ABSTRACT

The Greater Himalayan Sequence is the metamorphic core of the Himalaya and has been a focus of considerable study, yet its petrologic evolution remains controversial. Pre-Oligocene metamorphism was nearly obliterated by Miocene metamorphism and melting, which many workers ascribe to shear heating, unusually high concentrations of radioactive elements accompanying burial, and/or several kilometers of exhumation due to extensional faulting. Sparse Oligocene to Eocene ages are often assigned to a tectonically unspecified event. An alternative slab-breakoff model (subduction of Greater Himalayan rocks to ~100 km depth in the Eocene followed by buoyant extrusion due to decoupling of the oceanic lithosphere) has also been proposed based on rare Eocene eclogites, but without explanation of Miocene melting or metamorphic petrogenesis. We argue that slab breakoff readily explains the Eocene eclogites, Miocene partial melts, and late Eocene K-rich magmas in southeastern Tibet, and that metamorphic and plutonic ages help define the timing and rates of breakoff and extrusion. This model implies that (1) much of the Greater Himalayan Sequence was subducted to depths greater than commonly considered, (2) fluid-absent, decompression melting at 30–35 km depth was the consequence of as much as 100 km of extrusion, rather than radioactive heating or a smaller, crustal level extensional or erosional event, and (3) eruption of Eocene, K-rich Tibetan Plateau lavas has no implication for topography of the Tibetan Plateau.

Keywords: Greater Himalayan Sequence, Himalaya, Indo-Asian collision, slab breakoff.

INTRODUCTION

Collision between India and Asia commenced ca. 55 Ma (Klootwijk et al., 1992), ultimately creating the Himalaya and Tibet. The most deeply buried rocks now exposed are the Greater Himalayan Sequence, a relatively thin (~7 km, on average), coherent slab of crystalline supracrustal rocks bounded above and below by the South Tibetan detachment system and the Main Central thrust, respectively (Fig. 1). Many disparate models of Himalayan tectonics are based on the petrology of Greater Himalayan rocks, especially focusing on either extremely rare Eocene eclogites, or abundant early Miocene partial melts. We argue that disparate petrologic elements that have been used to support different models are explainable by continental subduction followed by Eocene slab breakoff. That is, of existing tectonic models, slab breakoff is most functional petrologically. In particular, (1) Miocene dehydration melting of the Greater Himalayan Sequence was likely forced by rebound of subducted continental crust out of the lithospheric mantle, (2) petrologic evolution of the Greater Himalayan Sequence was not restricted to the upper 35 km as commonly assumed, and (3) Eocene K-rich volcanic rocks in Tibet are genetically related to Greater Himalayan Sequence evolution. The slab-breakoff hypothesis is easily tested, and has major implications for Indo-Asian tectonics.

MODELS

The Greater Himalayan Sequence consists mainly of felsic migmatic schist and gneiss, calc-silicate, and quartzite, and extremely rare metamorphosed basaltic flows and sills. Protolith and inheritance ages are Proterozoic to early Paleozoic (DeCelles et al., 1998). The most obvious metamorphism occurred during partial melting ca. 20 Ma, but rare relict metamorphic minerals, textures, and isotope ages as old as 35–55 Ma attest to earlier Himalayan metamorphism (e.g., see Hodges, 2000; de Sigoyer et al., 2000; Kaneko et al., 2001; Catsos et al., 2002). The pressure-temperature (P-T) conditions of the early Cenozoic metamorphic stage are poorly known, although later Miocene reequilibration is well documented at 7–10 kbar and 600–700 °C (Guillot, 1999; Fig. 1). Curiously, a suite of K-rich basaltic rocks also erupted in southeastern Tibet at 35–40 Ma (Chung et al., 1998; Fig. 1), i.e., coeval with early metamorphism of the Greater Himalayan Sequence, but the rocks are ordinarily only considered in tectonic models of Tibet.

Four main tectonic models for Greater Himalayan metamorphism focus on different petrologic features and chronologies, particularly with respect to heat sources and the partial melting event ca. 20 Ma.
We refer to these models as (1) wedge accumulation, (2) shear heating, (3) decompression melting, and (4) slab breakoff. In wedge accumulation, Greater Himalayan rocks simultaneously accreted and eroded in a wedge over the past ~50 m.y. (e.g., Huerta et al., 1998), and high concentrations of heat-producing elements ultimately led to melting. In the shear-heating and decompression-melting models, Greater Himalayan rocks had been previously thickened and were close to their melting point. Melting was catalyzed ca. 20 Ma by initial Main Central thrust movement in the shear-heating model (Harrison et al., 1998), but by ~20 km of extensional exhumation along the South Tibetan detachment system in the decompression-melting model (Harris and Massey, 1994). The slab-breakoff model is based principally on two Eocene coesite localities and mechanical plausibility, not on subsequent Mio- cene petrogenesis (O’Brien et al., 2001; Chemenda et al., 2000). No model considers the K-rich volcanic rocks in southern Tibet.

ECLOGITES

Eclogites are extremely rare in the Himalaya (Fig. 1). Coesite, a dense polymorph of SiO₂ stable only at P > 27 kbar (depths ˃~90 km), occurs in eclogites in Kaghan, Pakistan and Ladakh, India (O’Brien et al., 2001; Sachan et al., 2001). Assignment of these eclogites to the Greater Himalayan Sequence is arguable, but lithologies and ages are appropriate (Baldwin et al., 1998; O’Brien et al., 2001). Retrograde eclogites that are indisputably Greater Himalayan occur in the Arun valley in eastern Nepal, similar to retrograde eclogite documented along strike in the nearby Kharta region of Tibet (Lombardo et al., 1999; Fig. 1). All eclogites are metamorphosed basaltic sills or flows, and are stratigraphically contiguous with the surrounding felsic rocks.

Ages for the coesite-bearing eclogites are 45–55 Ma (Tonarini et al., 1993; de Sigoyer et al., 2000; Kaneko et al., 2001). The other eclogites have not been dated directly, but Catlos et al. (2002) found 45 ± 2 Ma monazites in a Greater Himalayan gneiss from the region. Poor preservation of Eocene high-pressure or ultrahigh-pressure meta- morphism could well reflect: (1) paucity of appropriate bulk rock compositions—such as metabasites—which may retain eclogitic or other high-P and/or ultrahigh-P assemblages, and (2) obliteration of earlier matrix minerals and textures during Miocene melting and thermal reequilibration.

The occurrence of coesite-grade (ultrahigh-P) eclogites suggests that the Himalaya are comparable to other collisional orogens (e.g., Kokchetav, Kazakhstan, and Dabie-Sulu, China) that include relics of >100 km continental subduction. In these terranes, ultrahigh-P mineralogies are only readily identifiable in uncommon rocks, such as eclogite, garnet peridotite, and whiteschist (Maruyama and Parkinson, 2000). In the predominant felsic gneisses, preservation of ultrahigh-P minerals (e.g., coesite, diamond, jadeite) is restricted to micron-scale inclusions in chemically and mechanically resistant zircons (e.g., Kajtayama et al., 2000). Clearly, coherent slabs, hundreds of kilometers long and several kilometers thick, can undergo ultradepth burial (>100 km) and subsequent exhumation in subduction-collapse zones (e.g., Maruyama and Parkinson, 2000) qualitatively similar to the Indo-Asian collision. However, evidence for ultrahigh-P metamorphism may be overlooked in felsic rocks due to melting and reequilibration during exhumation.

MELTS

Partial melting textures are common in Greater Himalayan rocks from Bhutan to Pakistan (e.g., see Guillet, 1999), and in central Nepal melt textures occur throughout the sequence. Apparently wherever rock compositions were appropriate, the Greater Himalayan Sequence partially melted. Geochronology on the resulting leucogranites indicates that melting was almost simultaneous at 18–22 Ma over the length of the Himalaya (Harrison et al., 1998), a critical observation that must be explained in any tectonic model. Rock and mineral textures, trace elements, and experiments definitively identify muscovite dehydration melting as a primary cause at T-P conditions of at least 8–12 kbar and 750–800 °C (Inger and Harris, 1992; Harris et al., 1993; Patiño-Douce and Harris, 1998; Fig. 1). Biotite dehydration-melting at higher temperatures is also possible (e.g., Ganguly et al., 2000). However, workers dispute how the dehydration-melting reactions were crossed and how chronologic simultaneity was attained, which gives rise to the three different melting models (decompression melting, shear heating, and wedge accumulation). Melting eradicated most earlier textures and mineral assemblages, complicating evaluation of models and inferences of Himalayan tectonics prior to ca. 20 Ma.

Eocene (35–40 Ma) K-rich lavas occur in southeastern Tibet ~300 km north of the Greater Himalayan Sequence, and were likely sourced by enriched subcontinental lithosphere that was exposed to asthenospheric upwelling (Chung et al., 1998). These lavas are broadly coeval with early evolution of the Greater Himalayan Sequence. Other K-rich volcanic rocks occur on the plateau (e.g., Miller et al., 1999), but have ages ˂25 Ma. That is, no K-rich volcanic rocks older than ca. 40 Ma have been found associated with the Indo-Asian collision.

INTERPRETATIONS

Understanding the Himalayan orogen requires assessing the fate of the oceanic lithosphere that was formerly attached to Indian continental lithosphere. A Cretaceous to Eocene arc on the southern margin of Asia assures northward subduction of oceanic lithosphere (Dewey and Bird, 1970). However, gravity and teleseismic data suggest that the oceanic slab is not attached to Indian lithosphere today (Jin et al., 1996). The oceanic slab likely broke off and foundered some time in the past while India maintained its northward course into Asia. Mechanical models of continental subduction (Davies and von Blanckenburg, 1995; Chemenda et al., 2000) predict that lithospheric failure will occur at a depth of ~100–200 km. Lithospheric mantle may subduct, whereas buoyancy drives detached crustal slices upward, ultimately exposing eclogites (Maruyama et al., 1996). However, in the Himalaya there is no consensus for either the relationship of buoyancy-driven ascent to Greater Himalayan metamorphism and melting, or the timing of slab breakoff (if it occurred). We believe that Eocene slab breakoff best explains the petrologic evidence (Fig. 2).

In the slab-breakoff model, mechanical coupling between downgoing oceanic and Indian continental lithospheres between 55 and 45 Ma subducted the northern margin of India beneath Asia, producing widespread Greater Himalayan eclogites. At a convergence rate of ~5 cm/yr, and a subduction angle of 30°, Indian continental crust could have been subducted to 250 km depth in 10 m.y., although petrologic data require only ~100 km. Decoupling of continental and oceanic lithospheres at 40–45 Ma caused: (1) rapid removal of oceanic lithosphere, initiating asthenospheric upwelling, (2) initial heating of subcontinental lithosphere to produce Tibetan K-rich lavas by 40 Ma, and (3) buoyant rebound of the subducted Greater Himalayan rocks out of the mantle lithosphere. By analogy, slab breakoff is now occurring in the Banda arc of eastern Indonesia—subducted oceanic lithosphere has separated from the Australian lithosphere at depths of 100–300 km, causing rapid extrusion of formerly subducted sediments (Maruyama et al., 1996). Breakoff in the Himalaya occurred no earlier than 45–55 Ma (the oldest Cenozoic ages on metamorphic minerals), and no later than ca. 22 Ma (the oldest age of leucogranites). Possibly a younger breakoff age could be accommodated by placing greater emphasis on younger (ca. 25 Ma) K-rich lavas. Along-strike diachronicity is expected, although perhaps by as little as 5 m.y. (Davies and von Blanckenburg, 1995).

We propose that 50–100 km of exhumation of Greater Himalayan rocks between 45 and 25 Ma was accommodated by thrust-sense and
normal-sense slip on earlier fault systems now occupied by the Main Central thrust and South Tibetan detachment fault systems. Increased basal heat flow due to mantle upwelling may have maintained relatively high temperatures during this rapid exhumation. Most important, Greater Himalayan rocks crossed the muscovite dehydration-melting reaction at 18–22 Ma at $P \geq 8$–12 kbar. They were already hot because they had been partially subducted into the mantle and then exposed to enhanced mantle heat flow after breakoff. This interpretation of the cause of heating and melting departs critically from previous models, which have either never tried to explain it (model 4), or have instead interpreted melting to result from less radical, shallower level tectonic processes coupled with local heat sources (models 1–3). Extensive melts eradicated most prior Greater Himalayan high- and/or ultrahigh-$P$ history, except in rare mafic eclogites. Apparently the entire Greater Himalayan slab crossed the melting reaction(s) nearly synchronously, which implies that slab breakoff occurred over a period of only a few million years. Greater exhumation and higher temperatures in some areas (e.g., eastern Nepal and Sikkim) caused some rocks to cross other reactions to produce different key minerals (Fig. 1). Continued movement on the Main Central thrust and Southern Tibetan detachment system in the Miocene further exhumed the rocks.

Although we believe that our interpretation best explains petrologic observations, it raises serious stratigraphic, structural, and igneous issues. For example, there are no Eocene or Oligocene sediments in the foreland that directly record the exhumation we propose. However, breakoff may yield erosion rather than deposition as slab pull is eliminated (Davies and von Blanckenburg, 1995), and foreland sediments show a profound Oligocene unconformity (DeCelles et al., 1998). Or, sedimentation might shift elsewhere, as possibly indicated by Eocene through Oligocene clastic sediments in Pakistan and the Indus Fan (Qayyum et al., 1997), lateral to the modern foreland. We also recognize that there are no documented Greater Himalayan plutons or South Tibetan detachment system and Main Central thrust structures older than early Miocene. However, we question whether any plutons would have been present in the Oligocene to record the early deformation, and whether structures would be preserved through widespread melting. Major melting does not occur in the crust until dehydration-melting reactions are crossed. Until Greater Himalayan rocks had exhumed to ~35 km depth ca. 20 Ma, there is no reason why melts should have been present. The extensive melting that then occurred would likely have obliterated any preexisting structures.

Harrison et al. (1999) showed that both shear heating and a pressure decrease are capable of explaining Greater Himalayan melting. Our model includes both very large pressure decreases and thrust-sense shearing, and so is consistent with their calculations of melt production. We predict that regional Eocene eclogite facies metamorphism in Greater Himalayan rocks is preserved as inclusion microassemblages in zircon and possibly garnet in felsic rocks, and as rare eclogites in the cores of mafic boudins and layers. The presence of these inclusions and relics and the metamorphic ages of host phases provide a test of our model.

Our Himalayan tectonic model has major implications for Tibetan Plateau topography and tectonism. Genesis of K-rich lavas has been ascribed to lithospheric delamination (England, 1993), and Chung et al. (1998) argued that the lavas in southeastern Tibet indicate Eurasian plate delamination and rapid Eocene uplift. In contrast, slab breakoff has no direct implications for Tibetan topography because enriched subcontinental mantle is exposed via Indian plate dynamics. Thus we ascribe no topographic significance to K-rich lavas in Tibet until, at earliest, 25 Ma. Similarly, Nelson et al. (1996) described Greater Himalayan rocks as the extruded equivalent of modern partial melts in southern Tibet. However, melts in southern Tibet, if they occur, may result from high heat flow due to either lithospheric erosion or delamination, rather than rebound following slab breakoff. If extrusion drove Greater Himalayan Sequence melting, then it may not have a Tibetan equivalent.

**CONCLUSIONS**

Although many petrologic and tectonic models have been proposed for the Greater Himalayan Sequence, we believe that slab break-
off explains the greater body of petrologic observations. Petrologic justification for slab breakoff has previously focused on scattered eclogites, the paucity of which throughout the Greater Himalayan Sequence understandably engenders skepticism. Instead, other models have focused on widespread partial melting in support of different tectonic models. As we have shown, partial melting is at least equally well explained by extrusion of Greater Himalayan rocks from great depths (to 100 km) following separation of the oceanic slab during the Eocene, a mechanism that also explains Eocene K-rich magmas in Tibet. Thus, slab breakoff is the most petrologically functional model to date, and should be tested via examination of the mineralogy of microinclusions in garnet and zircon.

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