Provenance of the Greater Himalayan Sequence and associated rocks: Predictions of channel flow models

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Numerical models for channel flow in the Himalayan-Tibetan system (Beaumont *et al*., 2001, *Nature,* **414**, 738-42; *JGR,* in press; Jamieson *et al*., *JGR,* in press) predict that low-viscosity middle and lower crust has flowed outward from beneath the Tibetan plateau, and was exhumed between the Main Central Thrust zone (MCT) and South Tibetan Detachment system (STD) in response to focused denudation at the erosion front. Model results are compatible with a number of first-order tectonic and metamorphic features of the orogen. Here we compare the provenance of crustal material in representative channel flow models with observations from the Himalaya and southern Tibet.

South of the Indus-Tsangpo suture, the orogenic crust, including the Greater Himalayan Sequence (GHS) and Lesser Himalayan Sequence (LHS), is made up of the deformed and metamorphosed continental margin of northern India (e.g., Myrow *et al*., 2003, *EPSL,* **212**, 433-41). The pre-Cambrian isotopic signature of the GHS ($\varepsilon_{Nd} < 20$, $T_{DM} < 2.0$ Ga, detrital zircons 500-1000 Ma) indicates that it is a Neoproterozoic to early Paleozoic Gondwanan succession, whereas the isotopically distinct LHS ($\varepsilon_{Nd} > 20$, $T_{DM} > 2.0$ Ga, detrital zircons 1600-2600 Ma) is inferred to represent a Paleo- to Mesoproterozoic sequence (e.g. Parrish & Hodges, 1996, *GSAB,* **108**, 904-11; Hodges, 2000, *GSAB,* **112**, 324-50; DeCelles *et al*., 2000, *Science,* **288**, 497-99). Within the GHS, lithological units are laterally continuous for considerable distances, and a consistent regional stratigraphy can be recognized through much of the orogen.

In model HT1, the entire region between the model suture and the orogenic foreland is occupied by pro-side (Indian) material; on a crustal scale, therefore, material distribution in the model is compatible with observations. The model MCT is the protolith boundary between outflowing (GHS) and inflowing (LHS) material, and represents $\geq$ 600 km of offset. The model GHS is derived from Indian upper and middle crust that originated 400-800 km south of the model suture, whereas the LHS is derived mainly from crust originating $\geq$ 1400 km south of the suture. At the end of the model (54 My = 0 Ma), GHS material at the model surface, although strongly deformed, is largely derived from contiguous Indian middle crust. Particle tracking indicates little or no mixing of diverse crustal elements in the exhumed region, so that units exposed at the surface could appear to retain a coherent "stratigraphy". However, in the model, this material has been strongly transposed and attenuated, and the apparent stratigraphy does not reflect original depositional relationships.

The north Himalayan gneiss domes, which lie in the Tibetan plateau south of the Indus-Tsangpo suture, are cored by gneisses resembling those exposed in the GHS. These rocks exhibit condensed metamorphic sequences, are locally cut by leucogranites, and are separated from overlying lower grade rocks of the Tethyan Series by ductile shear zones and brittle normal faults (e.g. Lee *et al*., 2000, *Tectonics,* **19**, 872-95). In the models, the domes consist of extensionally attenuated middle and upper crust overlying channel material that flows upward in response to the differential pressure created when destabilized upper crust flows outward, e.g., during underthrusting by strong lower crust. The models therefore predict that the domes should be cored by rocks with Indian provenance resembling those in the GHS; simple models predict somewhat younger metamorphic, cooling, and intrusion ages in the domes than in the GHS. In contrast, domes located north of the Indus-Tsangpo suture are predicted to be cored by material with Asian protoliths.

Petrological and isotopic studies of Himalayan Miocene leucogranites indicate that they were mainly derived by dehydration melting of GHS protoliths at mid-crustal depths (e.g. Patiño Douce & Harris, 1998, *J.Petrol.,* **39**, 689-710), although in some cases both melting and emplacement are inferred to have taken place at relatively low pressure (<5 kb; e.g. Visona & Lombardo, 2002, *Lithos,* **62**, 125-50). In model HT1, P-T-t paths from the lower GHS pass through the dehydration melting field between 30 and 18 Ma, demonstrating that the simple model is capable of generating the necessary P-T conditions at the right time. However, model HT1 does not generate P-T conditions in the low-pressure melting field, suggesting that different tectonic conditions, possibly linked to the generation and subsequent extrusion of domes, are required to explain these examples.

Detrital minerals and ε_{Nd} data from Himalayan foreland basin sediments indicate that sediment was supplied mainly from Tethyan Series and GHS rocks until ca. 10 Ma, and that metamorphic detritus began to appear by ca. 22 Ma (e.g., DeCelles *et al.*, 1998, *GSAB,* **110**, 2-21; Najman & Garzanti, 2000, *GSAB,* **112**, 435-49). In model HT1, erosion begins at 30 Ma; rapid erosion continues until 15 Ma and erosion rate declines thereafter. All the eroded material comes from the Indian side of the system. Particle tracking indicates that mid-crustal material is first exhumed at ca. 25 Ma; material corresponding to the present-day LHS and GHS first appears at the surface at ca. 15 Ma and LHS material dominates after ca. 10 Ma. Greenschist facies rocks appear at the model surface at ca. 25 Ma and amphibolite facies at ca. 22 Ma, broadly compatible with observed detrital metamorphic minerals (Jamieson *et al.*, *JGR,* in press).

We conclude that within the spatial and temporal resolution of the models, channel flow model results are generally compatible with data on the provenance of a variety of igneous, metamorphic, and sedimentary rocks within the Himalaya and southern Tibet.