Earth and Planetary Science Letters 373 (2013) 20–30

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Experimental assessment of the relationships between electrical resistivity, crustal melting and strain localization beneath the Himalayan–Tibetan Belt

Leïla Hashim [a,b,c,*], Fabrice Gaillard [a,b,c], Rémi Champallier [a,b,c], Nicole Le Breton [a,b,c], Laurent Arbaret [a,b,c], Bruno Scaillet [a,b,c]

[a] Université d'Orléans, ISTO, UMR 7327, 45071 Orléans, France
[b] CNRS/INSU, ISTO, UMR 7327, 45071 Orléans, France
[c] BRGM, ISTO, UMR 7327, BP 36009, 45060 Orléans, France

ARTICLE INFO

Article history:
Received 9 October 2012
Received in revised form 18 April 2013
Accepted 19 April 2013
Editor: T.M. Harrison
Available online 25 May 2013

Keywords:
electrical resistivity
viscosity
partial melting

ABSTRACT

Seismic and magnetotelluric field campaigns carried out across the Himalaya and the Tibetan Plateau show mid-crustal low resistivity and low velocity zones. Interpretation of these anomalous observations, either saline fluids or partial melts, is still largely debated partly because experimental data simulating crustal melting under relevant pressure, temperature and water content conditions have not been provided. We report laboratory measurements constraining the resistivity as a function of temperature and the viscosity at 800 °C of natural metapelite during partial melting. Dehydration-melting of muscovite is simulated using a Paterson press at 300 MPa in the temperature range 600–850 °C. Electrical resistivity has been measured from the solid state (< 650 °C) to 25 vol% of partial melt (> 800 °C) and viscosity has been determined at 800 °C. Our results together with recent experimental constraints on seismic properties of partially molten rocks strongly suggest that the electrical and seismic anomalies measured underneath the Himalayan–Tibetan collisional orogen are best explained by partially molten rocks or local accumulation of pure melt bodies. This is also remarkably corroborated by the temperature–depth conditions of crustal partial melting and melt ponding expected from petrological surveys in the Himalayan range. However, our data suggest much higher melt fraction than previously thought and this implies regions in the middle crust having viscosities several orders of magnitude lower than previously assumed. High degree partial melting in the middle crust of the Himalayan–Tibetan orogenic system suggests revision of conceptual models on the development of mountain belts or that geophysical models addressing electrical resistivity at depth must be re-evaluated.

1. Introduction

The construction of mountain belts resulting from continental collisions involves crustal thickening, regional deformation and high-grade metamorphism. As observed in many ancient orogenic terrains, elevated temperatures locally induce melting and strain weakening, which may profoundly affect the rheology of the continental crust, its deformation regime and hence the development of these orogens (Jamieson et al., 2011; Sawyer et al., 2011).

The Himalaya–Tibetan system is an active collisional belt allowing us to probe the three-dimensional thermo-mechanical distribution of an archetypal continent–continent orogen. The Himalaya–Tibetan orogenic system was initiated 70–50 My ago by the Indo-Asian collision resulting in crustal thickening and uplifting of the Tibetan Plateau (Royden et al., 2008; Yin and Harrison, 2000). This vast plateau is separated from the Himalayan mountains by the Indus–Tsangpo suture. Two major faults are located south of this suture: the Main Central Thrust (MCT), which is a low angle high strain crustal shear zone, and the South Tibetan Detachment system (STDs), a low angle normal fault (Fig. 1). The MCT and the STDs bound the Greater Himalayan Sequence (GHS), composed of medium to high-grade metamorphic rocks, migmatites (i.e. once partially molten rocks) and kilometer-thick leucogranites pods (Law et al., 2004; Searle et al., 2006). These High Himalayan Leucogranites (HHL, Fig. 1), late Oligocene to Miocene in age (25–13 Ma), have been shown to be products of partial melting (750–800 °C) of underlying metapelites (Law et al., 2004; Patiño Douce and Harris, 1998; Scaillet et al., 1995; Searle et al., 2006). However, north of the Indus–Tsangpo suture young

* Correspondence to: Institut des Sciences de la Terre d'Orléans, UMR 7327, CNRS/Université d'Orléans, 1A, Rue de la Ferollerie, 45071 Orléans Cedex 2, France. Tel.: +33 2 38 25 53 94; fax: +33 2 38 63 64 88.
E-mail address: leila.hashim@univ-orleans.fr (L. Hashim).

0012-821X/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.epsl.2013.04.026

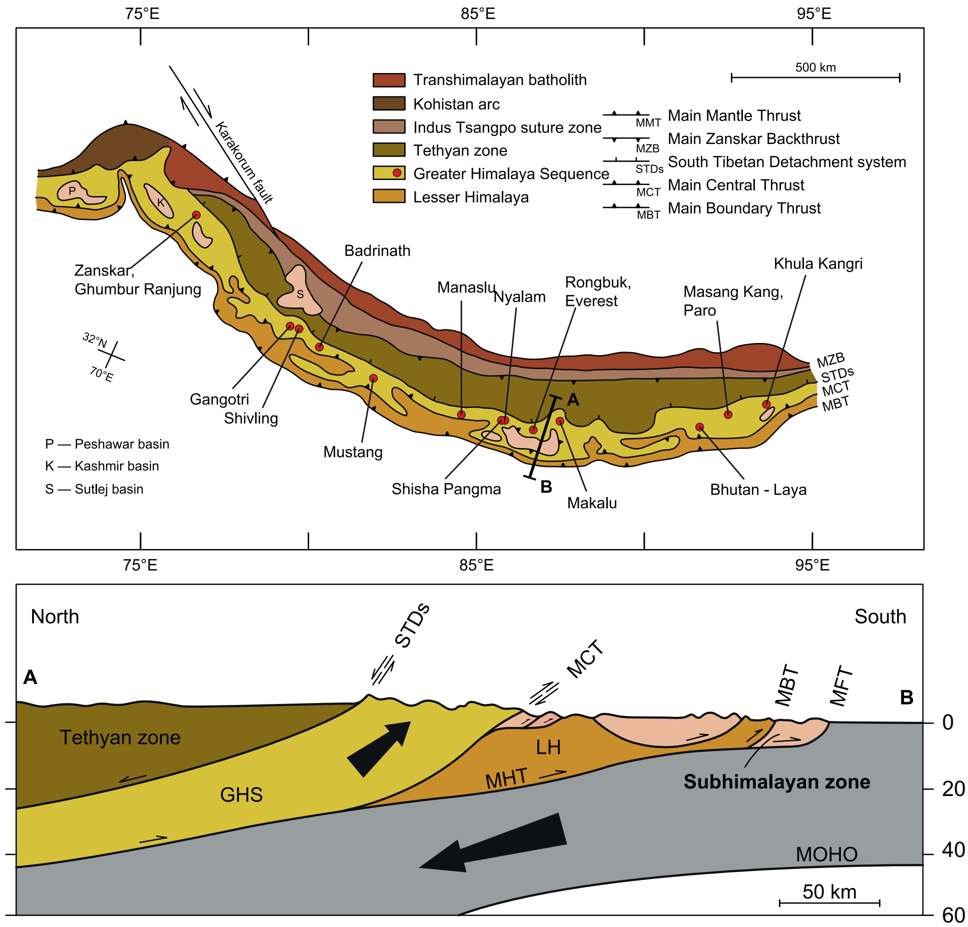

Fig. 1. Simplified geological map and cross-section of the Himalaya showing the main High Himalayan Leucogranites (red dots) along the Greater Himalaya Sequence (adapted after Law et al. (2004) and Searle et al. (2006)). Abbreviations—GHS: Greater Himalaya Sequence; LH: Lesser Himalaya; STDs: South Tibetan Detachment system; MCT: Main Central Thrust; MBT: Main Boundary Thrust; MFT: Main Frontal Thrust; MHT: Main Himalayan Thrust; MOHO: Mohorovic discontinuity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

granitoids (< 15 Ma) are typically biotite granodiorites with ^{3}He anomalies indicating a mantle contribution (Harrison, 2006; Hoke et al., 2000; Yokoyama et al., 1999).

Several magnetotelluric (MT) and seismic field campaigns (INDEPTH, Hi-CLIMB and HIMPROBE projects) have identified low resistivity layers with well-constrained tops at a depth of 10–15 km in southern Tibet (3 Ωm) and 20–25 km in northwestern Himalaya (10 Ωm), coincident with low seismic velocity zones (Arora et al., 2007; Brown et al., 1996; Caldwell et al., 2009; Hetényi et al., 2011; Li et al., 2003; Makovsky and Klemperer, 1999; Nábělek et al., 2009; Nelson et al., 1996; Unsworth et al., 2005; Wei et al., 2001; Zhao et al., 1993). Such electrical anomalies have been interpreted as evidence of high fluid concentrations and two main hypotheses are still largely debated today: either aqueous fluids (Hetényi et al., 2011; Li et al., 2003; Makovsky and Klemperer, 1999) or melts (Arora et al., 2007; Brown et al., 1996; Caldwell et al., 2009; Gaillard et al., 2004; Li et al., 2003; Nábělek et al., 2009; Nelson et al., 1996; Unsworth et al., 2005; Wei et al., 2001). However, both hypotheses remain poorly demonstrated (Harrison, 2006; Hetényi et al., 2011), each having considerable impact on the thermal structure of the thickened crust in the Himalayas. The melt hypothesis suggests low melt percentages, between 2 and 14 vol%, from electrical constraints (Arora et al., 2007; Unsworth et al., 2005), which would be in agreement with seismic observations (Caldwell et al., 2009) (less than 10 vol% for V_S=2.9–3.3 km s^{-1}). Recent experimental shear wave velocity measurements (Caricchi et al., 2008), however, indicate that such velocities better match 20–25 vol% partial melting. Experimental studies on the electrical resistivity of partially molten rocks have been carried out on dry granulite samples at atmospheric pressures (Roberts and Tyburczy, 1999; Schilling and Partzsch, 2001). Under these conditions, partial melting starts at temperatures higher than 1000 °C, which is well above expected crustal temperatures in continent-collisional settings. Melts produced by crustal melting are hydrous (Scaillet et al., 1995), which implies lower melting temperatures and lower electrical resistivity of rocks and melts (Gaillard et al., 2004). Notwithstanding, resistivity values on hydrous partially molten metapelites are still not well constrained from electrical modelling such as SIGMELTS (Pommier and Le Trong, 2011).

In this experimental study, we have performed electrical resistivity measurements as a function of temperature and determined the viscosity of metapelites undergoing partial melting at 800 °C. These experiments were conducted using a Paterson-type deformation apparatus on partially molten metapelites. By using these types of rocks in this study, we have simulated the appropriate geological processes happening at depth according to previous petrological studies in the Himalayan–Tibetan range (Law et al., 2004; Patiño Douce and Harris, 1998; Scaillet et al., 1995; Searle et al., 2006). We therefore show here that the geophysical anomalies underneath this orogenic system must pinpoint high degree crustal melting and local melt accumulation, forming low-viscous regions, which are several orders of magnitude weaker than previously assumed (Beaumont et al., 2001,