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Deep burial of Asian continental crust beneath the Pamir imaged with local earthquake tomography

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ABSTRACT

An inclined zone of intermediate-depth seismicity beneath the Pamir orogen in Central Asia has been interpreted as southward subduction of a slab of Asian lithosphere. However, it is not known whether Asian lithosphere subducts intact or only partially. We used arrival times of shallow and intermediate-depth earthquakes, recorded with a temporary (2008–2010) seismic network in this region, to invert for 3D models of seismic velocities in an attempt to answer this question. With local seismicity reaching depths of up to 240 km, the deep structure of the Pamir could be illuminated with high resolution.

The resulting velocity models show a north–south contrast in crustal seismic velocities in the Pamir, with very low P velocities (5.7–5.9 km/s at 15–30 km depth), coupled with relatively low v_p/v_s (<1.70), at mid-crustal levels in the southern part of the orogen. At sub-Moho depths, we image an arcuate high-velocity (8.2–8.6 km/s) slab dipping south in the eastern Pamir and east in the Pamir's southwest, underlying the intermediate-depth earthquakes. On top of the high-velocity slab and just above the onset of deep seismicity, between a depth of 60 to 100 km, very low compressional wavespeeds (around 7.1 km/s) and high v_p/v_s ratios ($\geqslant 1.80$) attest to subducted crustal rocks. Additionally, we carried out 2D numerical thermomechanical modeling of the continental collision in the Pamir, focusing on the fate of the crust and mantle lithosphere of the Asian and Indian plates. Seismic velocities were computed from the modeling results, and the resulting images were compared with the velocity distributions obtained from seismic traveltimes.

Combining tomography and modeling results, we infer that a substantial amount of crustal material is pulled down beneath the Pamir by cold mantle lithosphere to depths of at least 80–100 km. From there on, only lower crust and mantle lithosphere continue their subduction, and earthquakes occur inside the lower crustal layer probably due to metamorphic reactions. The buoyant Asian upper and middle crust does not penetrate deeper into the mantle, but pools at this depth level, from where it might eventually exhume or relaminate.

1. Introduction

Although continental collisions are among the most fundamental plate tectonic processes, their deep dynamics are still poorly understood. When crust is shortened and thickened, the underlying mantle lithosphere must shorten, too. This can be achieved by a number of deformation styles (Ghazian and Buiter, 2013) and processes that depend, e.g., on the rheology of the crustal and mantle layers or their convergence rate (Pysklywec et al., 2000). The whole lithosphere may thicken in a pure shear mode, and with time over-thickened lithosphere may become gravitationally unstable and drip (Houseman et al., 1981) or delaminate (Bird, 1979) from the overlying crustal layer. Alternatively, in a simple shear mode, one lithosphere may underthrust or subduct beneath the other. Continental subduction in particular is a process that is not intuitive because continental crust generally resists submergence due to its buoyancy. One way it may be achieved is in the last stage of the Wilson cycle, when a cold and dense leading oceanic plate pulls down an intact continental lithosphere after ocean closure (Toussaint et al., 2004). Alternatively, the lighter crust may be scraped off partly or entirely to allow the remnant lithosphere to sink into the mantle (Molnar and Gray, 1979). The Pamir, north of the western Himalayan syntaxis, is arguably one of the best places to study this process, as an active and steep

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Wadati–Benioff zone (Billington et al., 1977; Pegler and Das, 1998; Sippl et al., 2013) attests to subduction and xenoliths to deep burial of Asian crust (Ducea et al., 2003; Hacker et al., 2005). Crustal subduction has been corroborated by the association of the deep seismicity with low-velocity material both beneath the Hindu Kush (Roecker et al., 1982, using tomography) and more recently the Pamir (Schneider et al., 2013, using receiver functions). The Pamir formed far behind the former Tethys subduction and current deformation front, with no indication for any intervening oceanic subduction in the regional rock record (Burtman and Molnar, 1993; Schwab et al., 2004). Nevertheless, a remnant oceanic slab segment from a small landlocked ocean basin now entirely consumed (as proposed by, e.g., Chatelain et al., 1980) can currently not be excluded. These characteristics clearly distinguish the Pamir from the rest of the Himalaya–Tibet orogenic system, where Indian continental lithosphere (sub)horizontally underthrusts Asia in a northward direction (Yuan et al., 1997; Monsalve et al., 2006; Li et al., 2008) until the mantle lithosphere eventually detaches to plunge into the mantle (Tilmann et al., 2003). The Pamir–Hindu Kush intermediate-depth earthquakes are an oddity, too, because nearly everywhere else on Earth deep seismicity (depth > 100 km) is occurring in active or closed oceanic subduction zones. And it is these earthquakes that allow us to image structures at a resolution and scale that is not possible in other collisional orogens.

In this study, we invert phase arrival times from earthquakes that were recorded with a local seismometer array (Sippl et al., 2013) for three-dimensional models of seismic velocities down to uppermost mantle depths using local earthquake tomography. Compared to other orogens formed by continental collisions, like the Himalaya or the Alps, which are aseismic at mantle depths and where seismic imaging is thus limited to inherently lower-resolution techniques such as teleseismic (e.g. Lippitsch et al., 2003), surface wave (e.g. Chen et al., 2009) or P_n tomography (e.g. Liang and Song, 2006), we can resolve smaller-scale structures and determine absolute wavespeeds, which allow a more straightforward interpretation in terms of lithology. Our results, together with high-resolution earthquake locations (Sippl et al., 2013) and receiver function profiles (Schneider et al., 2013), reveal the detailed 3D structural architecture of the Pamir orogen. Taken together with geodynamic modeling results, these observations allow us to draw inferences on the deep processes of lithospheric deformation active beneath the Pamir.

2. Tectonic setting

Since the Early Miocene (e.g. Sobel and Dumitru, 1997), the northward convex Pamir orogen has indented northwards, into the former Tajik–Yarkand Basin (Burtman and Molnar, 1993); indentation is driven by the ongoing India–Asia convergence. Situated north of the western Himalayan syntaxis, the Pamir comprises several arcuate structural belts which represent micro-continents that collided with continental Asia before the arrival of India. The correlation of suture zones separating these belts with their counterparts in Afghanistan and Tibet (e.g. Burtman and Molnar, 1993; Yin and Harrison, 2000; Schwab et al., 2004) shows that the Pamir has been displaced northwards by at least 300 km relative to the regions east and west of it (e.g. Burtman, 2000). This relative displacement was accommodated by strike-slip faults along the orogenic flanks, i.e. the sinistral transpressive Darvaz Fault Zone (e.g. Trifonov, 1978) in the west and the Kashgar–Yecheng Transfer System (KYTS; Cowgill, 2010) in the east.

Along the Pamir's northern rim, the narrow intra-montane Alai Valley (Fig. 1) is the last vestige of the former Tajik–Yarkand Basin, separating the northern Pamir from the southern Tien Shan. The Main Pamir Thrust Zone (MPT) at the southern margin of the Alai Valley accommodates a significant part of India's convergence with Asia at this longitude (convergence rate 10–15 mm/yr; Zubovich et al., 2010), possibly by southward subduction of continental rocks (Burtman and Molnar, 1993; Sobel et al., 2013).

Large-scale exhumation of gneiss domes in the central and southern Pamir accompanied its northward indentation. These domes formed due to approximately N–S middle to upper crustal extension, exhuming rocks from crustal depths of 30–40 km; exhumation started at about 20 Ma (Schmidt et al., 2011; Stearns et al., 2013), but terminated earlier in the central Pamir domes (15–10 Ma; Rutte et al., 2013) than the southern Pamir Shakhdara–Alichur dome (about 2 Ma). The latter is the largest of these domes, accommodating about 90 km of NNE–SSW extension (Stübner et al., 2013, in press). An arcuate zone of intermediate-depth earthquakes underlies these domes (Fig. 1).

This sub-crustal seismicity outlines a narrow, curved zone interpreted as a south- to east-dipping slab of Asian provenance (Sippl et al., 2013). The Pamir shows several features typical for a mature orogen, such as apparently completed plateau uplift (Amidon and Hynek, 2010), high crustal thickness (>60 km; Beloussov et al., 1980; Mechie et al., 2012; Schneider et al., 2013), elevated heat flow (Duchkov et al., 2001), and crustal extension affecting the orogenic interior (Strecker et al., 1995; Stübner et al., 2013).

3. Tomographic inversion

Phase arrival times of earthquakes from a declustered version of the seismicity catalog of Sippl et al. (2013) were used for tomographic inversion. For a detailed discussion of the station deployment, picking procedure and arrival time uncertainties, the reader is referred to the aforementioned publication. We discarded arrivals with the lowest pick quality class 3 due to their large uncertainties. To achieve a well-balanced event distribution that evenly illuminates crustal and mantle depths, the declustering algorithm was configured to yield an earthquake distribution in which two thirds of all events are sub-crustal (Fig. 2a). The utilized dataset consisted of 56 229 P phases and 25 221 S–P travel time differences from 3 299 earthquakes, recorded at 110 different seismic stations. Fig. 2b summarizes the distribution of phase observations among the stations.

We employed the widely used code SIMUL2000 (Thurber, 1983, 1993; Eberhart-Phillips, 1993; Evans et al., 1994) in its most recent version to retrieve three-dimensional models of v_p and v_p/v_s throughout our study region. SIMUL2000 parameterizes velocities on nodes of a rectangular grid; tri-linear interpolation defines the velocities between grid nodes. Three-dimensional velocity models are retrieved via damped least-squares inversion. The forward problem is solved with a combination of an approximate ray tracer and a pseudo-bending scheme (Um and Thurber, 1987), i.e. an initial ray estimate obtained by selecting the fastest ray out of a three-dimensional fan shot by the approximate ray tracer is perturbed iteratively until it satisfies Fermat's principle within a defined error margin.

Our inversion grid reflects ray density, i.e. the grid cells are smaller in the center and larger at the fringes of the area of interest. Horizontal node spacing is 30–40 km throughout most of the study area, whereas the vertical distance between adjacent nodes is 15 km at crustal depths (until 60 km) and 20 km at mantle depths. Fig. 2a shows the distribution of the selected earthquakes, the utilized stations and the inversion grid.

Starting with the minimum 1D v_p model of Sippl et al. (2013) and a fixed homogeneous v_p/v_s model with $v_p/v_s = 1.74$, which was the overall best-fit value derived from a Wadati diagram, we inverted for the three-dimensional distribution of v_p. A total of ten iterations was performed, and earthquake hypocen-