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Mantle fluids in the Karakoram fault: Helium isotope evidence

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ABSTRACT

The Karakoram fault (KKF) is the 1000 km-long strike-slip fault separating the western Himalaya from the Tibetan Plateau. From geologic and geodetic data, the KKF is argued either to be a lithospheric-scale fault with hundreds of km of offset at several cm/a, or to be almost inactive with cumulative offset of only a few tens of kilometers and to be just the upper-crustal localization of distributed deformation at depth. Here we show $^3He/^4He$ ratios in geothermal springs along a 500-km segment of the KKF are 3–100 times the normal ratio in continental crust, providing unequivocal evidence that a component of these hydrologic systems is derived from tectonically active mantle. Mantle enrichment is absent along the Indus–Yarlung suture zone (ISZ) just 35 km southwest of the KKF, suggesting that the mantle fluids flow only within the KKF. Within the last few Ma, the KKF must have accessed tectonically active Tibetan mantle northeast of the "mantle suture" which we therefore locate vertically beneath the KKF, very close to the surface trace of the ISZ. Hence, in southwestern Tibet, Indian crust may not now be underthrusting substantially north of the ISZ, even though Miocene underthrusting may have placed Indian crust north of the ISZ in the lower half of the Tibetan Plateau crust. This is in significant contrast to central and eastern Tibet where underthrust Indian material not only forms the lower half of the Tibetan crust but is also currently underthrusting for ~200 km north of the ISZ. Our new constraint on KKF penetration to the mantle allows an improved description of the continuously evolving Karakoram fault, as a tectonically significant yet perhaps geologically ephemeral lithospheric structure.

1. Introduction

Observation of mantle contributions to ^3He at the surface requires both a source of helium in the mantle, and a path to the surface. In Tibet the mantle source is believed to be Tibetan mantle that is tectonically active (i.e., with incipient melting and likely deforming), as opposed to cratonic Indian mantle (Hoke et al., 2000). We propose that elevated $^3He/^4He$ ratios in hot springs along the Karakoram fault (KKF) (Fig. 1) demonstrate that within the last few Ma the KKF has channeled fluids to the surface from tectonically active Tibetan mantle. The KKF therefore marked the "mantle suture", or northern limit, at the Tibetan Moho, of actively subducting Indian lower lithosphere. Our new data showing no mantle contamination of hot springs on the Indus–Yarlung suture (ISZ) complement our new and existing data showing clear mantle enrichment along the KKF and together imply focusing of the mantle fluids by the strike-slip fault system.

1.1. The Karakoram fault controversy and the northern limit of India

The structure of Tibet as a geodynamic response to the collision of India with Asia, and the distribution of deformation, are particularly contentious in west Tibet (for the purpose of this paper, west of about 82°E). Two continental-scale strike-slip faults—the dextral KKF and the sinistral Altyn Tagh fault (ATF) (Fig. 1)—play a disputed role in the eastward extrusion of Tibet since the onset of the India–Asia collision at ~57 Ma (Leech et al., 2005). Two extreme and opposing views exist for the mechanism(s) responsible for crustal accommodation of shortening across Tibet: (1) discrete tectonic blocks, internally relatively undeformed, are extruded eastward between lithospheric strike-slip faults (e.g. Tapponnier et al., 2001; Thatcher, 2007) and (2) deformation is continuously distributed within the lithosphere via ductile flow of the lower crust and upper mantle matched by brittle failure throughout a ubiquitously faulted

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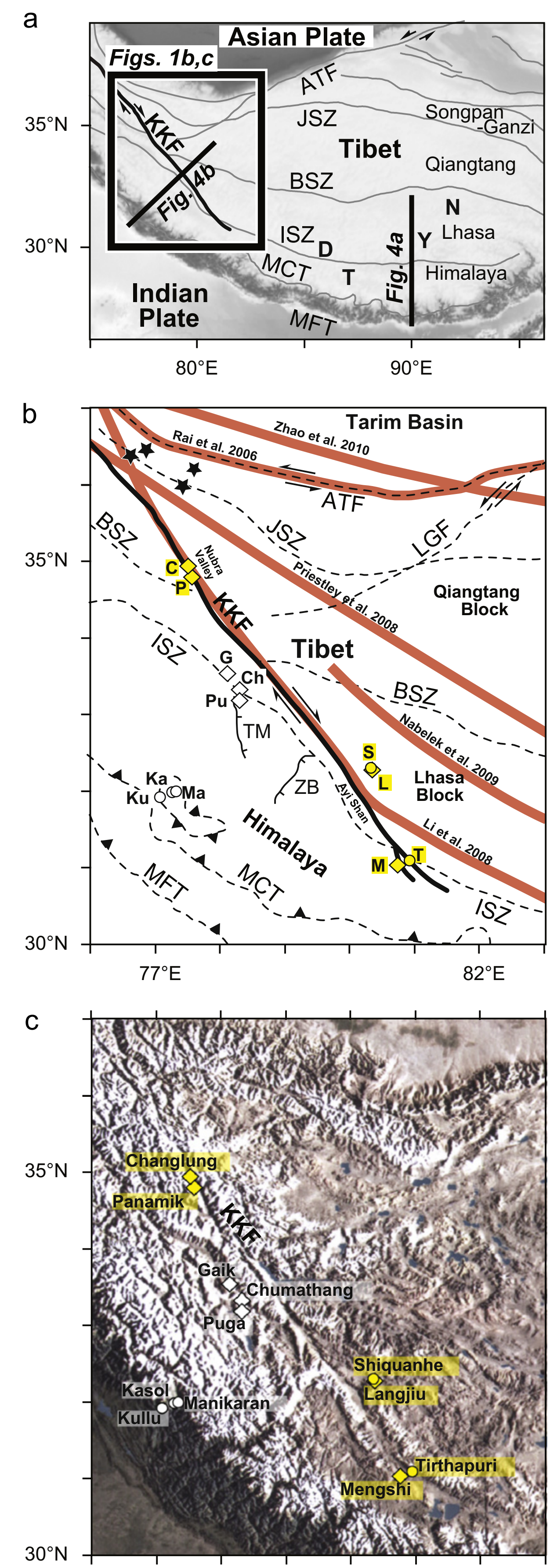

Fig. 1. $^3He/^4He$ sample locations and faults in Tibet, and previous estimates of the northern limit of India beneath western Tibet. (a) Shaded relief index map of Tibet and major faults: KKF—Karakoram fault, MFT—Main Frontal thrust, MCT—Main Central thrust, ISZ—Indus-Yarlung suture zone, BSZ—Banggong–Nujiang suture zone, JSZ—Jinsha suture zone, ATF—Altyn Tagh fault (Karakax fault). N: Nagqu; Y, T, D: Yangbajain, Tingri, and Daggyai Co graben systems; Y is location of mantle suture of Hoke et al. (2000). (b) ^3He data locations (diamonds—this study; circles—previous studies in Tibet) (Hoke et al., 2000) and the Himalaya (Walia et al., 2005) superimposed on tectonic map (Murphy et al., 2000). Letters identifying geothermal sites (C, P, G, Ch, Pu, S, L, M, T, Ku, Ka, Ma) are spelled out in Fig. 1c and used in Figs. 2 and 3. Yellow shading (C, P, S, L, M, T): $R_C/R_A > 0.05/R_A$—all on or immediately north of the KKF. White symbols: no mantle signature. Bold red lines: previous interpretations of northern limit of Indian lithosphere at the Moho from S-receiver functions (Zhao et al., 2010), from P-receiver functions (Nábělek et al., 2009; Wittlinger et al., 2004), from northern limit of deep earthquakes (at 85–95 km depth—black stars) (Priestley et al., 2008), and from body-wave tomography (Li et al., 2008). LGF—Longmu Co-Gozha Co fault system. TM and ZB: Tso Morari and Zada basin (Leo Pargil) normal faults. (c) Satellite image of KKF (same area and scale as (b)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

upper crust (e.g. England and Molnar, 1997; cf. Beaumont et al., 2006).

The relative merit of these viewpoints in western Tibet has been assessed in part from studies of slip rate on the KKF and ATF. Geologic inferences of rapid slip up to 32 mm/a (Valli et al., 2008) and large offsets up to 555 km (Replumaz and Tapponnier, 2003) or ~300 km (Rolland et al., 2009) on the KKF seem to support plate-like behavior, and an important role for the KKF as a lithospheric structure. In contrast, geodetic measurements of slow or zero modern slip on the KKF (3 ± 5 mm/a: Jade et al., 2004; 0–6 mm/a: Wang and Wright, 2012) seem to support continuous deformation of Tibet. Geologic claims for small total offset compatible with slow slip (66–150 km: Murphy et al., 2000; 40–150 km: Phillips et al., 2004) also suggest only a minor upper-crustal role for the KKF.

At a regional scale the depth of penetration of the KKF defines the tectonic interaction between India and Tibet. Hypothesized active channel flow (e.g. Beaumont et al., 2006) of mid-to-lower crust from Tibet into the northwest Himalaya driven by gravitational potential energy of the Tibetan Plateau would require that the KKF is limited to the shallow crust (Phillips et al., 2004), terminating downwards at a partial melt/channel flow zone at ca. 20 km depth above underthrusting Indian crust. Alternatively the KKF may reach into the middle crust to form a southern bound to this channel flow (Leech, 2008) or penetrate the whole lithosphere and constrain the northern limit of the underthrust Indian plate below the Tibetan Moho (Rolland et al., 2009).

Seismic imaging of western Tibet has not yet imaged the KKF, as opposed to the ATF that is widely accepted from teleseismic imaging to be of lithospheric scale (Wittlinger et al., 2004), in part because the KKF is located close to disputed international boundaries. However, the northern limit of Indian crust beneath Tibet may constrain the depth of penetration of the KKF, now or in the past. Some tomographic images of west Tibet (Li et al., 2008) allow Tibetan mantle as far south as the KKF, consistent with but not requiring a crustal-penetrating KKF. However, most seismologic estimates of the northern limit of India (Nábělek et al., 2009; Priestley et al., 2008; Rai et al., 2006; Zhao et al., 2010) (Fig. 1b) nominally preclude penetration of the KKF into the mantle because they interpret an unbroken subthrust Indian crust, and infer this Indian crust is being subducted almost horizontally at the present day. A receiver-function "doublet" of Ps converters at ~80°E (Wittlinger et al., 2004) may mark the top and bottom of underthrust Indian crust forming the lower half of the Tibetan crust northward to about the Banggong–Nujiang suture (Nábělek et al., 2009). Similar Moho depths immediately north (Wittlinger et al., 2004) and south (Rai et al., 2006) of the KKF may imply