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Zooming into the Hindu Kush slab break-off: A rare glimpse on the terminal stage of subduction

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A B S T R A C T

The terminal stage of subduction sets in when the continental margin arrives at the trench and the opposite forces of the sinking slab and buoyant continent extend and ultimately sever the subducted lithosphere. This process, although common in geological history, is short-lived, and therefore rarely observed. The deep seismicity under the Hindu Kush (Central Asia), including the 2015 M_w 7.5 event, is a rare case that testifies to this process. Here, we use new seismological data to create a high resolution picture of slab break-off and infer its dynamics. High precision earthquake locations and tomographic images show subduction of continental crust down to ~180 km. A large dataset of source mechanisms indicates sub-vertical extension in the entire slab but a strain rate analysis showed that the deeper seismogenic portion of the slab, below the subducted crust, extends at higher rates (~40 km/Ma). Most $M_w > 7$ earthquakes between 1983–2015, relocated relative to our new well-constrained earthquake catalog, cluster in a small volume below 180 km, and indicate shearing on an overturned interface. A slip model for the latest 2015 M_w 7.5 event suggests that it ruptured into a seismic gap on this interface. From this configuration we conclude that a horizontal slab tear develops along-strike of the Hindu Kush seismic zone at the base of the subducted continental crust. Below the subducted crust, the deepest and also largest earthquakes (180–265 km) are likely associated with deformation in the mantle lithosphere. From the seismicity distribution and the rupture mechanisms we further deduce that the dominant deformation mechanism in this deeper portion of the slab changes along-strike from simple to pure shear. The fastest detachment rates and largest earthquakes occur during the simple shear dominated stage. Earthquakes in the upper part (60–180 km), above the rapidly extending slab, might be triggered by processes related to the subduction of crustal rocks.

1. Introduction

The Pamir–Hindu Kush mountains in Central Asia are one of the few regions where intermediate-depth seismicity (seismicity between ~60–300 km depth) is not obviously associated with oceanic plate subduction. Instead, it is thought to occur in continental lithosphere, probably of Indian provenance (Kufner et al., 2016), where the most commonly adduced mechanism for intermediate-depth seismogenesis, dehydration embrittlement, is not easily applicable because of the lack of hydrated rocks. This makes the occurrence of these deep earthquakes more enigmatic because the pressure–temperature conditions in the upper mantle would require very large differential stresses to allow brittle failure (Thielmann et al., 2015). Sub-crustal seismicity beneath the Hindu Kush clusters in a near-vertically dipping narrow volume (Billington et al., 1977; Pegler and Das, 1998; Sippl et al., 2013b; Bai and Zhang, 2015) featuring repeating large earthquakes deeper than 200 km (e.g. 15 $M_w > 7$ in the last 100 yr; USGS, 2016). The most recent and largest of these struck the Hindu Kush region in October 2015 ($M_w = 7.5$, 210 km depth; GEOFON, 2016).

In the Hindu Kush case, ongoing subducted slab break-off of a narrow lithospheric plate sliver has been suggested to create sufficient high strain rates to trigger seismicity (Koulakov and Sobolev, 2006; Lister et al., 2008; Kufner et al., 2016; Zhan and Kanamori, 2016). Even if this is agreed on, it is not known in which part of the subducted lithosphere and by which mechanism intermediate-

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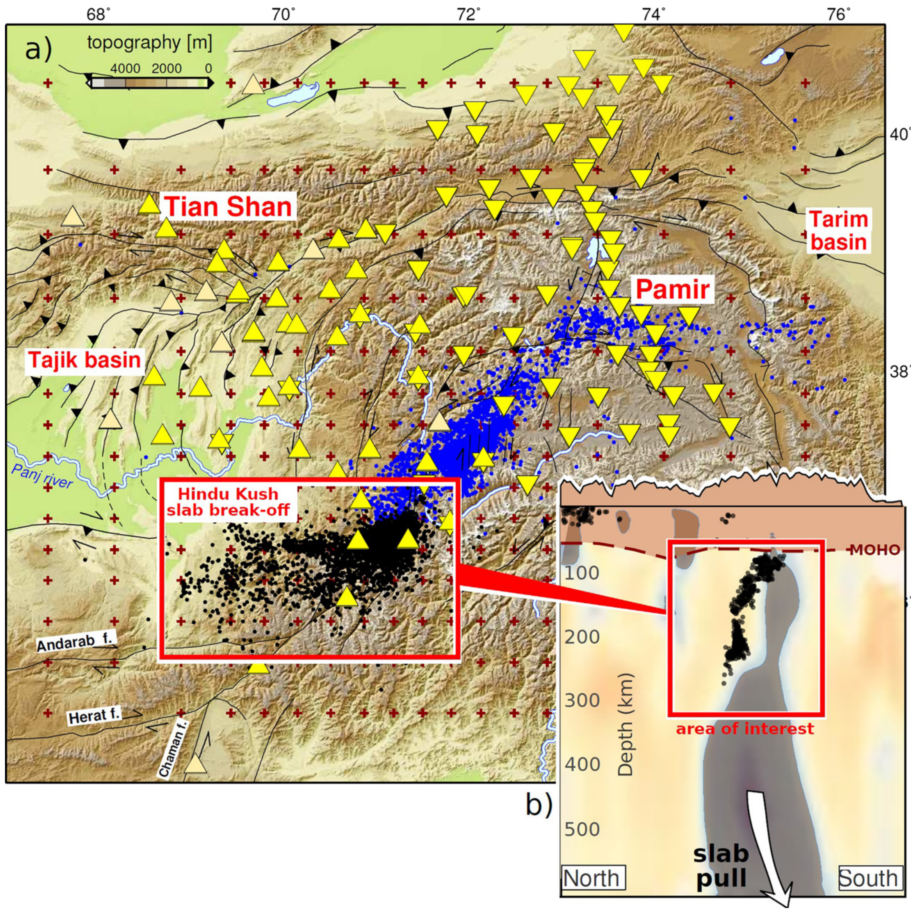

Fig. 1. Study region. a) Topographic map of the Hindu Kush and surroundings. Yellow triangles are the local seismic stations used in this study (triangles – TIPTIMON; inverted triangles – TIPAGE/FERGHANA; light yellow – permanent stations (TJ network in Tajikistan and the station KBL (IU network) in Kabul)). Intermediate-depth (depth > 60 km) seismicity from this study is plotted in blue beneath the Pamir and black beneath the Hindu Kush. Dark red crosses mark nodes used for local earthquake tomography. Tectonic features are taken from Kufner et al. (2016). b) Depth section through the Hindu Kush from teleseismic tomography. Seismicity in black. Velocity anomalies relative to ak135 larger than 1% are highlighted in brown. Crustal thickness (orange) was constrained from receiver functions (modified from Kufner et al., 2016). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

depth earthquakes occur and how they relate to the slab break-off. Numerical simulations of slab break-off indicate that its spatio-temporal evolution, and thus the conditions under which brittle failure can occur, depend on multiple parameters, i.e. the imposed convergence rate, the slab rheology and thickness and its 3D geometry (van Hunen and Allen, 2011; Duretz et al., 2012; Duretz and Gerya, 2013). Despite a variety of modeling studies, actual observations on the development of slab break-off are rare as the final pinching-off is supposed to be an ephemeral process. Hence, the Hindu Kush offers a rare opportunity to observe break-off directly.

In the following, we will present a suite of seismological observations aiming to characterize the processes associated with the Hindu Kush slab break-off including seismogenesis. Our results are primarily gained from the analysis of records from temporarily deployed seismic stations (triangles in Fig. 1a). These data allowed us to determine the geometry of the seismicity (Section 3.1), the source mechanisms of many of these earthquakes (Section 3.4) and the velocity structure of the surrounding material (Section 4) at higher precision than was possible before by just using regional or teleseismic data. We then extended our analysis to global seismic data for the largest digitally recorded Hindu Kush earthquakes to relate our results to a longer observation period (Sections 3.2, 3.3, 5). This allowed us, e.g., to calculate the strain rate within the seismogenic portion of the slab. This also entailed a detailed analysis of the most recent M_W 7.5 Badakhshan earthquake (26.10.2015) and several of its aftershocks.

We combine our results to suggest a comprehensive scenario to explain the anomalous Hindu Kush intermediate-depth seismicity and its relation to break-off dynamics (Section 6). We propose that crustal rocks are pulled to ∼180 km depth together with the subducting mantle lithosphere. A horizontal slab tear develops along-strike of the Hindu Kush seismic zone at the base of the subducted continental crust. The largest earthquakes occur along an interface below the subducted crust, indicating that the final pinching off occurs by simple-shear deformation in the subducted mantle lithosphere.

2. Tectonic setting

The Pamir–Hindu Kush mountains are located north of the western syntaxis of the India–Asia collision system (Fig. 1a). Although India–Asia collision is ongoing already since ∼50–55 Ma (van Hinsbergen et al., 2011), the current convergence rate of India relative to Asia is still high (∼34 mm/yr at the longitudinal position of the Hindu Kush; DeMets et al., 2010). The Pamir mountains formed on the Asian side of this collision; the Hindu Kush mountains, located south-west of the Pamir are divided by the Cenozoic India–Asia suture zone. Beneath the Hindu Kush, a narrow, sub-vertically dipping seismic velocity anomaly, which extends down to the transition zone (Van der Voo et al., 1999; Koulakov and Sobolev, 2006; Kufner et al., 2016), has been related to the northward subduction of a narrow slablet of India's thinned continental margin (Kufner et al., 2016; Fig. 1b). The Pamir zone of