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

Sofia-Katerina KUFNER (kufner@gfz-potsdam.de)^{a,*}, Bernd SCHURR (schurr@gfz-potsdam.de)^a,
Christian HABERLAND (haber@gfz-potsdam.de)^a, Yong ZHANG (zhygn@163.com)^b, Joachim
SAUL (saul@gfz-potsdam.de)^a, Anatoly ISCHUK (anatoly.ischuk@gmail.com)^c and Ilhomjon
OIMAHMADOV (ilhomjon_55@mail.ru)^c

^(a) Deutsches GeoForschungsZentrum GFZ, Telegrafenberg, Potsdam, 14473, Germany

^(b) School of Earth and Space Sciences, Peking University, Beijing, 100871, China

^(c) Tajik Academy of Sciences, 267 Ainy Str., Dushanbe, 734063, Republic of Tajikistan

*Correspondence to: kufner@gfz-potsdam.de

Abstract:

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.

Keywords:

(1) Pamir-Hindu Kush, (2) Slab break-off, (3) Intermediate-depth seismicity, (4) Continental crust subduction, (5) Continental collision, (6) Repeating earthquakes

1 **1 Introduction**

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

14 In the Hindu Kush case, ongoing subducted slab break-off of a narrow lithospheric plate sliver has been
15 suggested to create sufficient high strain rates to trigger seismicity (Koulakov and Sobolev, 2006; Lister
16 et al., 2008; Kufner et al. 2016; Zhan and Kanamori, 2016). Even if this is agreed on, it is not known in
17 which part of the subducted lithosphere and by which mechanism intermediate-depth earthquakes occur
18 and how they relate to the slab break-off. Numerical simulations of slab break-off indicate that its
19 spatio-temporal evolution, and thus the conditions under which brittle failure can occur, depend on
20 multiple parameters, i.e. the imposed convergence rate, the slab rheology and thickness and its 3D
21 geometry (van Hunen and Allen, 2011; Duretz et al., 2012; Duretz and Gerya, 2013). Despite a variety
22 of modeling studies, actual observations on the development of slab break-off are rare as the final
23 pinching-off is supposed to be an ephemeral process. Hence, the Hindu Kush offers a rare opportunity
24 to observe break-off directly.

25 In the following, we will present a suite of seismological observations aiming to characterize the
26 processes associated with the Hindu Kush slab break-off including seismogenesis. Our results are
27 primarily gained from the analysis of records from temporarily deployed seismic stations (triangles in
28 Fig. 1a). These data allowed us to determine the geometry of the seismicity (Section 3.1), the source
29 mechanisms of many of these earthquakes (Section 3.4) and the velocity structure of the surrounding
30 material (Section 4) at higher precision than was possible before by just using regional or teleseismic
31 data. We then extended our analysis to global seismic data for the largest digitally recorded Hindu Kush
32 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 intermediate-depth seismicity (blue in Fig. 1a), north-east of the Hindu Kush, has been associated to Asian lithosphere subduction (Schneider et al., 2013; Sippl et al., 2013a), forced to delaminate by a northward penetrating Indian indenter (Kufner et al., 2016). Thus, it is only indirectly related to the Hindu Kush intermediate-depth seismicity (black in Fig. 1a).

3 Seismicity analysis

3.1 Local earthquake catalog and travel time tomography

Our local earthquake catalog comprises all earthquakes registered during July 2012 to April 2014 by the TIPTIMON seismic deployment (Schurr et al., 2012, 2013) and few additional permanent stations (TJ network and KBL station (IU network)), jointly relocated with a subset of the catalog from Sippl et al. (2013b), based on the TIPAGE and FERGHANA networks (Mechie et al., 2012; Feld et al. 2015). The TIPTIMON network was operating between 2012-14 in the Tajik basin, Hindu Kush and western

Pamir; the TIPAGE and FERGHANA networks between 2008-10 in the Pamir and Tian Shan. TIPAGE and TIPTIMON share several common stations in the western Pamir. Thus, the joint network allowed us to illuminate the subsurface beneath both Pamir and Hindu Kush. Hypocenters were initially obtained using an automated procedure for event detection, location and relocation (Sippl et al., 2013b). All events included in the final TIPTIMON catalog from this initial step were required to have a root mean square (RMS) residual smaller than two seconds, at least five P picks and at least one S pick.

We used a high quality subset of this catalog (5298 events; $\sim 101,000$ P and $\sim 45,000$ S picks) to calculate a local earthquake tomography utilizing the software *simulps* (Evans et al. (1994) and references therein). Our velocity model was parameterized with $19 \times 19 \times 17$ nodes in west, north and depth direction (dark red crosses in Fig. 1a). Node spacing at the center ($37^\circ\text{N}/71.5^\circ\text{E}$) of the model domain was 35 km, which roughly equals to the average station spacing in the Tajik basin, and was increased towards the edges. Depth layers were implemented in 15 km intervals in the crust and increased to 20 and 30 km intervals in the mantle. A starting minimum 1D P-wave velocity model was derived using the software *velest* (Kissling et al., 1994). Damping parameters for the tomography were determined from trade-off curves seeking to find the optimum between model roughness and data variance. Station corrections were damped such that no systematic variation with tectonic structures could be observed. To ensure a stable inversion, we kept the initial earthquake hypocenters fixed for the first two iterations. After the 10th iteration, the inversion was stopped. The chosen damping parameters yielded a reduction of the data variance by 80% and 77% for v_p (P-wave velocity) and v_p/v_s (P-wave to S-wave velocity ratio), respectively. The model resolution was assessed from synthetic tests and by analyzing the resolution matrix (see Section A1 and Figs. A1-A3 for details on the model creation and synthetic tests).

Based on this regional 3D velocity model the complete seismic catalogue was relocated: First using a single event (implemented in *simulps*) and then a double difference relocation scheme (*hypoDD3D* - Waldhauser, 2001). Absolute errors were estimated in *NonLinLoc* (Lomax, 2000) using the inversion approach of Tarantola and Valette (1982) for event location. Relative errors were obtained from *hypoDD3D* applying the singular value decomposition mode. The joint catalog west of 71.8°E , which will be primarily discussed in the following, consists of 4369 events, 94% thereof from the TIPTIMON deployment. The mean RMS of the single event locations is 0.23 seconds. The average absolute location uncertainty is 4.9 km (this value refers to the radius of a sphere with the same volume as the error ellipsoids calculated in *NonLinLoc*). 90.3% of all events could be relocated with the double difference

96 scheme. The average relative error of these events is ± 1.9 km (a table with all intermediate depth hypo-
97 centers is attached as supplementary file; see Section A2 and Figs. A4/A5 for details on the catalog
98 composition and location errors).

99

100 **3.2 Relocation of all magnitude seven earthquakes since 1983**

101 None of the digitally recorded $M_w \geq 7$ Hindu Kush earthquakes occurred in the deployment time of our
102 local networks. However, these large events are listed in global catalogs in which they were located
103 using regional and teleseismic stations and global velocity models. To allow nevertheless a direct
104 comparison between the locations of these large events relative to our high precision local earthquake
105 catalog, we implemented a relative relocation scheme: we derived station corrections for the
106 regional/teleseismic stations based on 15 representative earthquakes from our local catalog, also listed
107 in the global ISC and GEOFON catalogs (*master events*; Fig. 2, Tab. A1). These station corrections
108 then allowed us to transfer the hypocenters of the large Hindu Kush events into the framework of our
109 local catalog.

110 We derived corrections for two catalogs, i.e. the ISC catalog dating back to the 1980s and terminating
111 in 2013, and the GEOFON catalog for the remaining years until 2016. To avoid possibly misinterpreted
112 phase picks, only P, pP and S picks in the epicentral distance smaller than 90° were considered. For the
113 ISC catalog, travel time residuals larger than 9.5 seconds were excluded. For each master event, all
114 residuals of the same phase were reduced to have zero mean. The final correction term at each station
115 was calculated as the median of all available residuals. For a station to be included in the set of final
116 station corrections, we required at least two phase picks from the master events and the standard
117 deviation (std) from all residuals to be smaller than 0.5 seconds. For all steps involving travel time
118 calculation, the software NonLinLoc (Lomax et al., 2000) was used. In total, 680 (614 P, 47 pP and 19
119 S) and 572 (487 P, 78 pP, 7 S) station terms from 639 and 487 stations could be determined for the ISC
120 and GEOFON catalogs respectively (Fig. A6). These two station correction sets show similar trends as
121 both datasets are based on networks with a large overlap.

122 We relocated the five largest Hindu Kush events since 1983 (according to their moment magnitude
123 given in the Global Centroid Moment Tensor catalog (GCMT; Dziewoński et al., 1981; Ekström et al.,
124 2012)), 21 aftershocks of the 2015 event and the foreshock of the 2002 event (*relocation events*; see
125 Tabs. A2/3 for detailed event information). For each event only the station terms with matching phases
126 could be used (e.g. average of used phases for the aftershocks and $M_w \geq 7$ events of 31 and 215,

127 respectively). To assess the relocation error, we implemented three types of tests:

- 128 - We changed the set of station terms by varying the selection criteria (maximum std between
129 0.5-1.0 seconds; minimum number of picks 2-3). This test should serve as a measure of how
130 vulnerable the method is to wrong picks or how much the solution depends on individual
131 stations. Generally, the event locations were relatively robust towards these variations (average
132 ~ 0.1 -4 km horizontal and ~ 2 -4 km depth error; see example in Fig. 3).
- 133 - To assess the impact of station-event geometry we calculated for each master event an
134 individual set of station corrections from the remaining master events. We then relocated this
135 specific event from its position in the ISC/GEOFON catalog using a station geometry
136 mimicking the geometry that has been used for the *relocation event*. This approach only worked
137 if the remaining master events had enough suitable picks, thus, mainly when the smaller
138 aftershocks were used as test events. Location errors were always smaller than the initial offset
139 between the event hypocenter in the global and local catalogs and decreased when more stations
140 could be used for relocation ($\sim \leq 4$ km).
- 141 - As a final test, a magnitude 6.6 earthquake, which was listed in both global catalogs, was
142 relocated using the two different sets of station corrections. The relocated ISC and GEOFON
143 hypocenters overlap within their error ellipses (Tabs. A2/3).

144 Based on these tests, we concluded that the relocation scheme is reliable for the given error range and
145 the relocated events can be interpreted in the context of our local event catalog.

146

147 **3.3 Finite fault model for the $M_w=7.5$ Badakhshan 2015 event**

148 We calculated a finite fault slip model for the most recent and largest Hindu Kush earthquake from
149 October 2015 following Zhang et al. (2012). P-wave displacement records from 48 seismic stations
150 with epicentral distances between 15 - 90° were used to constrain the source (Fig. A7a). The hypocenter
151 determined by GEOFON and the nodal planes given in the GCMT catalog were used. In the inversion,
152 a 105 km long and 45 km wide fault was assumed, and discretized into $21 \times 9 = 189$ equal sub-faults of 5
153 km $\times$ 5 km dimension. We filtered the waveforms into the 0.01-0.4 Hz pass band to ensure that the
154 minimum wavelength of P waves were much larger than the sub-fault size.

155 The Green's functions were calculated with the reflectivity method (Wang, 1999) for the velocity and
156 density crustal model Crust2.0 (Bassin et al., 2000) and the mantle velocity model ak135. To constrain
157 the rupture velocity, we estimated first the centroid rupture velocity to ~ 1.3 km/s by calculating

158 azimuth-dependent apparent source time functions (ASTFs) of the earthquake. In the rupture process
159 inversion, the maximum rupture velocity was demanded to be larger than the average rupture velocity
160 of the earthquake centroid (1.5 km/s). Thus, we assumed a maximum rupture velocity of 2.5 km/s. The
161 length of the rupture window was 15 seconds. We tested the two nodal planes (plane 1: strike=104°,
162 dip=69°; plane 2: 280°/21°), but found they fit the data almost equally well (waveforms fits: Figs.
163 A7b/c; models and source time functions: Fig. A8). Maximum slip was 3.8 and 3.1 meters for nodal
164 plane 1 and 2, respectively. The rupture dimension for both planes was ~50 km along-strike and ~35
165 km along-dip.

166

167 **3.4 Earthquake source mechanisms for catalog events**

168 We collected 264 earthquake source mechanisms for the study region. 106 from the TIPAGE network
169 and catalog were published already in Kufner et al. (2016). 158 additional mechanisms were
170 determined here based on TIPTIMON data. For the 114 largest of these events ($3.5 \leq M_w \leq 5.6$), the
171 mechanisms were constrained by waveform modeling of full local and regional three component
172 displacement records (Nábělek and Xia, 1995; Schurr and Nábělek, 1999). All data traces were
173 inspected visually, problematic traces were removed, and filter bandwidth was adjusted depending on
174 the signal power (lower period: 10-15 s; upper period: 30-50 s). Green's functions were calculated for
175 the minimum 1D velocity model derived here (Fig. A1). Inversions were performed for several depths
176 around the initial hypocenter; the depth with the smallest variance was taken as the final centroid.

177 For 44 smaller events with favorable station-event geometry, the mechanisms were determined from
178 manually picked first motion polarities using the software HASH (Hardebeck and Shearer, 2002).
179 Based on an input set of polarity picks, event-station azimuths and take-off angles, HASH determines a
180 set of mechanisms explaining the observed polarities based on a grid search. The spread of all possible
181 solutions relative to the preferred one determines the quality of the solution. This quality can be
182 expressed in terms of the RMS fault plane uncertainty, which is the RMS angular difference of the
183 acceptable fault planes from the preferred plane (Kilb and Hardebeck, 2006). We derived 1329 first
184 motion picks, yielding an average of 30 picks per event. Take-off angles and event-station azimuths
185 were calculated in NonLinLoc (Lomax et al., 2000) based on our 3D velocity model (Sec. 3.1). All
186 mechanisms were visually inspected to ensure that the other possible fault planes indicated the same
187 faulting type than the preferred mechanism. The average RMS fault plane uncertainty of the 44
188 mechanisms shown here is 44° (min/max 20°/60°). All 264 mechanisms were plotted at their
189 hypocentral position in the relocated event catalog (see Figure A10 for detail regarding the subdivision

190 of the mechanisms with respect to recording time and applied method).

191

192 **3.5 Results of seismicity analysis**

193 Figure 4 shows our complete earthquake catalog with the relocated large events. The Hindu Kush
194 (symbols plotted with black outlines) and Pamir (blue outlines) seismic zones have different dips and
195 characteristics: the Pamir seismic zone forms an arcuate structure, offset northward relative to the
196 Hindu Kush seismicity. Most Pamir events cluster at ~100-120 km depth (histogram in Fig. 4d).
197 Hypocenters of Hindu Kush intermediate-depth earthquakes form a west-east striking curtain of
198 seismicity. The depth-earthquake count histogram shows two peaks, separated by a zone of reduced
199 seismic activity at ~160-180 km depth (Fig. 4d). In cross section, this aseismic region forms a vague
200 sub-horizontal seismic gap, which follows the Hindu Kush seismicity along-strike (Fig. 4c). In the
201 following, we will refer to the upper seismogenic portion of the Hindu Kush slab as the *shallow domain*
202 (~60-180 km depth), to the deeper portion as *deep domain* (~180-265 km depth). The shallow domain
203 structure dips clearly north, whereas the deeper domain is split in several subparallel earthquake
204 clusters with varying dip angles ('fingers', Figs. 4b, c). In contrast to the Pamir intermediate-depth
205 seismicity where the number of events decreases with depth, most Hindu Kush events, including the
206 relocated $M_w > 7$ events, occur in the deep domain.

207

208 Figures 5-7 zoom into the Hindu Kush seismicity, focusing on the seismicity distribution, the rupture
209 mechanisms and the relation to the $M_w > 7$ events. All $M_w > 7$ events and most of the earthquakes in our
210 catalog have down-dip extensional mechanisms (Fig. 5a) with vertically dipping tension (T) axes (Fig.
211 6a) and pressure (P) axes indicating north-south compression, oriented roughly perpendicular to the
212 strike of the seismogenic structure (Fig. 5b). Strike-slip events in map view, which would indicate
213 along-strike extension in a vertically dipping structure, are generally restricted to the margins of the
214 seismogenic structures. Seismicity in the shallow domain is more diffuse compared to the deep domain,
215 where seismicity arranges to several narrow "fingers" (labels F1-F4 in Fig. 6).

216 The relation between seismically active and aseismic regions in the deep domain of the Hindu Kush
217 slab can be further explored by investigating the October 2015, M_w 7.5 Badakhshan earthquake. The
218 event locates on the same seismogenic finger as the second largest event (1983, M_w =7.4; F2 in Fig. 6c)
219 and both earthquakes have a similar down-dip extensional focal mechanism. In Figure 6c, we plot the
220 steeper of the two tested nodal planes of our finite fault slip model (dip=69°). This fault plane has the

same dip as the southward dipping structure outlined by the relocated aftershocks (see also north-south cross sections in Fig. 7). Its dip also accurately parallels the plane outlined by the background seismicity (label S1 in Fig. 7). Based on the seismicity and aftershock distribution, we consider this sub-vertical nodal plane the more likely fault plane. The finite fault solution further indicates that maximum slip occurred west of the hypocenter. Slip propagated westward into a seismic gap and tapers to zero where seismicity in the local catalog revives and where the relocated aftershocks cluster (Fig. 6c).

The embedment of these structures into the surrounding seismic velocity architecture is shown in Figure 7. Local earthquake tomography resolves a thick crust beneath the Hindu Kush ($v_p \leq 7.8$ down to ~ 60 km). The low velocities of the crust extend into the mantle as a zone of localized low v_p . The upper part of the Hindu Kush seismicity-curtain sets in approximately at the crust-mantle boundary. At mantle depths, the low velocity domain spatially coincides with the shallow domain of intermediate-depth seismicity. At ~ 160 - 180 km depth, this low velocity zone thickens to a blob-like anomaly and then terminates. The deep domain of seismicity is located in a high velocity area, not distinguishable from the ambient mantle velocities. The change from high velocity to low velocity also coincides with the steepening of the dip of the seismic zone and the transition from the shallow to the deep seismic domain defined above. The north-south cross sections further show that the dip angle of the deep seismogenic ‘fingers’ changes along-strike: In the very west the seismogenic structure dips near-vertically (Profile 0 in Fig. 7). In the center (Profiles 1 and 2), it is partly overturned (labels S1/2). In the east (Profiles 3 and 4), it is split into a north- and a south dipping sub-branch (labels N1/2).

4 Character of the low velocity zone resolved in local earthquake tomography

We used synthetic tests to further constrain the characteristics of the Hindu Kush low velocity zone. We were particularly interested in the resolvable limits of its thickness, penetration depth and amplitude and their respective trade-offs. This information is important for interpreting the anomaly in a geodynamic context, e.g., whether the low velocity anomaly could present subducted crust. We constructed a synthetic velocity model with two lithospheric slabs, mimicking the situation under Pamir and Hindu Kush. Each slab consisted of a layer of mantle lithosphere (50 km thickness, $v_p = 8.3$ km/s), overlain by a crustal layer. The overall geometry of the model (Fig. 8b) was constrained by interpolating two planes through the seismicity beneath Pamir and Hindu Kush. Our 1D velocity model (Fig. A1) was used in the background with a constant v_p/v_s ratio of 1.73. To better understand the effect

252 of the tomography on such anomalies, we tested four end member cases (Figs. 8c-f) by varying
253 thickness (10/20 km) and intensity ($v_p=7.3/7.7$ km/s) of the low velocity layer beneath the Hindu Kush.
254 To gauge vertical smearing the low velocity layer terminated at 160 km in one test; in the other tests at
255 280 km. The crustal layer beneath the Pamir had a thickness of 20 km and v_p of 6.9 km/s in all tests as
256 suggested by previous studies (Schneider et al., 2013; Sippl et al., 2013a). Rays were traced on a grid
257 with 1×1 km spacing using a 3D finite difference code, which allowed us to construct velocity
258 anomalies much finer than the inversion grid (Haberland et al., 2009, and references therein). Gaussian
259 noise was added to the synthetic travel times, scaled with the standard deviation of the quality class
260 which had been assigned to each pick (min/max std of 0.05/0.2 seconds). Synthetic travel-time data
261 was calculated for the same event-station distribution as in the real data.

262 Results along Profile 1 of Figure 7 are plotted in Figures 8c-f: Generally, the amplitudes of the
263 recovered low velocity zones are lower than the input. This effect is largest at depths >100 km and in
264 the two tests with the thinnest subducted crustal layer and the smallest low velocity amplitude.
265 However, in the two tests with a thicker low velocity zone and a higher v_p contrast (20 km
266 thickness/ $v_p=7.3$ km/s), the recovered anomaly appears as a continuous low velocity zone and with
267 well recovered geometry. The model with the shallower terminating low velocity layer (Fig. 8c) can
268 clearly be distinguished from the model with the anomaly penetrating deeper. Due to the amplitude
269 decrease at the edge of the low velocity zone, the subducting crustal layer even appears to terminate
270 ~ 20 km shallower in the recovered velocity model. In all models, the outline of the mantle lithosphere
271 (high velocity structure) appears patchy and not well recovered because it is located at the edge of the
272 recovered region (outlined by the white thick contour in Fig. 7; see Section A1.3 for further resolution
273 tests).

274 Comparing the output of the synthetic tests on our local velocity model with the real data (Figs. 7 and
275 8a), the low velocity structure in the upper mantle beneath the Hindu Kush appears thicker and more
276 intense than in any of the synthetic tests. However, it terminates at ~ 160 - 180 km. Thus, we can
277 conclude that a layer of low velocity material, probably thicker than ~ 20 km and/or velocities lower
278 than 7.3 km/s is present in the mantle beneath the Hindu Kush. This zone does not penetrate beyond the
279 deepest earthquakes and probably terminates at ~ 180 km depth.

280

281 **5 Strain rate during slab detachment**

282 The Hindu Kush intermediate-depth earthquakes occur in a small volume (Figs. 4-7). Following

283 Kostrov (1974), we can obtain the average strain rate tensor by summing up the earthquake moment
284 tensors in the volume:

$$\dot{\varepsilon}_{ij} = \frac{1}{2\mu V t} \sum_{k=1}^N M_{ij}^{(k)} \quad \text{Equation (1)}$$

286 where N is the total number of earthquakes in a given time interval t , V is the considered volume, M_{ij}
287 are the seismic moment tensor elements of the k^{th} event and μ is the shear modulus.

288 We used all earthquakes listed in the GCMT catalog from 1977 to 2013 (Fig. A11) to estimate the strain
289 rate in the seismically active part of the Hindu Kush slab. To extend the catalog until present, we
290 included the October 2015 M_w 7.5 event (no other earthquake between 2013 and autumn 2015 was
291 stronger than M_w 6.0, thus would significantly affect our calculation). Calculations were done in a
292 Cartesian coordinate system and tensor elements listed in the GCMT solutions were changed
293 accordingly (Holt, 1995; Lorinczi and Houseman, 2009). We estimated the strain rate tensor for the
294 shallow and deep domain of the seismic zone separately. To constrain the volume, we started from the
295 plane fitted through the earthquakes (Fig. 8b) and used a seismogenic thickness of 15 km. We repeated
296 the calculation by further subdividing the shallow and deep parts into three domains along-strike,
297 corresponding roughly to the seismogenic fingers identified earlier (e.g. Fig. 6). The shear modulus was
298 set to $6.6 \times 10^{10} \text{ N/m}^2$, which is its value in the upper mantle according to the PREM earth model
299 (Dziewoński and Anderson, 1981).

300 To estimate uncertainties of the strain rate tensors, we ran a sensitivity analyses over all parameters in
301 Equation (1). The final error was then deduced by error propagation over these variations. These
302 uncertainty estimates are visualized in Figure 9: Changing the volume by 25%, for instance, or
303 excluding 10 years of data change the maximum strain rate by $\sim 20\%$. The effect of changing the shear
304 modulus is smaller and changes the vertical strain rate by only $\sim 5\%$. However, the difference in strain
305 rate between the deep and the shallow part remained relatively stable upon such variations.

306 In Figure 6b, the strain rate tensors are plotted in a stereonet, next to the focal mechanisms from the
307 local earthquake catalog. The strain rate tensors reveal a vertical extensional, north-south
308 compressional regime. NW-SE compression dominates in the shallow part and NNE-SSW compression
309 dominates in the deeper part, which is similar to the P- and T-axes of the large earthquakes (Figs. 5b
310 and 6a). The maximum vertical extension rate is 42% per Myr ($(0.13 \pm 0.035) \times 10^{-13} \text{ s}^{-1}$) and 6% per
311 Myr ($(0.21 \pm 0.11) \times 10^{-14} \text{ s}^{-1}$) in the deeper and shallow part, respectively (Fig. 9; Tab. A4). Subdividing
312 the volume into three seismically active segments along-strike, the largest strain rate occurs in the
313 central portion of the deep Hindu Kush seismicity, which contained the October 2015 event (Fig. 9a).

314 By integrating all vertical strain rates above, we can calculate the relative vertical displacement of a
315 point at the base of the shallow and deep domains. The relative vertical displacement rate of a point at
316 265 km is 43 mm/yr and 8 mm/yr for a point at 180 km (see Tab. A4 for detailed information on these
317 calculations). Thus, the separation rate between these two domains is higher than the convergence
318 velocity at the surface.

319

320 **6 Discussion and interpretation – a break-off scenario for the Hindu Kush slab**

321 **6.1 Subduction of continental crust and rate of slab detachment**

322 We interpret the low velocity zone in the mantle beneath the Hindu Kush as subducting continental
323 crust based on its characteristics (thickness $\sim \geq 20$ km; $v_p \sim \leq 7.3$ km/s; see Section 4). Velocities slightly
324 above 7 km/s at depths > 60 km might occur in rocks with compositions typical for lower or middle
325 crust (Sobolev and Babeyko, 1994; Hacker et al., 2011). According to our synthetic tests, the crustal
326 layer in the mantle beneath the Hindu Kush is thicker than typical oceanic or lower crust alone, but is in
327 turn thinner than the whole Hindu Kush crust. Thus, these tests suggest a scenario in which a layer of
328 lower and possibly middle crust subducts. Additionally, above a depth of ~ 180 km our images look
329 very similar to the situation beneath the Pamir, where subduction of continental crust was proposed
330 based on seismological studies and petrological modelling (Scheider et al., 2013; Sippl et al., 2013a).
331 The accumulation of low velocity material at ~ 180 km depth imaged beneath the Hindu Kush might
332 then represent the level where parts of the lower crust eclogitize, accompanied by a density and v_p
333 increase (Sobolev and Babeyko, 1994; Krystopowicz and Currie, 2013), and where the remaining
334 middle crust resists subduction and pools (schematically shown in Fig. 10b).

335 Deeper in the mantle, the seismic characteristics beneath Pamir and Hindu Kush differ: The overturned
336 dip of the deeper Hindu Kush seismic zone (S1 in Fig. 7) and the accumulation of the largest
337 earthquakes in a deep cluster are exclusive to the Hindu Kush. These properties must be directly related
338 to the ongoing slab break-off, which apparently splits the Hindu Kush slab into two distinct depth
339 domains. The interface along which the final break-off happens seems to develop at the base of the
340 subducted crust. Using the strain rates from Figure 9, it is possible to calculate how fast the break-off
341 proceeds: the distance of a point at 180 km depth and a point at 265 km depth, for instance, would have
342 increased by ~ 150 km after 4 Ma. Such a fast separation is in good agreement with numerical
343 modeling studies (Duretz et al., 2012; Magni et al., 2012; Duretz and Gerya, 2013) as well as seismicity
344 studies from Vrancea (Lorinczi and Houseman, 2009). These fast detachment rates also provide an

explanation why ongoing break-off is currently rarely observed. Further, as the separation between deep and shallow domains coincides with the change from low v_p to high v_p material, the depth at which the break-off initiates seems to depend critically on the maximum penetration depth of crustal material.

Zhan and Kanamori (2016) obtained a slip rate of 9.6 cm/yr for the Hindu Kush by computing the cumulative slip of all large events since 1949. Although not directly comparable, this value is higher than e.g. the average vertical displacement rate of 4.3 cm/yr calculated here as average for the bottom of the deep domain of the Hindu Kush (Tab. A4). This difference can be explained as Zhan and Kanamori (2016) assume a single fault and not a seismogenic volume. Decreasing the seismogenic volume in Equation (1) has the strongest effect on the strain rate (Fig. 9). However, the relative strain rate difference between shallow and deep domain remains relatively stable upon such variations. This relative difference in turn, is the crucial parameter to constrain the speed of slab detachment, which we used here.

6.2 Along-strike propagating slab detachment

We observe not only a variation in the characteristics of the Hindu Kush seismicity with depth, but also along-strike. On a lithospheric scale, teleseismic tomography imaged a progressively opening horizontal tear in the subducting Hindu Kush slablet (Kufner et al., 2016). This together with the seismicity distribution suggests that the seismogenic characteristics of slab break-off might change during its advance. It was shown in thermomechanical numerical simulations that the dominant deformation mechanism during break-off can change from an initially simple-shear dominated regime, where a shear-zone through the mantle lithosphere develops, to a pure-shear dominated regime once the lithosphere is sufficiently thinned, resulting in the necking of the last connection (Duretz et al., 2012). These modeling results match the main characteristics we observe under the Hindu Kush astonishingly well (see the schematic sketch in Fig. 10a and the results in Figs. 6/7 for the following description):

The overturned dip of the seismogenic structure in the western Hindu Kush (profiles P1 and P2 in Fig. 7), the accumulation of large earthquakes with similar focal mechanisms, with the steeper of the two nodal planes almost perfectly matching the overturned plane delineated by the seismicity, and the termination of the low velocity zone could be explained by a developing mantle shear zone. The sharp kink in the plane outlined by the Hindu Kush seismicity, separating the shallow and deep domains might indicate the up-dip limit of such a shear-zone. By contrast, in the eastern Hindu Kush (profiles

P3 and P4), the deep seismic zone dips near-vertically and a sub-branch splits off from the main structure (N1/2 in Fig. 7). The splitting of the seismic zone into these two branches might indicate a strain localization at both sides of the nearly detached lithospheric slab. Thus, the eastern Hindu Kush could be already in the necking dominated stage of break-off, where shallow and detaching fragment are now only connected by extremely thinned lithosphere. Hence, we suggest that the Hindu Kush slab hosts an eastward propagating slab tear. The along-strike variation of seismic characteristics then mirrors a change of active deformation mechanism with advance of this tear.

6.3 Processes triggering intermediate-depth seismicity

Our observations on the seismic structures and style of faulting allow to narrow down the range of possible processes responsible for the intra-continental intermediate-depth seismicity. Seismicity in the shallow domain of the Hindu Kush seismic zone (~60-180 km depth) is less intense and more distributed in cross section compared to the deeper parts. Additionally, the earthquake source mechanisms in the shallow domain show more scatter (Fig. 5) and the seismicity appears to occur in subducting crustal rocks (Figs. 7/8; Sec. 6.1). The Bergen arc in Norway may be considered an accessible analog for the shallower intermediate-depth Hindu Kush seismicity. There, a network of eclogite-facies pseudotachylite veins in exhumed lower crustal rocks (exhumation depth ~60 km) testifies of past earthquakes, controlled by fluids penetrating into deep crustal shear-zones (Austrheim, 1987; Austrheim et al., 1996). However, partial eclogitization of subducted lower crust in the Hindu Kush reaches possibly much deeper than recorded by the Norwegian outcrops, as colder temperatures are preserved at larger depths due to faster subduction rates (Zhan and Kanamori, 2016). Eclogitization might be further delayed due to a high hydration level of the lower crust, e.g. as has been supposed for Indian lower crust underthrusting beneath the Himalayas (Hetényi et al., 2007).

The high seismic velocities at the depths of the deep seismicity (~180-265 km depth) prohibit large volumes of non-eclogitized crustal rocks there. Thus, mineral phase transitions in crustal rocks, possibly releasing fluids, seem to be unlikely here. Additionally, hydrous minerals in the mantle lithosphere might be less common than in oceanic subduction zones, where mantle dehydration has been suggested to trigger intermediate-depth seismicity (Kirby et al., 1996; Peyrat et al., 2006). Thielmann et al. (2015) showed from numerical modeling that grain size reduction might facilitate the initiation of thermal runaway, as it weakens the rocks. Localized shear along a lithospheric fault could cause grain size reduction. Thus, shear instability and thermal runaway might be a more likely

mechanism for sudden and fast failure in the deep domain of the Hindu Kush seismicity. Such a process was also suggested by Poli et al. (2016) based on the investigation of the radiation patterns of the latest large Hindu Kush earthquakes.

Seismicity in the deep domain of the Hindu Kush seismic zone forms to several distinct finger-like structures with varying dips (F1-4 in Fig. 6c). This pattern of alternating seismic and aseismic zones was also observed in previous studies (e.g. Pegler and Das, 1998; Bai and Zhang, 2015). We showed that the October 2015 earthquake rupture likely propagated into one of the quiet zones between two fingers. Although the slip pattern depends on choice of model parameters (e.g. trade-off between rupture velocity and rupture area), the observation of maximum slip west of the hypocenter is robust even for higher rupture velocities (Fig. A9). This spatial relation between large earthquakes and background seismicity suggests that the seismic zone consists of distinct patches, which behave differently in response to stresses (e.g. creeping and stick-slip segments). The clustering could be caused by inherited heterogeneities or due to processes linked to the break-off. Kufner et al. (2016) suggested that the slab currently subducting beneath the Hindu Kush is India's stretched margin. Accessible examples of fossil stretched margins, e.g. in the western Alps or the western Iberian margin, consist of symmetrically tilted blocks with a spacing from several to tens of kilometers (Coward et al., 1991; Pinheiro et al., 1996). This block size corresponds to the spacing of the Hindu Kush fingers. Thus, the different seismogenic pattern ('fingers' and 'gaps') in the deep domain of the Hindu Kush seismicity might arise from inherited fault structures built during the formation of the margin.

7 Conclusion

The Hindu Kush region in Central Asia hosts a nest of intense intermediate-depth seismicity (hypocenters between ~60 and 300 km depth; Pegler and Das, 1998; Sippl et al., 2013b) and frequent large earthquakes with moment magnitudes larger than seven (Poli et al., 2016, Zhan and Kanamori, 2016), which have been attributed to the detachment of a lithospheric slab (Koulakov and Sobolev, 2006; Lister et al., 2008, Kufner et al., 2016). Here, we used seismological data from temporarily deployed local and a few global stations to study the details of this slab detachment. Our results indicate that the intermediate-depth Hindu Kush seismicity is primarily driven by the down-dip extensional stress regime exerted by the foundering lithospheric slab. However, the seismicity exhibits different characteristics in its shallower (~60-180 km depth) and deeper (~180-265 km depth) domains. The shallower domain is seismically less active and coincides with a zone of low seismic P-

438 wave velocity, which we interpreted as subducting continental crust. The seismically more active
439 deeper domain is associated with a high seismic velocities. Most of the large earthquakes cluster in the
440 deeper domain. From a strain rate analysis we deduce that the deep portion of the slab is separating
441 from the shallower part. Such a separation could arise as the buoyant crustal material resists
442 subduction, whereas the earlier subducted lithospheric slab pulls from underneath. Based on the
443 geometry of the deep seismic domain we suggest that the break-off propagates along-strike. Whereas
444 the slab appears mostly intact in its western part, the break-off advances towards the east, featuring
445 shearing across the mantle lithosphere and finally necking along the remaining thin connection (Fig.
446 10). The large earthquakes most likely rupture along the lithospheric shearing plane as indicated by
447 their fault planes and the aftershock locations of the last large Hindu Kush earthquake. Along such an
448 interface, thermal runaway, possibly facilitated by grain size reduction in the shear-zone (Thielmann et
449 al., 2015), might be the dominant rupture mechanism. In contrast, the shallower portion of the
450 intermediate-depth seismicity coincides with the domain of subducted crustal. Thus, metamorphic
451 reactions in the subducting crustal layer could trigger the smaller and less frequent events there.

453 **Acknowledgements**

454 This research is part of the CAME project bundle TIPTIMON, funded by the German Federal Ministry
455 of Education and Research (support code 03G0809), and the DFG bundle TIPAGE (PAK 443). The
456 Geophysical Instrument Pool Potsdam (GIPP) provided seismic instruments for the temporary
457 networks. Temporary networks (FDSN codes: 7B 2008–2010; 6C 2009–2010 and 2013–2014 (Schurr
458 et al., 2013); 4B 2008–2009; 5C 2012–2014 (Schurr et al., 2012)) are archived at GEOFON data center,
459 permanent station waveform data can be obtained through the IRIS DMC (TJ – 7 stations used here
460 (PMP International (Tajikistan), 2005), IU – 1 station used here (Albuquerque Seismological
461 Laboratory (ASL)/USGS, 1988)), GEOFON (GE – 1 station (GEOFON Data Centre, 1993)). Focus
462 Humanitarian Assistance organized the seismometer deployment in Afghanistan. The TIPAGE and
463 TIPTIMON groups at GFZ Potsdam and TU Bergakademie Freiberg contributed fieldwork, technical
464 support and discussions. M. Dziggel helped in preparation of the schematic figures. Most plots were
465 created with the Generic Mapping Tool (GMT).

466 **Figure captions**

467 **Figure 1: Study region.** a) Topographic map of the Hindu Kush and surroundings. Yellow triangles are
468 the local seismic stations used in this study (triangles - TIPTIMON; inverted triangles -
469 TIPAGE/FERGHANA; light yellow - permanent stations (TJ network in Tajikistan and the station KBL
470 (IU network) in Kabul)). Intermediate-depth (depth >60 km) seismicity from this study is plotted in
471 blue beneath the Pamir and black beneath the Hindu Kush. Dark red crosses mark nodes used for local
472 earthquake tomography. Tectonic features are taken from Kufner et al. (2016). b) Depth section through
473 the Hindu Kush from teleseismic tomography. Seismicity in black. Velocity anomalies relative to ak135
474 larger than 1% are highlighted in brown. Crustal thickness (orange) was constrained from receiver
475 functions (modified from Kufner et al., 2016).

476

477 **Figure 2: Master events used to derive station corrections for event relocation of the largest**
478 **Hindu Kush earthquakes of the last 30 years.** a) Location of the master events in the local and in the
479 GEOFON catalog (top - map view; bottom - longitude-depth section). Small gray circles are all other
480 earthquakes from the local event catalog with depth greater than 130 km. The inset-globe shows the
481 location of the 561 global stations used by GEOFON to locate the master events. Red box outlines plot
482 domain of Figure 3. b) The same information as in a) but showing the ISC locations of the master
483 events instead.

484

485 **Figure 3: Examples for error assessment during the relocation of the October 2015 $M_w=7.5$**
486 **Hindu Kush events.** Yellow circle marks the GEOFON hypocenter (event time: 26.10.2015,
487 09:09:32), the colored diamonds mark the relocated hypocenters using different sets of station terms
488 (location of the regional/teleseismic stations used is shown in the inset globes with the same color than
489 the different hypocenters). Small gray circles are the events of the background catalog as shown in
490 Figure 2. See also Figure 2 for the location of the here plotted domain.

491

492 **Figure 4: Local earthquake catalog and relocated large events.** a) Map view: events are color cod-
493 ed by depth. The outline of the circles indicates the affinity of the earthquake to the Pamir or Hindu
494 Kush seismic zone. The relocated events from the global catalogs are plotted in pink. b,c) North-south-
495 and west-east-depth sections. Earthquakes shallower than 50 km are outlined in gray and are not dis-
496 cussed further in this paper. Other plotted features as in Subfigure 4a. (A data-file containing the here

497 plotted earthquake locations can be downloaded from Supplementary Material A3.) d) Depth vs. num-
498 ber of events histograms with 25 km bin width.

500 **Figure 5: Depth sections showing the Hindu Kush seismicity together with focal mechanisms.** a)
501 Local seismicity and beach ball representations of the focal mechanisms. The mechanisms are color
502 coded according to their faulting type (red - strike-slip; blue - normal; gray - thrust). Seismicity
503 associated with the Pamir and Hindu Kush seismic zone is outlined in blue and black, respectively.
504 Hypocenters and beach balls of large relocated events in purple. b) Pressure (P) axes of the events with
505 focal mechanism from the local catalog (black) and the relocated large events (purple, with year of the
506 event). Axes are normalized to one and projected into map view. Seismicity in each depth level is
507 plotted as in Subfigure 5a.

509 **Figure 6: Zoom into the Hindu Kush intermediate-depth seismicity and results of strain rate**
510 **calculation.** a) West-east cross section along 36.45°N . Hindu Kush seismicity in black, Pamir
511 seismicity in blue. Pink beach balls are projected focal mechanisms of the large relocated events. For
512 all catalog events where a mechanism could be determined, the T-axes are plotted in red (normalized to
513 one and projected into the cross section). The green outline denotes the 1 m slip contour of the October
514 2015 event constrained from the finite fault inversion (Sec. 3.3). Inset map shows profile location. b)
515 Stereonet plot (rotated into the west-east cross section) of the strain rate tensor computed from all
516 moment tensors listed in the GCMT catalog for the shallow domain of the Hindu Kush seismicity (60-
517 180 km depth) since 1976 (see Section 5 for further information). c) Zoom into the deep domain
518 illuminating details of the 2015 M_w 7.5 event: Star is the hypocenter of the main shock, pink dots the
519 relocated aftershocks. Contours denote its slip distribution constrained from the finite fault model. The
520 labels F1-F4 refer to features ('seismogenic fingers') mentioned in the text.

522 **Figure 7: Results of seismic tomography on north-south cross sections.** Contours in the sub-crustal
523 low velocity domains (green) are from 7.8 to 8.2 km/s in 0.2 km/s intervals and from 8.6 to 9.0 km/s in
524 0.1 km/s intervals in the high velocity domains (blue). Thick white contour depicts the minimum
525 resolution limit of the tomography (see Section A1.3 for explanation). Seismicity is plotted in a 15 km
526 projection range. Pink beach balls are projected focal mechanisms of the large relocated events. The
527 labels on top of the beach balls refer to the moment magnitude and the year of the specific event. The
528 2004-event is plotted twice at its relocated position using GEOFON and ISC data, respectively, to

529 illustrate the accuracy of the relocated events. The labels S1/2 and N1/2 refer to features mentioned in
530 the text. Projected topography is plotted in gray. All other annotations as in Figure 6.

531

532 **Figure 8: Synthetic tests to evaluate the resolution capability of the local earthquake tomography**
533 **with respect to a thin low velocity structure in the mantle.** a) Real data along profile P1 of Figure 7.
534 Contours in 0.25 km/s intervals. Thick white line depicts the resolution limit. b) Geometry of the input
535 anomalies for the synthetic test, constrained by interpolating planes through the seismicity: the Hindu
536 Kush (green) and Pamir (yellow) anomalies consist of both crust and mantle velocities. c-f) Four end
537 member synthetic tests where the penetration depth and the amplitude of the Hindu Kush crustal
538 anomaly were varied: the bottom panels show the input anomaly (v_p refers to the P-wave velocity of
539 the different structures). The top panels show the inversion result. Dashed white lines depict the outline
540 of the input anomalies.

541

542 **Figure 9: Results of the strain rate analysis.** a) Results of strain rate analysis separated in shallow
543 (gray; 60-180 km depth) and deep (blue; 180-265 km depth) domain for the whole longitudinal range
544 of the seismogenic portion (69°-71.5°E) and for three sub-regions (70°-70.6°E, 70.6°-71.0°E, 71°-
545 71.5°E). The error estimates are obtained from a sensitivity analysis. b) Example of the sensitivity
546 analysis for the whole longitudinal range of the seismogenic domain, varying the input parameters of
547 Equation (1): The values for the shear modulus span the range from 80 to 310 km depth in the PREM
548 earth model (Dziewoński and Anderson, 1981). The observation time is varied in two ways by
549 subsequently excluding data at the beginning and the ending of the observation period, respectively.
550 Varying the seismogenic thickness directly affects the volume (V) used in Equation (1).

551

552 **Figure 10: Interpretative sketch illustrating the proposed geodynamic processes during the**
553 **Hindu Kush slab break-off.** a) The along-strike variation in the geometry of the intermediate-depth
554 seismicity can be explained by an eastward advancing slab-tear. The bold red and yellow lines (P2/4)
555 mark the interpolated planes through the seismicity along the profiles in Figure 7. Only the mantle
556 lithosphere is shown here: from an initially intact slab (blue bold line), a shear plane develops through
557 the mantle lithosphere (P2, yellow line). As the lithosphere is thinned sufficiently, necking becomes the
558 dominant deformation mechanism (P4, red line). Largest earthquakes cluster on the shear-plane. b)
559 Interpretative sketches to demonstrate the involvement of crust in the continental subduction process,

560 which, in turn, affects the rupture mechanisms driving seismicity. The sketches are drawn on top of the
561 observational data shown in Figure 7: the slab pull drags buoyant lower and middle continental crust to
562 depth, attached to the descending mantle lithosphere. The lower crust undergoes gradual eclogitization.
563 Possibly released fluids and/or other metamorphic reactions trigger seismicity in the shallow domain
564 (small pink dots). Slab break-off through the mantle lithosphere occurs in a simple (profile P2) or pure
565 (P4) shear dominated regime. Only the denser, eclogitized fragments of the lower crust might continue
566 to descend, whereas the buoyant part of the crust detaches. Larger earthquakes (pink beach balls)
567 cluster along the shearing plane and to a minor extent in the necking zone. The labels N1/2 and S1/2
568 refer to the labels attached to the seismogenic structures in Figure 7.

569 **References:**

570 Austrheim, H. (1987). Eclogitization of lower crustal granulites by fluid migration through shear zones.
571 Earth and Planetary Science Letters, 81(2):221–232.

572

573 Austrheim, H., Erambert, M., and Boundy, T. M. (1996). Garnets recording deep crustal earthquakes.
574 Earth and Planetary Science Letters, 139(1):223–238.

575

576 Bai, L. and Zhang, T. (2015). Complex deformation pattern of the Pamir–Hindu Kush region inferred
577 from multi-scale double-difference earthquake relocations. Tectonophysics, 638:177–184.

578

579 Bassin, C. (2000). The current limits of resolution for surface wave tomography in North America. Eos
580 Trans. AGU.

581

582 Billington, S., Isacks, B. L., and Barazangi, M. (1977). Spatial distribution and focal mechanisms of
583 mantle earthquakes in the Hindu Kush–Pamir region: A contorted Benioff zone. Geology, 5(11):699–
584 704.

585

586 Coward, M., Gillcrist, R., and Trudgill, B. (1991). Extensional structures and their tectonic inversion in
587 the Western Alps. Geological Society, London, Special Publications, 56(1):93–112.

588

589 DeMets, C., Gordon, R. G., & Argus, D. F. (2010). Geologically current plate motions. Geophysical
590 Journal International, 181(1), 1-80.

591

592 Duretz, T. and Gerya, T. V. (2013). Slab detachment during continental collision: Influence of crustal
593 rheology and interaction with lithospheric delamination. Tectonophysics, 602:124–140.

594

595 Duretz, T., Schmalholz, S., and Gerya, T. V. (2012). Dynamics of slab detachment. Geochemistry, Ge-
596 ophysics, Geosystems, 13(3).

597

598 Dziewoński, A. M. and Anderson, D. L. (1981). Preliminary reference Earth model. *Physics of the*
599 *Earth and Planetary Interiors*, 25(4):297–356.

600

601 Dziewoński, A. M., Chou, T.-A., and Woodhouse, J. (1981). Determination of earthquake source pa-
602 rameters from waveform data for studies of global and regional seismicity. *Journal of Geophysical Re-*
603 *search: Solid Earth*, 86(B4):2,825–2,852.

604

605 Ekström, G., Nettles, M., and Dziewoński, A. M. (2012). The global CMT project 2004-2010: centroid-
606 moment tensors for 13,017 earthquakes. *Physics of the Earth and Planetary Interiors*, 200:1–9.

607

608 Evans, J. R., Eberhart-Phillips, D., and Thurber, C. (1994). User's manual for simulps12 for imaging
609 vp and vp/vs; a derivative of the "Thurber" tomographic inversion simul3 for local earthquakes and
610 explosions. Technical report, Open File Report 94–431, US Geological Survey.

611

612 Feld, C., Haberland, C., Schurr, B., Sippl, C., Wetzels, H.-U., Roessner, S., Ickrath, M., Abdybachaev,
613 U., and Orunbaev, S. (2015). Seismotectonic study of the Fergana Region (Southern Kyrgyzstan): dis-
614 tribution and kinematics of local seismicity. *Earth, Planets and Space*, 67(1):1-13.

615

616 GEOFON (2016). GEOFON earthquake bulletins, On-line Bulletin. GermanResearchCentre for Geo-
617 sciences. <http://geofon.gfz-potsdam.de/>.

618

619 Haberland, C., Rietbrock, A., Lange, D., Bataille, K., and Dahm, T. (2009). Structure of the
620 seismogenic zone of the southcentral Chilean margin revealed by local earthquake traveltime tomogra-
621 phy. *Journal of Geophysical Research: Solid Earth*, 114(B1).

622

623 Hacker, B., Kelemen, P. B., and Behn, M. D. (2011). Differentiation of the continental crust by
624 relamination. *Earth and Planetary Science Letters*, 307(3):501–516.

625

626 Hardebeck, J. L. and Shearer, P. M. (2002). A new method for determining first-motion focal mecha-

627 nisms. *Bulletin of the Seismological Society of America*, 92(6):2264–2276.

628

629 Hetényi, G., Cattin, R., Brunet, F., Bollinger, L., Vergne, J., Nábělek, J. L., and Diament, M. (2007).
630 Density distribution of the India plate beneath the Tibetan plateau: geophysical and petrological con-
631 straints on the kinetics of lower-crustal eclogitization. *Earth and Planetary Science Letters*, 264(1):226–
632 244.

633

634 Holt, W. E. (1995). Flow fields within the Tonga slab determined from the moment tensors of deep
635 earthquakes. *Geophysical Research Letters*, 22(8):989–992.

636

637 Kilb, D. and Hardebeck, J. L. (2006). Fault parameter constraints using relocated earthquakes: a valida-
638 tion of first-motion focal-mechanism data. *Bulletin of the Seismological Society of America*,
639 96(3):1140–1158.

640

641 Kirby, S., Engdahl, R. E., & Denlinger, R. (1996). Intermediate-depth intraslab earthquakes and arc
642 volcanism as physical expressions of crustal and uppermost mantle metamorphism in subducting slabs.
643 *Subduction top to bottom*, 195-214.

644

645 Kissling, E., Ellsworth, W., Eberhart-Phillips, D., and Kradolfer, U. (1994). Initial reference models in
646 local earthquake tomography. *Journal of Geophysical Research*, 99(B10):19,635–19,646.

647

648 Kostrov, V. (1974). Seismic moment and energy of earthquakes, and seismic flow of rock. *Physics of*
649 *the Solid Earth*, 1:13–21.

650

651 Koulakov, I. and Sobolev, S. (2006). A tomographic image of Indian lithosphere break-off beneath the
652 Pamir–Hindukush region. *Geophysical Journal International*, 164(2):425–440.

653

654 Kufner, S.-K., Schurr, B., Sippl, C., Yuan, X., Ratschbacher, L., s/of Mohammad Akbar, A., Ischuk,

655 A., Murodkulov, S., Schneider, F. M., Mechie, J., and Tilmann, F. (2016). Deep India meets deep Asia:
 656 Lithospheric indentation, delamination and break-off under Pamir and Hindu Kush (Central Asia).
 657 Earth and Planetary Science Letters, 435:171–184.
 658

659 Lister, G., Kennett, B., Richards, S., and Forster, M. (2008). Boudinage of a stretching slablet implicat-
 660 ed in earthquakes beneath the Hindu Kush. Nature Geoscience, 1(3):196–201.
 661

662 Lomax, A., Virieux, J., Volant, P., and Berge-Thierry, C. (2000). Probabilistic earthquake location in
 663 3D and layered models. In Advances in seismic event location, edited by C. Thurber and N.
 664 Rabinowitz, Kluwer, Amsterdam, pp. 101–134.
 665

666 Lorinczi, P. and Houseman, G. (2009). Lithospheric gravitational instability beneath the Southeast
 667 Carpathians. Tectonophysics, 474(1):322–336.
 668

669 Magni, V., Van Hunen, J., Funicello, F., and Faccenna, C. (2012). Numerical models of slab migration
 670 in continental collision zones. Solid Earth, 3(2):293.
 671

672 Mechie, J., Yuan, X., Schurr, B., Schneider, F. M., Sippl, C., Ratschbacher, L., Minaev, V., Gadoev,
 673 M., Oimahmadov, I., Abdybachaev, U., et al. (2012). Crustal and uppermost mantle velocity structure
 674 along a profile across the Pamir and southern Tien Shan as derived from project TIPAGE wide-angle
 675 seismic data. Geophysical Journal International, 188(2):385–407.
 676

677 Nábělek, J. and Xia, G. (1995). Momenttensor analysis using regional data: Application to the 25
 678 March, 1993, Scotts Mills, Oregon, Earthquake. Geophysical Research Letters, 22(1):13–16.
 679

680 Pegler, G. and Das, S. (1998). An enhanced image of the Pamir–Hindu Kush seismic zone from relo-
 681 cated earthquake hypocentres. Geophysical Journal International, 134(2):573–595.
 682

683 Peyrat, S., Campos, J., De Chabaliér, J., Pérez, A., Bonvalot, S., Bouin, M.-P., Legrand, D., Nercessian,
684 A., Charade, O., Patau, G., et al. (2006). Tarapaca intermediate-depth earthquake (mw 7.7, 2005,
685 northern chile): A slab-pull event with horizontal fault plane constrained from seismologic and geodetic
686 observations. *Geophysical research letters*, 33(22).

687

688 Pinheiro, L., Wilson, R., Pena dos Reis, R., Whitmarsh, R., and Ribeiro, A. (1996). The western Iberia
689 margin: a geophysical and geological overview. In *Proceedings-Ocean Drilling Program Scientific Re-*
690 *sults*, pages 3–26. National science foundation.

691

692 Poli, P., Prieto, G., Rivera, E., and Ruiz, S. (2016). Earthquakes initiation and thermal shear instability
693 in the Hindu-Kush intermediate-depth nest. *Geophysical Research Letters*, 308:131–190.

694

695 Schneider, F. M. (2014). *Imaging an Intra-continental Subduction in Central Asia with Teleseismic*
696 *Receiver Functions*. Doctoral thesis, Freie Universität Berlin, Germany, 151 pp.

697

698 Schneider, F. M., Yuan, X., Schurr, B., Mechie, J., Sippl, C., Haberland, C., Minaev, V., Oimahmadov,
699 I., Gadoev, M., Radjabov, N., et al. (2013). Seismic imaging of subducting continental lower crust be-
700 neath the Pamir. *Earth and Planetary Science Letters*, 375:101–112.

701

702 Schurr, B. and Nábělek, J. (1999). New techniques for the analysis of earthquake sources from local
703 array data with an application to the 1993 Scotts Mills, Oregon, aftershock sequence. *Geophysical*
704 *Journal International*, 137(3):585–600.

705

706 Schurr, B., Yuan, X., Haberland, C., and Kufner, S.-K. (2012). TIPTIMON (Tien Shan-Pamir Monitor-
707 ing Program) TAJIKISTAN (2012/2014). Deutsches GeoForschungsZentrum GFZ.

708

709 Schurr, B., Yuan, X., Haberland, C., and Kufner, S.-K. (2013). TIPTIMON (Tien Shan-Pamir Monitor-
710 ing Program) AFGHANISTAN (2013/2014). Deutsches GeoForschungsZentrum GFZ.

711

712 Sippl, C., Schurr, B., Tymphel, J., Angiboust, S., Mechie, J., Yuan, X., Schneider, F. M., Sobolev, S. V.,
713 Ratschbacher, L., and Haberland, C. (2013a). Deep burial of Asian continental crust beneath the Pamir
714 imaged with local earthquake tomography. *Earth and Planetary Science Letters*, 384:165–177.

715

716 Sippl, C., Schurr, B., Yuan, X., Mechie, J., Schneider, F. M., Gadoev, M., Orunbaev, S., Oimahmadov,
717 I., Haberland, C., Abdybachaev, U., et al. (2013b). Geometry of the Pamir-Hindu Kush intermediate-
718 depth earthquake zone from local seismic data. *Journal of Geophysical Research: Solid Earth*,
719 118(4):1438–1457.

720

721 Sobolev, S. V. and Babeyko, A. Y. (1994). Modeling of mineralogical composition, density and elastic
722 wave velocities in anhydrous magmatic rocks. *Surveys in Geophysics*, 15(5):515–544.

723

724 Tarantola, A., and Valette, B. (1982). Generalized nonlinear inverse problems solved using the least
725 squares criterion. *Reviews of Geophysics*, 20(2), 219-232.

726

727 Thielmann, M., Rozel, A., Kaus, B., and Ricard, Y. (2015). Intermediate-depth earthquake generation
728 and shear zone formation caused by grain size reduction and shear heating. *Geology*, 43(9):791–794.

729

730 USGS (2016). USGS earthquake bulletins, On-line Bulletin. United States Geological Survey.
731 <http://earthquake.usgs.gov/>.

732

733 Van der Voo, R., Spakman, W., and Bijwaard, H. (1999). Tethyan subducted slabs under India. *Earth*
734 *and Planetary Science Letters*, 171(1):7–20.

735

736 van Hinsbergen, D. J., Kapp, P., Dupont-Nivet, G., Lippert, P. C., DeCelles, P. G., and sTorsvik, T. H.
737 (2011). Restoration of Cenozoic deformation in Asia and the size of Greater India. *Tectonics*, 30(5).

738

739 van Hunen, J. and Allen, M. B. (2011). Continental collision and slab break-off: a comparison of 3-D
740 numerical models with observations. *Earth and Planetary Science Letters*, 302(1):27–37.
741

742 Waldhauser, F. (2001). hypoDD—A program to compute double-difference hypocenter locations. Tech-
743 nical report, Open File Report 94–431, US Geological Survey, 01-113, 25 pp.
744

745 Wang, R. (1999). A simple orthonormalization method for stable and efficient computation of Green’s
746 functions. *Bulletin of the Seismological Society of America*, 89(3):733–741.
747

748 Zhan, Z. and Kanamori, H. (2016). Recurring large deep earthquakes in Hindu Kush driven by a sink-
749 ing slab. *Geophysical Research Letters*, 43(14), 7433–7441.
750

751 Zhang, Y., Feng, W., Chen, Y., Xu, L., Li, Z., and Forrest, D. (2012). The 2009 L’Aquila MW 6.3
752 earthquake: a new technique to locate the hypocentre in the joint inversion of earthquake rupture pro-
753 cess. *Geophysical Journal International*, 191(3):1417–1426.
754

a) GEOFON - 561 stations

b) ISC - 1307 stations

a) focal mechanisms

b) pressure axes

a) strain rate variation with longitude

b) sensitivity analysis for error estimate