 900°C (fig. 1, *boxes*). At these tem-

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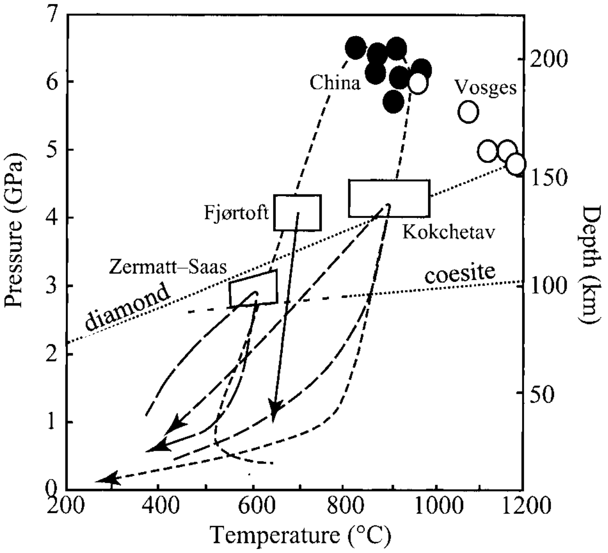

Figure 1. Peak conditions and *PT* paths for ultrahigh-pressure (UHP) crustal rocks (*boxes*) and peridotites (*circles*). The coldest and hottest known UHP crustal rocks are shown: Zermatt-Saas (Reinecke 1998); Fjørtoft, Norway (Larsen et al. 1998); and Kokchetav (Zhang et al. 1997). The highest *P* and highest *T* UHP ultramafic rocks are shown: China (Liou et al. 2000) and Vosges (Altherr and Kalt 1996). Graphite-diamond equilibrium was calculated with 1998 Thermocalc database (Holland and Powell 1998), and coesite-quartz equilibrium is from Hemingway et al. (1998).

peratures, the presence of diamond constrains the minimum metamorphic pressures to >35–40 kbar, corresponding to depths of ~110–130 km (Liou et al. 1998). The preservation of UHP minerals and the absence of higher-temperature overprints sufficient to erase evidence of UHP implies the absence of fluid or cooling during exhumation (Hacker and Peacock 1995; Austrheim 1998; Ernst et al. 1998). The best constraint on the exhumation rate of UHP rocks is that of Amato et al. (1999); they used Sm/Nd and Rb/Sr multimineral isochrons to infer a minimum rate of exhumation of the Zermatt-Saas UHP rocks through mantle depths of ~26 km m.yr.$^{-1}$.

Ultrahigh-pressure gneisses locally contain blocks or layers of garnet peridotite that contain evidence of even higher pressures (Zhang and Liou 1998; Liou et al. 2000; fig. 1, *circles*). The most direct evidence of this is the presence of pyroxene needles within garnets in Norway, indicating the former existence of majorite formed at depths >185 km (Terry et al. 1998; Van Roermund and Drury 1998), but low-*P* clinoenstatite within diopside at Alpe Arami may point to the former presence of high-pressure clinoenstatite formed at depths >250 km (Bozhilov et al. 1999). These deep, mantle-born garnet peridotites are a tantalizing suggestion that continental crust may be subducted to a >185–250-km depth, although it is equally plausible that such garnet peridotites were transported upward by asthenospheric upwelling and tectonically inserted into subducted continental crust at a 110–130-km depth.

This article briefly reviews three major tectonic settings where continental rocks may be buried to depths where UHP metamorphism occurs: beneath oceanic crust or ophiolite, beneath island arcs, and in a continent-continent collision setting. We then describe the three-dimensional geometry of the active Hindu Kush seismic zone in NW Pakistan, Afghanistan, and Tadjikistan, and interpret the geological evolution of this zone since the early Miocene. Finally, we propose a tectonic model based on the Hindu Kush seismic zone, which serves as a paradigm for the creation, preservation, and exhumation of UHP metamorphic rocks.

Burial and Exhumation Mechanisms

Ultrahigh-pressure metamorphism of continental crust can occur in three main tectonic settings: (1) subduction of continental crust beneath oceanic crust or ophiolite, (2) subduction of continental crust beneath an island arc, and (3) subduction of continental crust beneath another colliding continent. The geology of ancient high-pressure and UHP rocks provides evidence of subduction-zone processes at depths inaccessible in presently active zones.

Subduction of Continental Crust beneath Oceanic Crust or Ophiolite. The southeastern Oman Mountains is one of the few examples in the world where continental crust can be demonstrated to have subducted to depths of 90–100 km beneath a hanging-wall of purely oceanic crust and mantle. Subduction of the leading edge of the Arabian continental margin resulted in the formation of a regional HP terrain, including a variety of carpholite-bearing metasediments (7–8 kbar), blueschist (14–17 kbar), and eclogite (20–23 kbar)–facies rocks (Goffé et al. 1988; Searle et al. 1994; Searle and Cox 1999; fig. 2). Major extensional shear zones, with large gaps in pressure, separate major tectonic slices. The protoliths of the eclogites are Mid-Permian basaltic flows and pelitic rocks enclosed in more common calc-schists representing the metamorphosed impure carbonates of the continental margin. The entire thinned continental crust of the Arabian plate

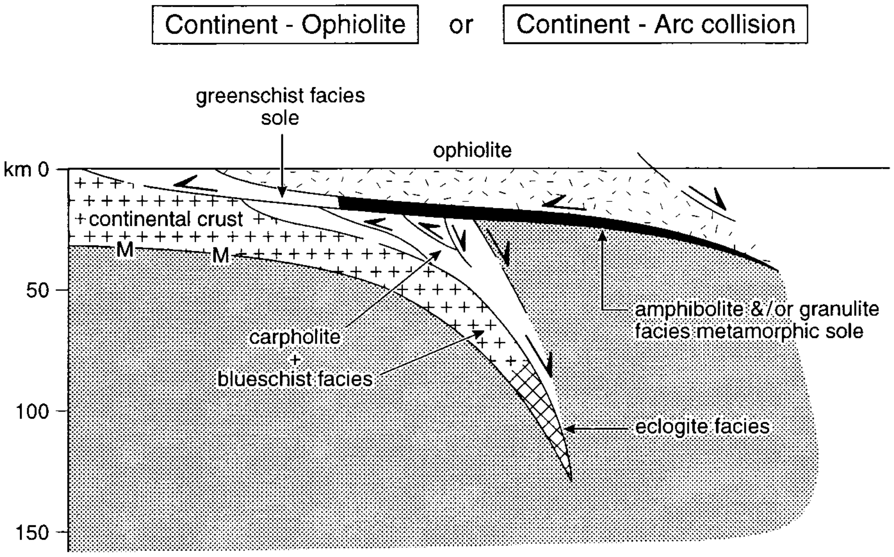

Figure 2. Tectonic model for the formation of HP eclogites by subduction of a thinned slab of continental-margin rock beneath an obducting ophiolite. This model is based on the subduction-zone model proposed by Searle et al. (1994) and Searle and Cox (1999) for the southeastern Oman Mountains. The amphibolite-facies metamorphic sole along the base of the ophiolite was formed over a pressure range of 5–12 kbar during initial obduction. Subduction of the leading edge of continental crust formed eclogite-facies rocks at pressures of 20–23 kbar during the later stages of obduction in the same subduction zone.

was dragged down the subduction zone during the final stages of ophiolite emplacement and must have been rapidly exhumed toward the earth's surface along the same zone as a result of buoyancy forces (fig. 2). The incorporation of dense blocks of eclogite within a lighter, more buoyant carbonate material was responsible for the exhumation of many Alpine and Franciscan HP rocks (e.g., England and Holland 1979). Chemenda et al. (1996) showed through analog modeling that subduction of continental lithosphere continues until the buoyancy force exceeds the strength of the upper crust, causing the buoyant upper crust to rise by thrusting over the neutrally buoyant part of the subducting plate. The upper limit of the exhuming HP zone is a normal fault.

Subduction of Continental Crust beneath an Island Arc. Present-day examples of active subduction of continental-margin crust beneath an active island arc include the northern Australian margin, which is subducting beneath Timor and the Java-Banda Arc, and the SE China margin, which is subducting beneath the Luzon-Philippine Arc. Perhaps the best example from the geological record comes from the western Himalaya in Pakistan where recently discovered eclogites along the northernmost part of the Indian crust formed within a subduction zone beneath the Cretaceous Kohistan Arc. These eclogites contain coesite inclusions in omphacite (O'Brien et al. 1999) and are metamorphosed Permian basaltic lavas and sills occurring within the northernmost Indian plate rocks structurally beneath the Kohistan Arc. The UHP metamorphism occurred before the Himalayan orogeny and is not related to the continental collision process (Searle et al. 1999).

Subduction of Continental Crust beneath Another Colliding Continent. Himalayan-type continental collision involves fold-and-thrust related crustal thickening resulting in regional Barrovian-type metamorphism. Pressure-temperature profiles across the High Himalaya suggest that thrust stacking and folding in a Himalayan-type setting can account for the burial and exhumation of only 35–45 km of crustal material, and this would usually occur at temperatures high enough to generate crustal melting (e.g., Searle et al. 1992, 1997). Oligocene kyanite-grade rocks were metamorphosed at pressures between 9.5–10.5 kbar. Later early Miocene sillimanite-grade gneisses formed at higher temperatures (650°–770°C) but lower pressures (4.5–7 kbar). This phase of metamorphism is related to widespread muscovite-dehydration melting. Metamorphism and melting in the High Himalaya are purely crustal events, with no involvement from the mantle. Neither the early kyanite-grade nor the later sillimanite-grade metamorphic events are compatible with the formation of HP or UHP rocks.

Despite the lack of evidence for HP or UHP metamorphism during the Himalayan orogeny, many other orogenic belts contain evidence of UHP metamorphism during continent-continent collision (e.g., Dabie Shan–Sulu Belt, Kazakhstan, western Norway, and the Alps). Clearly some mechanism other than Himalayan-type crustal stacking is required to produce UHP rocks in collisional mountain belts. Platt (1987) suggested a mechanism whereby extension in the upper part of an accretionary wedge thickened by underplating could account for the exhumation of some Alpine HP rocks. Extensional faulting is common in the final stages of exhumation, but this process alone could never account for the amounts of exhumation in UHP terrains. Thompson et al. (1997) proposed a model whereby a narrow zone of ~100-km-thick crust was exhumed vertically upward by horizontal contraction between two rigid blocks and subsequent erosion. Although nowhere on Earth today is the crust thicker than ~75 km, heating during thermal equilibration of such a thick root would destroy any UHP rocks. Erosion could, however, play some role in the exhumation of UHP rocks. In central China, the Songpan-Ganze flysch contains 2×10^6 km^3 of detritus apparently derived from the UHP Dabie Shan Belt (Zhou and Graham 1996).

The formation of coesite- and diamond-bearing UHP rocks clearly requires subduction of crustal material to depths much greater than those of the surrounding blocks. Requirements for the formation of diamond and coesite in continental crustal rocks are, first, availability of graphitic shale, carbonate, and basalt protolith along a continental margin; second, a mechanism to rapidly bury these rocks to depths of 110–130 km; and finally, a mechanism to rapidly exhume deeply buried slabs of thinned continental crust between "normal" orogenic crust that has not been deeply buried. We propose that all three criteria are satisfied in the present-day active Hindu Kush seismic zone in NW Pakistan, NE Afghanistan, and southern Tadjikistan.

Hindu Kush Seismic Zone

The Hindu Kush seismic zone along the borders of NW Pakistan, far NE Afghanistan, and Tadjkistan is one of the most active regions of intermediate-depth seismicity and by far the most active such region not associated with the subduction of oceanic lithosphere (fig. 3). The Pamir–Hindu Kush seismic zones have been the subject of numerous studies (e.g., Billington et al. 1977; Chatelain et al. 1980; Roeker 1982), and a variety of models have been proposed to account for the three-dimensional pattern of seismicity. These models can be divided into two categories. The first model suggests that there are two converging seismic zones—northward subduction of Indian lithosphere beneath the Hindu Kush and southward subduction of Asian lithosphere beneath the Pamir (Chatelain et al. 1980; Burtman and Molnar 1993; Fan et al. 1994). The second model suggests that the intermediate-depth seismicity beneath the Pamir and the Hindu Kush is caused by a single, highly contorted slab (Billington et al. 1977; Vinnik et al. 1977).

The Hindu Kush zone is associated with very low attenuation of seismic waves, in common with Benioff zones beneath island arcs. Early seismic studies of the Pamir-Hindu Kush seismic zone suggested that the prominent zone of intermediate-depth seismicity occurs along thin (<30 km) and deep slablike zones similar to oceanic subduction zones (Chatelain et al. 1980). This indicated the subduction of small, trapped oceanic basins, similar to the present-day Black Sea. However, the geology of the Pamir, Hindu Kush, and Tadjik Basin region clearly demonstrates that there has been no oceanic crust in the region (including the Pamir, Hindu Kush, Karakoram, and western Tibet) since at least the Mid- to Late Cretaceous (Searle 1991; Hamburger et al. 1992; Hendrix et al. 1992; Burtman and Molnar 1993; Hildebrand et al. 2000, 2001). The youngest marine sediments along the Indus suture zone and north Indian plate margin (Himalaya) are earliest Eocene (54–50 Ma). Roecker (1982) reported lower P- and S-wave velocities near the seismic zone than outside it and suggested that some continental crust must have been subducted to at least 150–200 km beneath the Hindu Kush. Subsequent authors have also suggested that the seismic zone must represent subduction of thinned continental crust. Precisely located earthquakes also revealed a seismic gap between the southward-dipping Pamir and the northward-dipping Hindu Kush seismic zones. Quaternary deformation and a high frequency of earthquakes along the Alai Valley indicate that the Pamir subduction zone reaches the earth's surface there (Strecker et al. 1995; Arrowsmith and Strecker 1999).

Pegler (1995) and Pegler and Das (1998) relocated about 6000 earthquakes in this area between 1964 and 1992 and published more precise maps and depth profiles of the earthquakes. They concluded that the simplest explanation was a single, highly contorted, S-shaped seismic zone, 700 km long and no more than 30 km wide. Their profiles show that the north-dipping Hindu Kush seismic zone is ac-

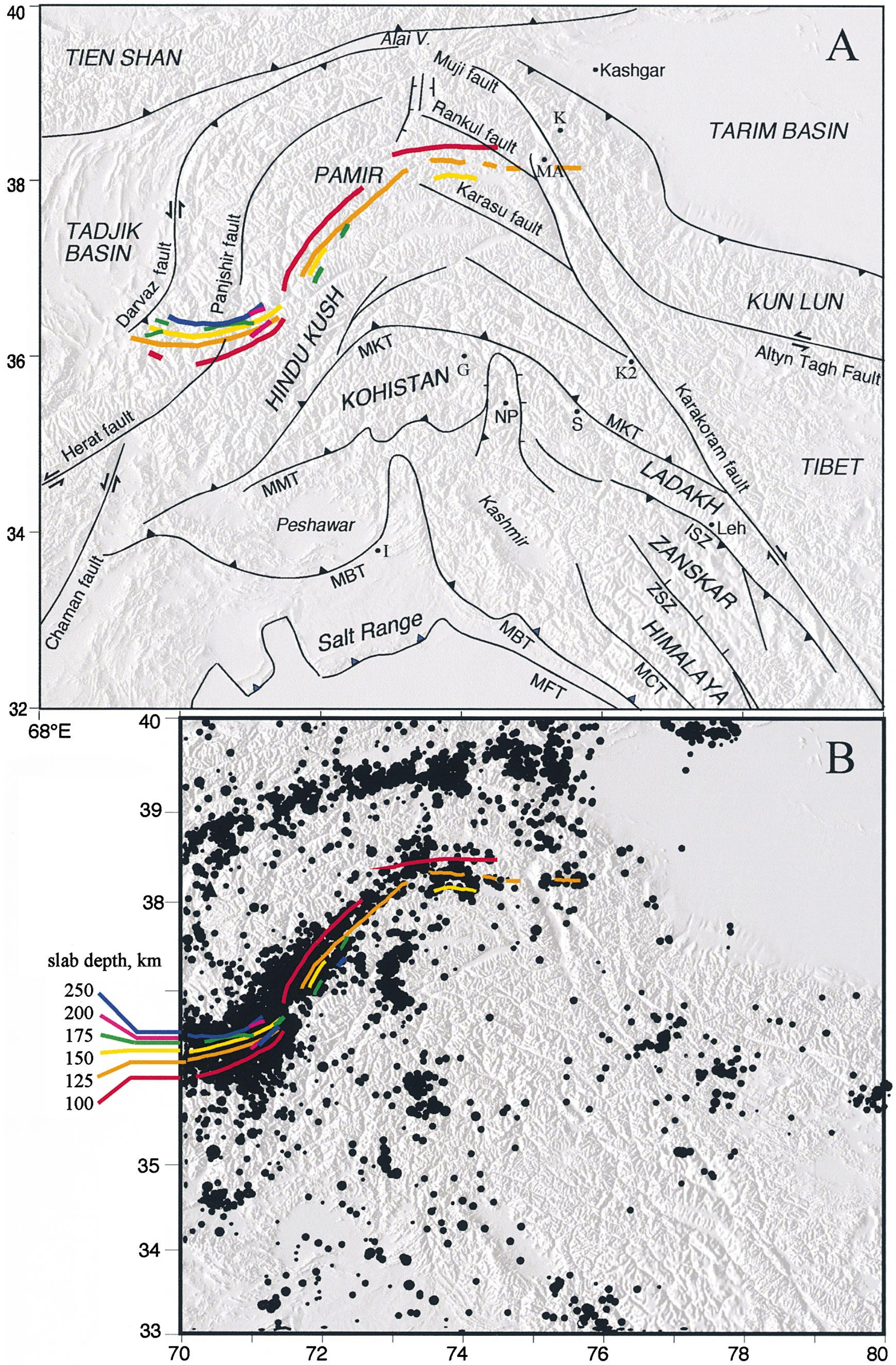

Figure 3. *A*, Digital topographic elevation map and a structural map of the western Himalaya, Hindu Kush, Pamir, Karakoram, and western Tibet, which also shows the major structures and the location of the Hindu Kush deep seismic zone. *NP*, Nanga Parbat; *MKT*, Main Karakoram thrust; *ISZ*, Indus suture zone; *MMT*, Main mantle thrust; *ZSZ*, Zanskar shear zone; *MCT*, Main central thrust; *MBT*, Main boundary thrust; *I*, Islamabad; *S*, Skardu; *K* and *MA* are the Kongur and Muztagh Ata gneiss domes between the dextral Karakoram Fault and the sinistral Altyn Tagh Fault at the far western end of Tibet. *B*, Map of the Hindu Kush, Pamir, Karakoram, and western Himalaya showing all seismicity covering the period 1964–1992 and depth contours, from 100 to 250 km, of the Hindu Kush seismic zone (after Pegler and Das 1998).

tive at depths of 90–280 km (fig. 4*a*). Despite the more detailed knowledge of the geometry of the seismic zone, controversy continues as to whether it represents subduction of continental crust or a trapped oceanic basin (Pavlis and Das 2000) and whether it represents a single subduction zone or two converging (Pamir and Hindu Kush) subduction zones. None of these previous studies of the Hindu Kush and Pamir seismic zones have related the pattern of seismicity to the geological evolution and structure of the Hindu Kush, which has only recently become well known (Searle and Asif Khan 1996; Hildebrand et al. 1998, 2000, 2001).

The Pamir and the Hindu Kush are both relatively old (Jurassic-Cretaceous) mountain ranges, which have been uplifted and reactivated during the Neogene continental collision of India. Field mapping and U-Pb geochronology in the eastern Hindu Kush have recently proven that most of the crustal thickening and metamorphism (staurolite-, andalusite-, and sillimanite-grade, high-temperature, low-pressure metamorphism) took place in the Jurassic-Early

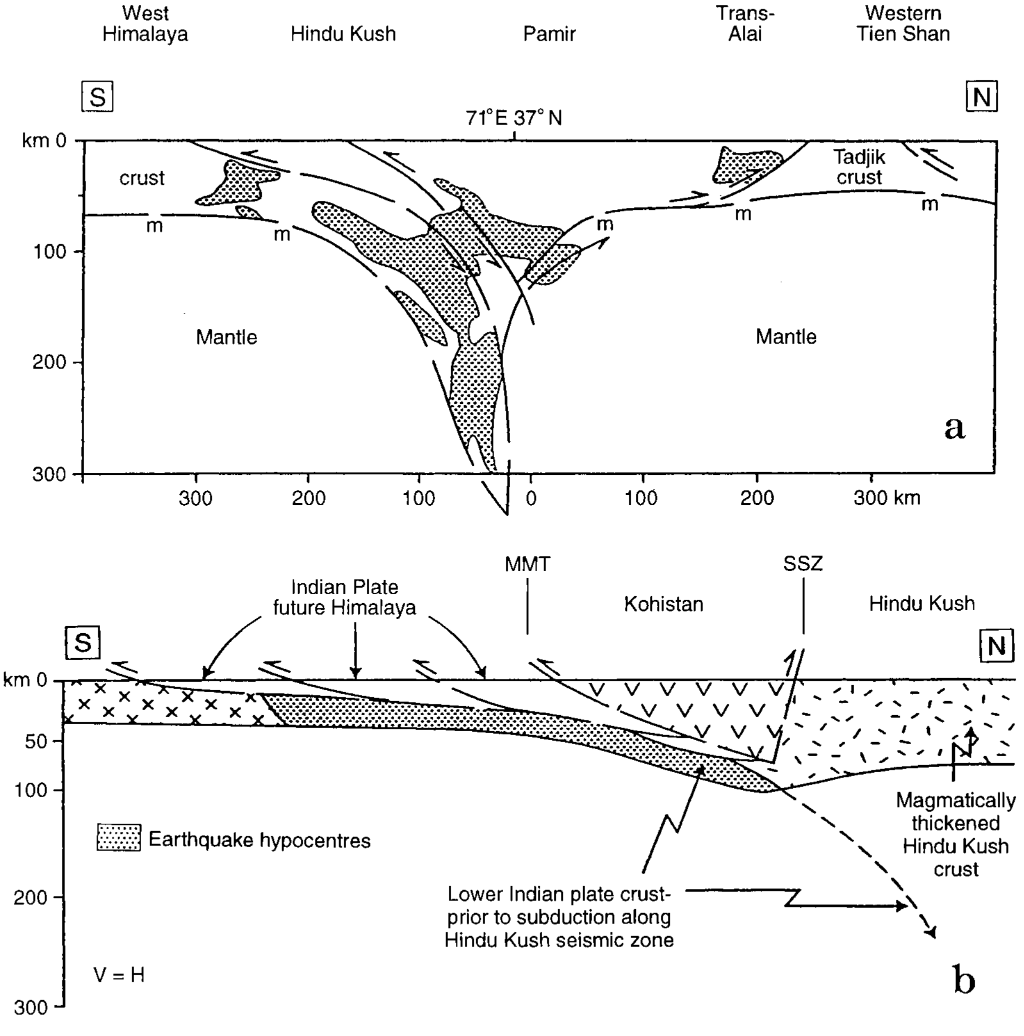

Figure 4. *a*, Cross section of the western Himalaya, Hindu Kush, and Pamir showing the distribution of earthquake hypocenters, after Pegler (1995) and Pegler and Das (1998). We distinguish the Hindu Kush seismic zone, representing subducted Indian plate lithosphere dipping steeply north, from the Pamir seismic zone, representing subducted Tarim Basin lithosphere dipping gently south from the Alai Valley north of the Pamir to a depth of around 60 km beneath the central Pamir. *b*, Restored cross section of the geometry shown in figure 4*a*, showing that when restored, the rocks presently in the Hindu Kush seismic zone (*shaded region*) were along the leading edge of the Indian plate continental crust. These graphite-rich shales would be the protolith for potential diamond-bearing pelitic eclogites forming in the Hindu Kush subduction zone today.

Cretaceous, before the collision of both Kohistan and India to the south (Hildebrand et al. 2000, 2001). Magmatism in the Hindu Kush is dominated by precollision, hornblende-bearing granodiorites and granites (e.g., Tirich Mir and Kafiristan plutons) related to Andean-type plutonism above a north-dipping Tethyan oceanic subduction zone. The only postcollisional magmatism is the migmatization and melting event that produced the small, 24-Ma Gharam Chasma two mica + garnet + tourmaline leucogranite pluton (Hildebrand et al. 1998). Thus, it is surmised that the Hindu Kush represents a Jurassic-Cretaceous, Andean-type mountain belt that was reactivated during the Late Miocene. The Hindu Kush is very different from the Karakoram to the east, which is dominated by postcollisional metamorphism, melting, and deformation (Searle 1991; Searle and Tirrul 1991).

The Hindu Kush seismic zone is bounded in the west by a sinistral strike-slip fault system including the Darvaz and Chaman Faults and to the east by the dextral Karakoram Fault (fig. 3). The center of the Hindu Kush seismic zone lies immediately northwest of the topographic high axis of the Hindu Kush range and cuts diametrically across active, or recently active, faults such as the Panjshir and Darvaz Faults. This shows that the Hindu Kush seismic zone has become completely decoupled from the surface deformation. The south-dipping seismic zone beneath the central south Pamir underlies the high Pamir Plateau and extends east as far as the northern termination of the Karakoram Fault near Muztagh Ata (fig. 3*A*). Interestingly, this seismic zone appears to actually cut right across the Karakoram Fault, which in this region shows mainly dip-slip faulting.

Figure 4*a* shows a structural interpretation of the distribution of seismicity (after Pegler and Das 1998) across the Hindu Kush–western Pamir region along the 70°–71°E line of longitude. Because the amounts of crustal shortening are far greater in the Himalaya south of the Hindu Kush (470-km minimum shortening from the Pakistani foreland to the Main mantle thrust; Coward and Butler 1985) than across the Pamir to the north of the Hindu Kush (100-km internal shortening; Burtman and Molnar 1993), it seems likely that the deep seismic zone is related to subduction of Indian plate crust and not to subduction of Tadjik Basin crust.

The three-dimensional geometry of the subducting slab is not simple. The north-dipping Hindu Kush seismic zone steepens progressively toward the east, becoming vertical, then overturns toward its eastern end beneath the Pamirs, where it dips to the southeast. The region of earthquakes is not laterally nor vertically continuous but, instead, is characterized by clusters of earthquakes separated by several prominent seismic gaps. Oddly, there appear to be very few earthquakes at depths of 150–180 km. In the NW-SE profile, however (fig. 4*a*), there is continuous seismicity down to about 240 km, at which depth the region of seismicity becomes vertical, centered at 72°E, 37°N. The Hindu Kush seismic zone may extend to depths as shallow as 60 km, and its projection to the surface is probably in the region of the Main Karakoram thrust (MKT; Searle 1991). East of the Hindu Kush, seismicity beneath the Karakoram is considerably reduced and defines a triangular zone bounded to the south by the MKT and along the north by the southern margin of the Tarim Basin. This is consistent with the surface structure and topography of the Karakoram, which is a crustal-scale, pop-up zone thrusting rocks southward over Kohistan-Ladakh and the Himalaya along the MKT zone and northward over the Tarim Basin (Searle and Tirrul 1991). Interestingly, the Karakoram Fault shows very little seismicity along its trace (fig. 3*B*). The presence of postglacial surface offsets is presumably the result of large, infrequent earthquakes between which the fault is effectively locked. Total geological offset along the dextral Karakoram Fault has been <150–120 km since 17 Ma, and this has taken place mainly in the central sector of the fault (Searle 1996; Searle et al. 1998).

Hindu Kush Continental Subduction Model

Figure 4*b* shows the restored section before the subduction along the present-day Hindu Kush seismic zone (fig. 4*a*). The geometry of the slab clearly shows that the subducted rocks must have originated at the lower structural levels of the northernmost, leading edge of the Indian crust. This interpretation is consistent with the geological evidence that considerably greater crustal shortening occurred south of the Hindu Kush (Indian lithosphere) than to the north (Tadjik and Tarim Basin lithosphere). Figure 5 shows our preferred model for formation of UHP metamorphic rocks based on the geological interpretation of the Hindu Kush seismic zone. This model predicts that the Indian crust subducting beneath the Hindu Kush is the old, cold lower crust of the Indian shield comprising Precambrian granulite-facies basement and cover of Palaeozoic–early Mesozoic black shales that would have been subducted and transformed to eclogite at an approximate 60–70-km depth. Temperatures at the base of the subducting continental slab may have reached 800°–900°C at

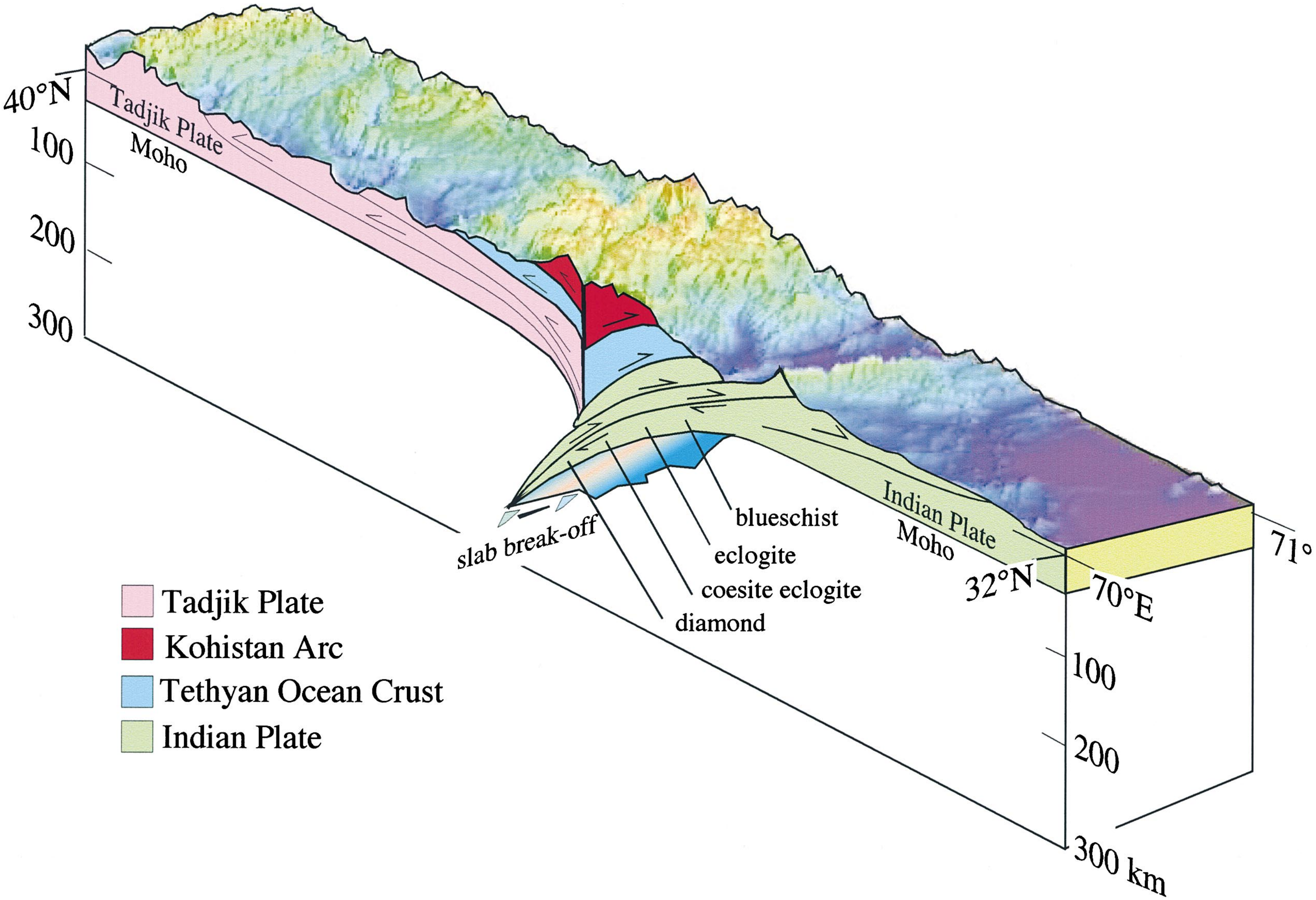

Figure 5. Model for the formation of UHP metamorphic rocks by deep subduction of continental crust, based on the geological interpretation of the Hindu Kush seismic zone. The section line follows the line of 70°E longitude. The vertical scale below sea level equals the horizontal scale.

4–6 GPa, consistent with the *PT* conditions of formation of the diamond-bearing rocks of the Dabie Shan–Sulu Belt and Kazakhstan (fig. 1). The upper crust, which originally overlay this delaminated lower crust, was the upper crustal levels of the Pakistani Himalaya (equivalent to the Zanskar continental shelf margin sediments in India; Searle et al. 1988), which eroded and were deposited in the Indus foreland basin or the offshore Indus Fan.

It is difficult to relate short-term seismic deformation to deformation over geological time. However, at present convergence rates (40 mm yr^{-1}; DeMets et al. 1990; Bilham et al. 1997), ~7.5 Ma would have been required to transform the restored geometry in figure 4*b* into the present-day geometry in figure 4*a*. Therefore, it seems likely that the zone of deep earthquakes beneath the Hindu Kush represents mainly Indian plate lower crustal rocks subducted beneath the Hindu Kush. Rocks that form the lower part of the Hindu Kush seismic zone today would have been near the upper 30 km of the earth's crust between 6 and 15 Ma. There is no geological evidence of trapped oceanic crust at that time anywhere in the region. The India-Asia collision occurred between 60 and 50 Ma, and both Asian and Indian margins have been thickened and metamorphosed since (Searle et al. 1988; Searle and Tirrul 1991). The seismic gap at around a 160–180-km depth (Pegler and Das 1998) may represent the depth at which the eclogitic root detaches and sinks into the mantle.

It is noteworthy that finite-strain calculations of deformation in Asia predict that maximum topography and maximum strain occur precisely at the Himalayan syntaxes (England and Houseman 1989). Mantle tomography indicates that a northward-dipping slab, apparently still attached to Indian lithosphere, is seen in the entire upper 600 km of the mantle under the Hindu Kush (Van der Voo et al. 1999). The Hindu Kush seismic zone steepens with increasing depth and even overturns in the eastern part beneath the southern Pamir–northern Hindu Raj. Crustal rocks subducted to these depths would be undergoing UHP metamorphism. The large volumes of black shales present along the NW Indian plate margin would provide suitable graphitic protoliths to produce UHP diamonds. The Hindu Kush zone of continental subduction, therefore, provides a present-day analog for the formation of coesite-bearing (>24–28 kbar) and diamond-bearing (>ca. 35–40 kbar) eclogite-facies rocks in old mountain belts formed by continent-continent collision.

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