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Deep India meets deep Asia: Lithospheric indentation, delamination and break-off under Pamir and Hindu Kush (Central Asia)

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ABSTRACT

Subduction of buoyant continental lithosphere is one of the least understood plate-tectonic processes. Yet under the Pamir–Hindu Kush, at the northwestern margin of the India–Asia collision zone, unusual deep earthquakes and seismic velocity anomalies suggest subduction of Asian and Indian lithosphere. Here, we report new precise earthquake hypocenters, detailed tomographic images and earthquake source mechanisms, which allow distinguishing a narrow sliver of Indian lithosphere beneath the deepest Hindu Kush earthquakes and a broad, arcuate slab of Asian lithosphere beneath the Pamir. We suggest that this double subduction zone arises by contrasting modes of convergence under the Pamir and Hindu Kush, imposed by the different mechanical properties of the three types of lithosphere involved. While the buoyant northwestern salient of Cratonic India bulldozes into Cratonic Asia, forcing delamination and rollback of its lithosphere, India's thinned western continental margin separates from Cratonic India and subducts beneath Asia. This torn-off narrow plate sliver forms a prominent high-velocity anomaly down to the mantle transition zone. Our images show that its uppermost section is thinned or already severed and that intermediate depth earthquakes cluster at the neck connecting it to the deeper slab, providing a rare glimpse at the ephemeral process of slab break-off.

1. Introduction

The Pamir and Hindu Kush, located northwest of Tibet, are part of Earth's largest active continental collision (Fig. 1a). As in Tibet, the Pamir–Hindu Kush crust comprises terranes that rifted from Gondwana (the Gondwana terranes of Fig. 1b) and then amalgamated to the southern margin of Asia (Tapponnier et al., 1981; Burtman and Molnar, 1993; Schwab et al., 2004). Unlike Tibet, the Pamir–Hindu Kush mantle exhibits vigorous intermediate depth (>100 km) seismicity (Billington et al., 1977; Chatelain et al., 1980; Pegler and Das, 1998; Sippl et al., 2013a) (Fig. 1a) and strong velocity anomalies down to the bottom of the transition zone (Koulakov and Sobolev, 2006; Negredo et al., 2007). Fifteen earthquakes with magnitude greater than 7.0 have occurred in the Hindu Kush deep seismic zone in the last 100 years, including the recent destructive October 2015 Mw 7.5 Badakhshan, Afghanistan event (ISC bulletins, 2013; USGS, 2015). Intense intermediate depth seismicity is generally confined to oceanic subduction zones and its occurrence inside a continent is enigmatic (Billington et al., 1977; Vinnik et al., 1977; Chatelain et al., 1980; Roecker, 1982; Burtman and Molnar, 1993; Pegler and Das, 1998). The Pamir and Hindu Kush earthquakes form two separate zones (Fig. 1); the provenance of the Hindu Kush earthquakes is debated (Pegler and Das, 1998; Sippl et al., 2013a), but in the Pamir they are associated with continental Asian plate subduction (Schneider et al., 2013; Sippl et al., 2013b). This contradicts the plate-tectonic paradigm that con-

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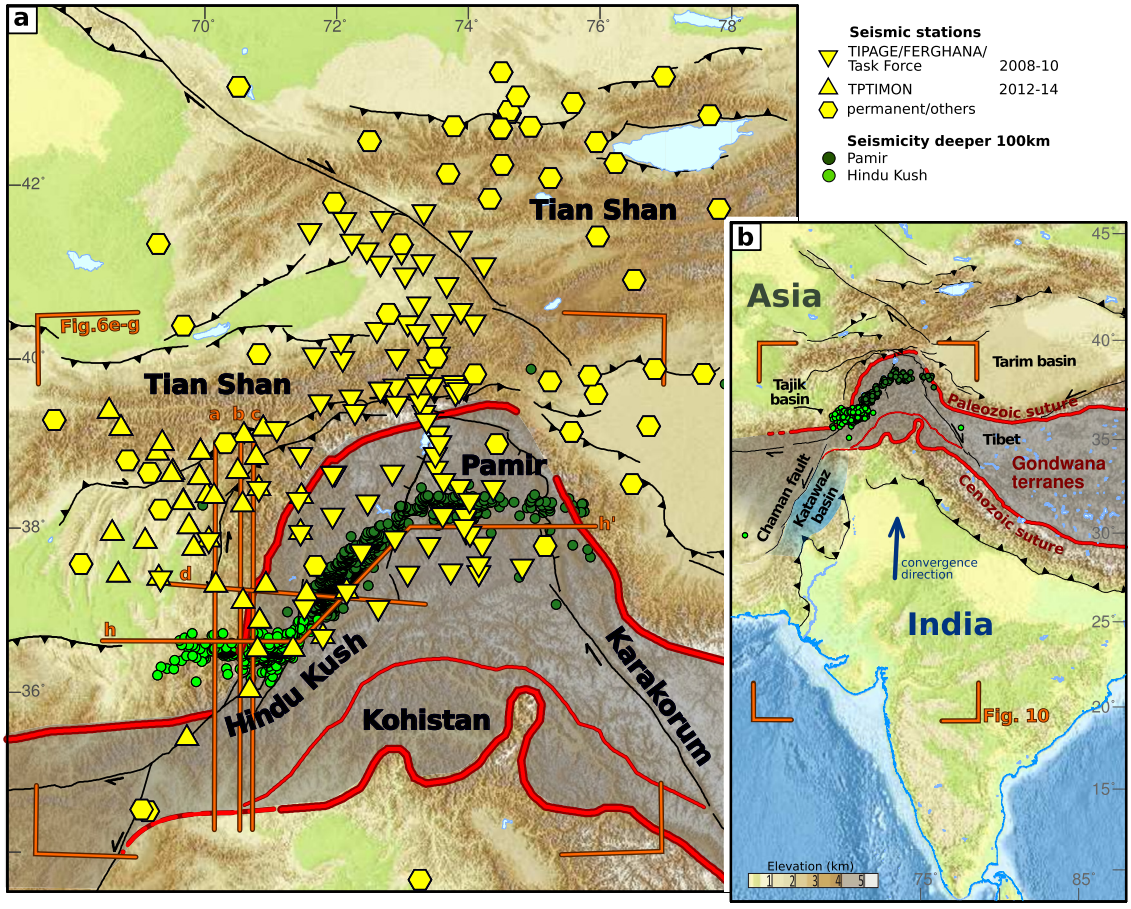

Fig. 1. Seismicity and seismic stations used in this study plotted onto a topographic map of Central Asia. (**a**) Yellow symbols mark seismic stations. Northern red line follows the Late Paleozoic-Triassic suture separating cratonic Asia in the north from the Gondwana terranes (shaded grey) in the south. Southern line is the Cenozoic Indus-Yarlung suture, separating Indian from Asian rocks. Thin red line marks the Shyok suture. Seismicity (Sippl et al., 2013a) for depths greater than 100 km is plotted in light and dark green under the Hindu Kush and Pamir, respectively. Orange markers locate the sections in Fig. 6. (**b**) India and its collision with Asia. Deep (>100 km) seismicity for the last 50 years from a global catalogue (Engdahl et al., 1998). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

tinental lithosphere does not subduct to significant depth without the pull-force of a leading, negatively buoyant oceanic plate. The understanding of the origin of these anomalies is a key to the deep-seated processes of the India–Asia collision and continental dynamics in general.

We present a regional tomographic model, new earthquake hypocenters and source mechanisms, all based on recent seismic experiments. The detailed lithospheric structure revealed by the tomography and seismicity, and the stress field inferred from earthquake focal mechanisms allow us to deduce the geodynamic processes currently acting under the Pamir and Hindu Kush. We propose a tectonic scenario that led to the unique constellation observed today, suggesting a solution to the long-standing controversy on slab provenance and explaining the formation of the peculiar double subduction zone.

2. Data

Our results were obtained from the analysis of seismic data recorded by three temporary networks (Fig. 1a), namely the TIPAGE (Mechie et al., 2012) and FERGHANA (Feld et al., 2015) networks operated between 2008 and 2010 in the Pamir and Tian Shan, and the TIPTIMON network (Schurr et al., 2012, 2013) from 2012–2014 in the western Pamir, Tajik basin and Hindu Kush. TIPTIMON operated 33 broadband stations in Tajikistan and eight short period sensors in Afghanistan (Mark L-3D, 1 Hz natural frequency) and shared seven sites with the TIPAGE network. The stations in Afghanistan were situated on top of the Hindu Kush intermediate depth seismic zone, allowing to constrain its geometry at high resolution. Additional permanent station data were collected for the operating periods of the temporary networks (Fig. 1b). In total, we analyzed data from 180 seismograph sites with a spacing between ~20 km along a north-south profile in the central Pamir and 40–60 km in the western Pamir, Hindu Kush and Tajik basin. Waveforms from the permanent stations were accessed via the GEOFON, IRIS and Chinese Earthquake Network data centers.

3. Earthquake analysis

3.1. Extended earthquake catalogue

We augmented the existing Pamir–Hindu Kush earthquake catalogue (Sippl et al., 2013a), which is based on the TIPAGE and FERGHANA networks, with the events located during the TIPTIMON experiment between 2013 and 2014, i.e. while the Afghan stations were recording. The superior event–station geometry of this network in relation to the Hindu Kush earthquakes significantly improved their locations. For the earthquake-catalogue production, we followed essentially the same automated procedure applied for the TIPAGE catalogue (see details in Sippl et al., 2013a). Here, we aimed to improve the image of the Hindu Kush seismic zone, therefore only earthquakes that were registered by at least one of the seismic stations in Afghanistan and located west of 71.8°E, the approximate border between the Pamir and Hindu Kush seismic

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