Quantifying crustal flow in Tibet with magnetotelluric data

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The Himalaya and the Tibetan plateau have been formed by the collision of the Indian and Eurasian plates over the last 40-70 million years (see Yin and Harrison, 2000 for a general overview). A wide range of tectonic processes have been active during the development of this orogen. Many geodynamic models have been developed to explain the evolution of the Himalayan orogen and the Tibetan plateau and to define the overall mass balance required in this continent-continent collision. These include complete continental underthrusting, distributed shortening, indention tectonics and extrusion, delamination and lower crustal flow. The observed deformation may occur through a combination of these tectonic processes that cover the spectrum from brittle deformation localized on a number of major strike-slip faults defining a set of rigid blocks (Tapponnier et al., 2001) to ductile deformation of the crust and upper mantle with spatially continuous distribution over large parts of the plateau (Shen et al., 2001).

Models invoking ductile deformation through crustal flow are based on the assumption that the strength of the middle to lower crust is less than the strength of the upper crust and the underlying mantle. In this case, deformation in the weakened mid- to lower crustal layer may occur as a response to plate motion, topography-induced pressure gradients or a combination thereof. Two regions of crustal flow have been suggested to be active in Tibet. In Southern Tibet, the observation of leucogranites and high grade metamorphic rocks exposed in the High Himalaya, combined with geophysical observations of a partially molten crust (Nelson et al., 1996) led to the suggestion of a southward directed crustal flow driven by topography-induced pressure gradients and surface erosion (Beaumont et al., 2001). In Eastern Tibet, it is observed that large areas have been uplifted with little surface deformation (Royden et al., 1997). This led to the suggestion that outward crustal flow had occurred from regions of the Tibetan plateau with a thickened crust (Clark and Royden, 2000).

For crustal flow to occur, the crust must be relatively weak, such that it is susceptible to deformation by pressure gradients caused by the topography. The strength of the crust is controlled by its composition, temperature and the presence of fluid phases such as partial melt. Laboratory measurements on partially molten rocks suggest that melt fractions of 5-10 % reduce the crustal strength by one order of magnitude (Rosenberg and Handy, 2005). By relating these laboratory measurements to magnetotelluric observations, which are sensitive to the presence of partial melts, it is possible to establish a direct relationship between the electrical conductance and the flow parameters associated with flow in this weak lower crustal layer (Fig. 1; Rippe and Unsworth, 2010).

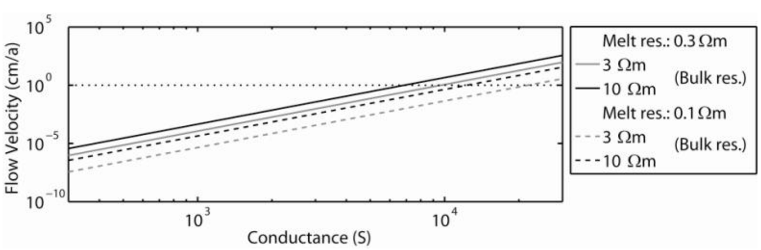

Figure 1. Topography induced flow velocity as a function of conductance for granite. Constant bulk resistivities of 3 and 10 Ωm and melt resistivities of 0.1 and 0.3 Ωm were assumed.

Magnetotelluric exploration uses variations in the naturally occurring electromagnetic fields at the Earth's surface to determine the subsurface electrical resistivity structure. Magnetotelluric data collected as part of the International Deep Profiling of Tibet and Himalaya (INDEPTH) project and the Eastern Himalayan Syntaxis 3D (EHS3D) project (Fig. 2) indicate a low-resistivity layer at mid- to lower crustal depths beneath the southern Lhasa block and the Qiangtang terrane extending from central Tibet to the eastern margin of the plateau. A joint interpretation of the magnetotelluric data with other geophysical observations suggests that the observed low-resistivity layer can be best explained by a layer of partial melting at mid- to lower crustal depths (Klemperer, 2006).

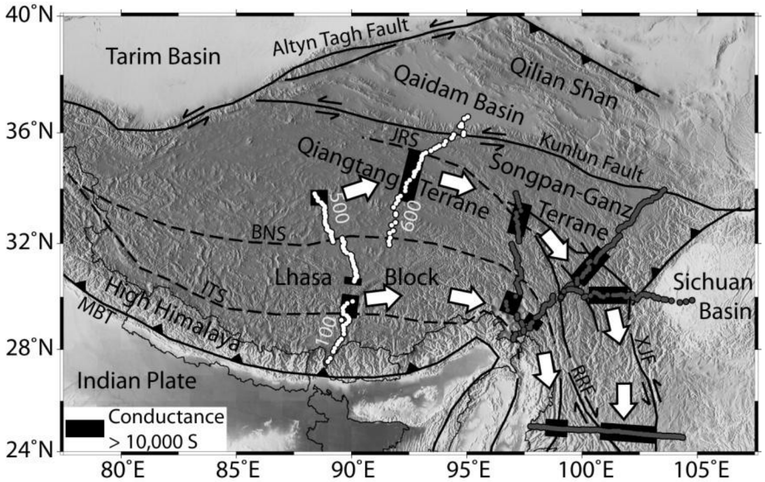

Figure 2. Topographic map of Tibet showing major tectonic features and boundaries (MBT: Main Boundary Thrust, ITS: Indus Tsangpo Suture, BNS: Banggong-Nuijang Suture, JRS: Jinsha River Suture, RRF: Red River Fault, XJF: Xiaojiang Fault, KF: Kunlun Fault). Locations of INDEPTH magnetotelluric measurements are shown as white dots. Locations of EHS3D magnetotelluric measurements are shown as grey dots. White arrows indicate suggested crustal flow pattern (after Bai et al., 2010).

Depending on the strength, the mid-to lower crustal low-resistivity layer might be weak enough for crustal flow to develop. For the Central Tibetan Plateau, if the weak lower crustal layer consists of partially molten felsic rocks, calculations show that conductances in the range 7000 - 27,000 S will produce flow velocities of the order 1 cm/a (Fig. 1, Rippe and Unsworth, 2010). Beneath the southern part of the Lhasa block and the Qiangtang terrane magnetotelluric studies indicate conductances of up to 20,000 S (Bai et al., 2010; Unsworth et al., 2005). These conductances suggest effective viscosities of $2.5\cdot10^{18}$ - $3\cdot10^{20}$ Pa s, corresponding to flow velocities between 0.02 and 4.5 cm/a (Rippe and Unsworth, 2010). Together with higher pressure gradients near the margins of the plateau, these flow parameters clearly support ductile deformation through crustal flow in these parts of Tibet.

Previous geophysical observations have not constrained the pattern of crustal flow beneath the Tibetan plateau. The magnetotelluric data suggest two flow channels with conductances exceeding 10,000 S extending horizontally over distances of 800 km from the Central Tibetan Plateau into southwestern China (Fig. 2; Bai et al., 2010). The suggested flow pattern supports the hypothesis of hydraulic uplift of large areas in Eastern Tibet caused by a topography-induced outward flow of crustal material, while revealing a more complex deformation pattern than previously suggested (Clark and Royden, 2000).

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