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Extensional extrusion: Insights into south-eastward expansion of Tibetan Plateau from magnetotelluric array data

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ABSTRACT

Despite extensive effort over many decades to understand the tectonic evolution of the Tibetan Plateau, the geodynamic processes creating the iconic south-eastward expansion of the plateau at the Eastern Himalayan Syntaxis (EHS) are still unclear and are hotly debated. Two popular (but not necessarily exclusive) geodynamic models, namely crustal flow at mid-to-lower crustal depths and coherent deformation between the crust and lithospheric mantle, are commonly invoked to explain the expansion mechanism. However, neither of these is able to reconcile all of the abundant geological and geophysical data. Here we present a three-dimensional (3D) geo-electrical model, derived from new SINOPROBE magnetotelluric (MT) array data, that reveals the geo-electrical, and by inference rheological, structure of southeast Tibet. Instead of NW–SE conductive channels proposed in prior two-dimensional (2D) MT studies, distinct NNE–SSW directed quasi-linear conductive anomalies are identified in the mid-to-lower crust, which are separated by a large-scale electrically resistive structure that extends from the crust to the upper mantle. This argues against the prior proposed model of south-eastward conductive anomalies, and hence against the southeast lower crust flow of material. To interpret our observations and resultant model, a new mechanism of "extensional extrusion" is proposed to address the lithospheric deformation of the south-eastward expansion of Tibetan Plateau.

1. Introduction

The continuous collision and convergence procedure between Indian and Asian plates has generated the Tibetan Plateau and the immense east–west mountain range of Himalaya since ∼55 Ma (Royden et al., 2008; Tapponnier, 2001). This nearly 3000 km orogenic belt terminates at both ends in almost transverse syntaxes, namely the Western Himalayan Syntaxis and Eastern Himalayan Syntaxis (EHS, Fig. 1). At the east end, the strong crustal deformation has resulted in the uplift and southeast-ward expansion of East Tibet by ∼8 to 10 Ma (Royden et al., 2008; Tapponnier, 2001). Geodetic studies also reveal fast on-going southeast-ward surface movement near the EHS (Zhang et al., 2004). However, the mechanisms for the plateau deformation and expansion remain subjects of debate. There are two canonical theses of (i) rigid block extrusion (Tapponnier et al., 1982) and (ii) internal deformation (England and Houseman, 1986) for the expansion mechanism. (i) suggests the landmass of Tibet fails (in a brittle manner) into several rigid blocks bounded by strike-slip faults as India collides into Asia. These blocks then extrude along these strike-slip faults to southeast into Indochina as the collision continues. On the other hand, (ii) assumes a more ductile Asia and suggests the deformation and expansion is internally continuous in the crust and upper mantle over broad areas (Klemperer, 2006).

Recent geophysical and geoid evidence tends to favour more than one type of internal deformation. Some involve crustal flow in restricted zones/layers (Clark et al., 2005) and others involve vertically coherent deformation (Bendick and Flesch, 2007; Sol et al., 2007). The major conflict between these two internal deformation paradigms lies in the degree of mechanical (de)coupling of the crust and the lithospheric mantle. For example, south-eastward lower crustal flow decoupled from the upper crust and mantle is supported by localised reduced resistivity (Bai et al., 2010) and

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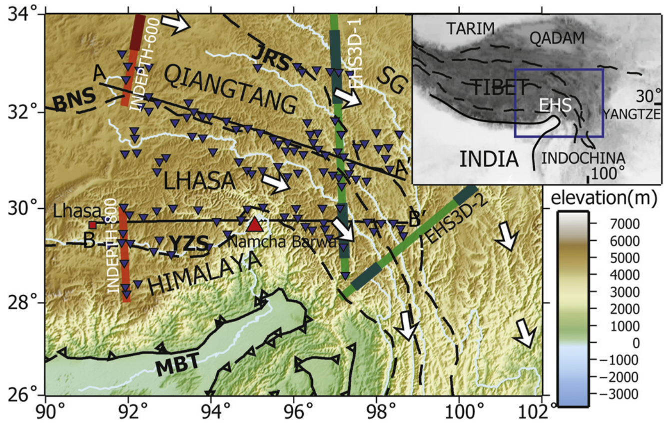

Fig. 1. Topographic map of southeast Tibet Plateau superposed with major thrusts and suture zones. The magnetotelluric stations used in the inversion and interpretation are shown in blue triangles. Previously proposed crustal flow channels are shown as white arrows (Bai et al., 2010). The green and orange lines show the previous profiles of project EHS3D and INDEPTH respectively. The darker portion in the profiles indicates the location with enhanced conductivity presented in previous publications (Bai et al., 2010; Unsworth et al., 2005). EHS: Eastern Himalayan Syntaxis; YZS: Yarlung-Zampo Suture; BNS: Bankong-Nujiang Suture; JRS: Jinsha River Suture; MBT: Main Boundary Thrust; SG: Songpan-Ganzi Terrance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Vs velocity (Liu et al., 2014). However, continuous crustal flow over long distances seems unlikely with the strong NW–SE lateral heterogeneity revealed by ambient noise interferometry (Yang et al., 2012) and receiver function studies (Wang et al., 2010). Conversely, vertically coherent deformation is supported by consistent GPS surface motion and mantle seismic anisotropy (Sol et al., 2007; Wang et al., 2008). Strong coupling between the lithospheric mantle and the crust is challenged by the contrasting anisotropies of the lower crust and upper mantle revealed by a Rayleigh wave dispersion study (Yao et al., 2010). All of these contradictions suggest that the geodynamic processes responsible for the expansion are far more complex than we have predicted in the past and may not be explained by a single simple mechanism. Hence, robust and higher resolution constraints on the physics and rheology of the crust and upper mantle are crucially needed to understand the true expansion process(es) of Southeast Tibet.

2. Magnetotelluric data and analysis

The magnetotelluric (MT) method measures natural time-varying electromagnetic waves on the surface to probe the subsurface electrical conductivity (σ, the inverse of resistivity $\rho = 1/\sigma$) (Chave and Jones, 2012). Since MT is sensitive to interconnected conductive hydrous fluids and melt phases, it has been widely used to constrain the presence of fluids and the rheology of the crust and mantle (Le Pape et al., 2015). As a part of the China-wide, multi-discipline geophysical deep probing project SINOPROBE (Dong et al., 2013), data from 290 MT stations were acquired in the study region from 2010 to 2012. The magnetotelluric stations of the SINOPROBE project were recorded using commercial MT instruments, namely Phoenix MTU-5 (broadband MT) and LVIV LEMI-417 (long period MT) systems. Electric and magnetic field time series were measured parallel and perpendicular to geomagnetic north. Typical recording time of the station was 24 h for broadband MT and 7 d for long period MT. The time series were processed using a statistically robust algorithm (Egbert and Booker, 1986) with remote reference technique (Gamble et al., 1979) to calculate MT transfer functions. The transfer functions were obtained with a broad period range of ∼0.01 to ∼6000 s, which is more than sufficient for probing into the upper mantle despite the relatively low resistivity in the lower crust. The transfer functions were rotated to geographical north according to the local magnetic declination. Thanks to the very low local population density and cultural noise level, the data are generally of good to excellent quality.

The new dataset fills the extensive gaps between the former 2D MT observation profiles (Bai et al., 2010; Li et al., 2003; Wei et al., 2001) and extends them to a 3D array covering the EHS and the southeast margin of Tibetan Plateau (Fig. 1). For the first time, we provide insight into the 3D geo-electrical structure of the region. The extreme regional topography was a severe challenge for data acquisition and explains the uneven site distribution (Fig. 1). A few sites that are strongly distorted by the extreme topography are not used for the inversion. Since inversion schemes may tend to over-fit the densely covered areas and left the other areas under-fitted, the data were selected for inversion to achieve as uniform a site distribution (Dong et al., 2014) as possible in order to avoid biased fitting induced by locally differential station distribution.

In 2D interpretations of MT, we make an approximation that magnetotelluric data can be separated into two independent modes, namely transverse electric (TE) mode and transverse magnetic (TM) mode, which corresponds to electric current flow along and across strike respectively (Chave and Jones, 2012). As the approximation may no longer be valid in a 3D earth, applying 2D methods to a 3D dataset can lead to misinterpretation of the underground structure (Garcia et al., 1999; Ledo, 2005). Phase tensor analysis (Caldwell et al., 2004) is hence derived to test the dimensionality of the resistivity of crust and upper mantle. As the depth of penetration of MT signal differ with period and the conductivity structure, the phase tensor data are plotted at a constant penetration depth rather than a constant period. The estimation of penetration depth uses the Niblett–Bostick transformation method (Jones, 1983). A Berdichevsky average for XY and YX mode of apparent resistivity is used for the Niblett–Bostick transformation to convert periods (frequencies) to depths. The data are hence selected at the corresponding periods to calculate the phase tensors. The orientations of the phase tensor ellipses indicate the direction of preferred current flow and reflect lateral conductivity variations of the underground structures, while circular ellipses show little or no major lateral variations (one dimensional structure) (Caldwell et al., 2004; Hill et al., 2009). The colours filling the phase tensor ellipses show the phase tensor skew angle β and indicate the asymmetry in the MT response, which reflects 3D structures. Please note that $\Phi(2 \times \beta)$ is plotted here instead of β to better displaying the asymmetry of the MT responses (Booker, 2013).

At 5 km, the orientations of phase tensor ellipses show a generally NNE–SSW direction in the northern part of the study region (Fig. 2a). The generally light colours of the PT skew angles suggest a 1D or quasi-2D structure in the uppermost crust. As depth increases the orientation of the phase tensor ellipses rotates to a dominant NWW direction across the whole study area (Figs. 2b–d). Regional geo-electrical structures can thus be inferred to be differently directed in the upper crust and in the lower crust/upper mantle. The extremely flattened ellipses in the lower crust suggest the existence of abrupt lateral geo-electrical interfaces parallel or perpendicular to the surface tectonics. The overall dark colours of the PT skew angles ($>5°$) reflect highly asymmetric conductive structures, which indicates regional 3D structures.

3. Magnetotelluric inversion

One hundred and seventeen out of the total 290 stations were inverted with a 3D modular electromagnetic inversion code (ModEM) utilizing nonlinear conjugate gradient optimising method