Earth and Planetary Science Letters 375 (2013) 101–112

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Seismic imaging of subducting continental lower crust beneath the Pamir

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ARTICLE INFO

Article history:
Received 19 March 2013
Received in revised form
7 May 2013
Accepted 8 May 2013
Editor: P. Shearer
Available online 4 June 2013

Keywords:
Pamir
subduction
continental crust
receiver function
Indian–Eurasian collision

ABSTRACT

Exhumation of ultra-high pressure metamorphic rocks testifies that the continental crust can subduct to significant depth into the mantle despite its buoyancy. However, direct observation of ongoing subduction of continental crust is rare. The Pamir is regarded as a possible place of active continental subduction because of the intermediate-depth seismicity, crustal xenoliths and estimates of crustal shortening versus convergence rates. Here we present for the first time receiver function images from a passive-source seismic array traversing the Tien Shan and the Pamir plateau showing southward subduction of Eurasian continental crust. In the eastern Pamir, we observe a southerly dipping 10–15 km thick low-velocity zone (LVZ) that extends from 50 km depth near the base of the crust to more than 150 km depth with a dip angle increasing to subvertical. While the upper- and mid-crustal material seems to be shortened and incorporated into the Pamir, the lower Eurasian crust detaches and subducts. In its deeper part (> 80 km) the LVZ envelopes the intermediate-depth earthquakes. Our observations imply that the complete arcuate intermediate depth seismic zone beneath the Pamir traces a slab of subducting Eurasian continental lower crust.

1. Introduction

The Pamir, situated north of the western Himalayan syntaxis, is thought to consist of the same collage of continental terranes as Tibet, that were progressively accreted to Eurasia prior to the Indian–Eurasian collision around 50 million yr ago (Schwab et al., 2004). To regard the Pamir as a place where subduction of continental crust may occur is motivated tectonically, since the correlation of the Pamir and Tibetan belts and sutures indicates that structures in the Pamir were translated northward by around 300 km with respect to Tibet. Thereby the crust connecting the Tajik and Tarim basins disappeared (Burtman and Molnar, 1993; Robinson et al., 2004), leading to the hypothesis that the Eurasian continental lithosphere is subducted along the Pamir's deformation front, which is today formed by the Main Pamir Thrust (MPT) (Burtman and Molnar, 1993; Hamburger et al., 1992; Sobel et al., 2013). Today, 10–15 mm/yr of concentrated shortening occurs across the MPT (Zubovich et al., 2010), which is about one-third of the total present-day Indian–Eurasian convergence rate. In the Pamir, the total amount of crustal shortening that occurred during the Cenozoic is even higher than in Tibet, since a similar amount of total convergence has been accommodated over a much smaller distance. Considering the relation of present to pre-Cenozoic crustal thicknesses, these extremely high amounts of crustal shortening in the Pamir yield realistic scenarios that require crustal excess (Schmidt et al., 2011). Besides, an indication for subduction of continental crust in this region was given by Roecker (1982), who first observed a low-velocity zone in the upper mantle dipping north beneath the Hindu Kush by local earthquake tomography. The most striking observation indicating continental subduction in the Pamir–Hindu Kush region is the vigorous intermediate-depth seismicity occurring from 70 to 250 km depth in this intra-continental setting. In map view, this seismicity forms a narrow S-shaped band of approximately 450 km length from the Hindu Kush in northeastern Afghanistan to the eastern Pamir (Fig. 1). The hypocentres of these mantle earthquakes form two separated Wadati–Benioff zones, one beneath the Pamir and one beneath the Hindu Kush (Burtman and Molnar, 1993; Fan et al., 1994; Negredo et al., 2007; Pegler and Das, 1998). N–S oriented cross sections reveal opposite dips for both zones. There is a long standing debate whether the geometry of the seismic

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http://dx.doi.org/10.1016/j.epsl.2013.05.015

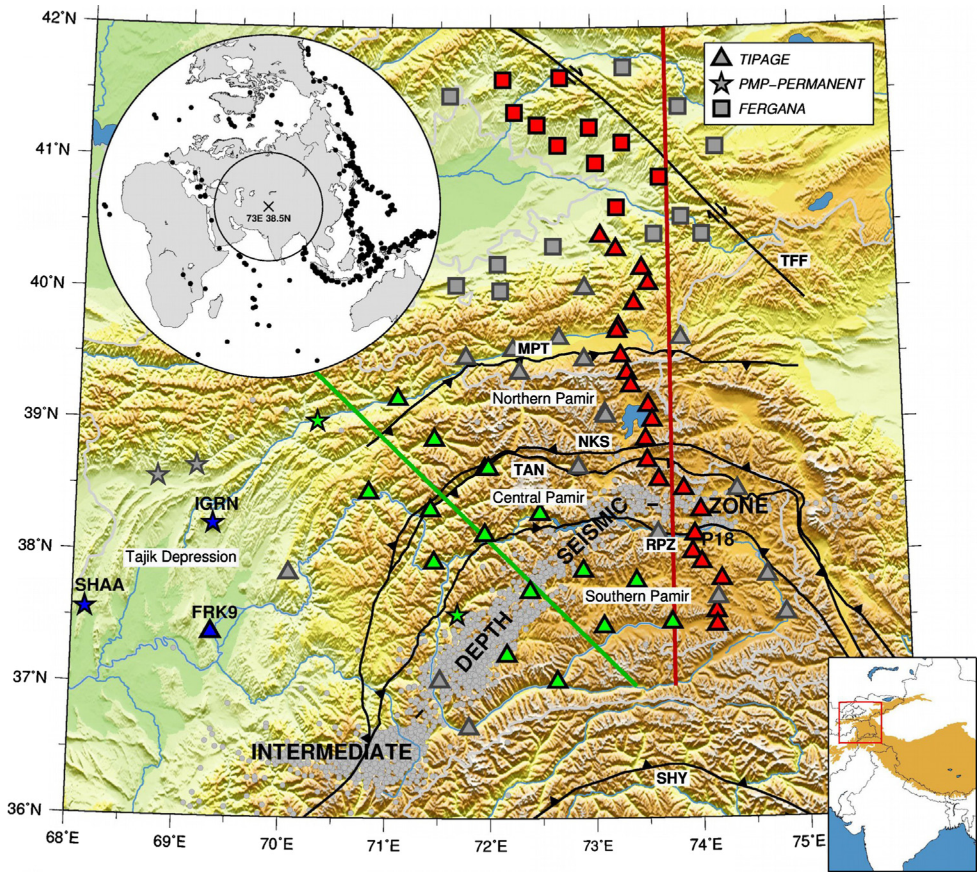

Fig. 1. Map of the Pamir with locations of the seismic stations used in this study. Major tectonic features such as sutures and faults marked in the map are (from north to south): Talas Fergana fault (TFF), Main Pamir thrust (MPT), Northern Pamir/Kunlun Suture (NKS), Tanymas Suture (TAN), Rushan Pshart Zone (RPZ), and Shyok suture (SHY). Red and green highlighted stations were used for the construction of the N–S and the NW–SE depth sections, respectively. The blue highlighted stations are used to determine the crustal thickness in the Tajik depression (Section 7.1). Insets show a map of teleseismic events used and a map of the Indian–Eurasian collision zone. The area of altitudes exceeding 3000 m is highlighted in brown, showing the area of Tibet, Himalaya, Pamir and Tien Shan. The red and green lines denote the projection planes of the N–S (Figs. 2 and 5) and NW–SE (Fig. 8) cross sections, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

zone results from a single originally northward dipping subduction interface, which was contorted and overturned under the eastern Pamir (Billington et al., 1977; Pegler and Das, 1998; Pavlis and Das, 2000), or if it is the result of two subduction zones, one dipping to the north beneath the Hindu Kush and one dipping to the south beneath the Pamir (Burtman and Molnar, 1993; Chatelain et al., 1980; Fan et al., 1994; Negredo et al., 2007). Recent high resolution earthquake locations from the local TIPAGE network (see next paragraph) show the seismicity in the Pamir as a curviplanar arc dipping to the south in the eastern Pamir and bending to an eastward dipping direction beneath the south-western Pamir, while the separated seismic zone beneath the Hindu Kush is a more complex structure striking east–west and dipping subvertically north to north-west (Sippl et al., 2013).

2. TIPAGE seismic experiment

The seismic data analyzed here were collected by a temporary experiment operated from 2008 to 2010 (Fig. 1). The experiment is the seismological component of the multi-disciplinary **Ti**en Shan **Pa**mir **Ge**odynamic Program (TIPAGE) (Mechie et al., 2012) and ran in two configurations. In the first year, 24 broadband stations were installed in the eastern Pamir forming a 350 km long north–south linear array from southern Kyrgyzstan to the Tajik–Afghan border with an average station spacing of 15 km. Additionally, eight broadband and eight short period stations were distributed in an areal network covering the whole Pamir. In the second year the network geometry was changed. Seventeen stations from the eastern Pamir linear array were relocated to densify the areal network in order to achieve an equidistant mesh with a station spacing of approximately 40 km. The areal array helped to accurately locate the local earthquakes (Sippl et al., 2013). We also included five permanent stations in western Tajikistan, operated by PMP International, Dushanbe. In the present work we concentrate on the receiver function analysis along the linear array. The profile was prolonged northward with 10 stations from the FERGANA seismic experiment, running from 2009 to 2010 in the Fergana Valley (Haberland et al., 2011).

3. Receiver function processing

The receiver function (RF) method is a widely used seismological tool to image crustal and upper mantle seismic discontinuities underneath seismic stations (Kind et al., 2012; Rondenay, 2009; Bostock, 2007). This technique identifies the discontinuities, e.g. the Moho, by detecting mode conversion from compressional (P) to shear (S) waves. The time delay between the converted wave (Ps) and the mother phase (P) determines the conversion depth. The amplitude and phase of the Ps conversions reflect the nature of the discontinuity, such as the sign, strength and sharpness of the velocity contrast. The kernel of the receiver function algorithm is composed of two main steps, a coordinate rotation that isolates the Ps converted waves from the P wave; and a deconvolution