Tectonophysics 584 (2013) 221–229

Contents lists available at SciVerse ScienceDirect

Tectonophysics

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

Crust–mantle coupling at the northern edge of the Tibetan plateau: Evidence from focal mechanisms and observations of seismic anisotropy

Vadim Levin [a,*], Guo-chin Dino Huang [a], Steven Roecker [b]

[a] Department of Earth and Planetary Sciences, Rutgers University, Piscataway, NJ, USA
[b] Department of Earth and Environmental Sciences, Rensellaer Polytechnic Institute, Troy, NY, USA

ARTICLE INFO

Article history:
Received 5 September 2011
Received in revised form 22 April 2012
Accepted 15 May 2012
Available online 25 May 2012

Keywords:
Continental lithosphere strength
Earthquake source mechanisms
Seismic anisotropy
Mantle deformation

ABSTRACT

The Tarim basin is distinct from the Tibetan plateau by the apparently low degree of internal deformation. Relative motion between the lithospheres of Tibet and Tarim likely results in coherent mantle deformation, with a diagnostic signature of anisotropic seismic wave speed. Birefringence (splitting) in core-refracted shear phases (SKS, PKS) observed along the Tibet–Tarim border is indicative of seismic anisotropy along their path. The mantle deformation direction inferred from shear wave splitting under the assumption of a single source of anisotropy is approximately E–W. The size of the splitting delays inferred in our analysis suggests that most of the anisotropic signature is coming from the mantle. Furthermore, our data suggest vertical stratification of rock fabric.

Focal mechanisms of regional earthquakes, both published and derived from new data, provide evidence for ~NNE–SSW compression within the Tarim basin north of the border with Tibet. This type of internal deformation in the lithosphere is consistent with its underthrusting (subduction?) beneath Tibet. Within the crust of the Tibetan plateau we find a more complex pattern suggestive of the ~E–W extension, and generally consistent with the sense of motion on the Altyn Tagh fault that extends along the Tibet–Tarim boundary. Therefore, at the Tibet–Tarim border we find close similarity between deformation directions within the crust of the plateau and within the upper mantle on both sides of the boundary. A plausible explanation of such similarity would be the coupling of the crust and the upper mantle, with no weak zone being present in the lower crust. One scenario for such coupling would involve an extension of a deformation zone associated with the Altyn Tagh fault into the uppermost mantle, making this fault zone very similar to a plate boundary.

1. Introduction

A key constraint on the distribution of strength in the lithosphere is the presence (or absence) of earthquakes in the lower crust and upper mantle. Arguments in favor of locating continental lithosphere's strength in both the upper crust and the uppermost mantle rely on observations of crustal deformation patterns (e.g., Royden et al., 1997), the long-term response of lithosphere to loads (glaciers, mountain belts) (e.g., Burov and Diament, 1996), and the rare but significant occurrence of subcrustal earthquakes in the continental lithosphere (e.g., Monsalve et al., 2006). This conceptual model envisages two "strong" layers (brittle upper crust, brittle uppermost mantle) separated by a "weak" lower crustal zone. Whether earthquakes do occur beneath the crust of the continental lithosphere is not universally accepted (e.g., Jackson, 2002; Maggi et al., 2000a, 2000b). The alternate model places the entire strength of the continental lithosphere in the brittle crust, and envisages a weak mantle lithosphere (e.g., Jackson, 2002; Maggi et al., 2000b). A key prediction of this model is the extreme paucity (possibly a total absence) of seismic activity in the upper mantle of the continents. Thus the presence or absence of earthquake activity below the crust–mantle transition in the continental lithosphere is a likely discriminant between the two end-member models. For earthquakes of $M>5.5$ in the continental lithosphere the determination of focal depth may be based on teleseismic data (e.g., Chen and Molnar, 1983; Maggi et al., 2000a). These earthquakes are not very frequent, and the short interval of the available instrumental seismic records (from 1960s to the present) has a potential to bias the overall distribution. Smaller events ($M<5.5$) are at least an order of magnitude more frequent, but it is difficult to obtain reliable locations and focal mechanisms for them using only teleseismic observations.

Linked with arguments regarding vertical distribution of strength in the lithosphere is the consideration of crust–mantle coupling in actively deforming regions. If the crust is strong throughout, it is likely to transfer the stress across the Moho, and we can expect coherent deformation of the crust and the uppermost mantle (e.g., England and McKenzie, 1982). In the weak lower crust scenario ductile flow is envisaged within it (e.g., Bendick et al., 2000; Molnar and Lyon-Caen, 1989; Royden et al., 2008), and consequently the deformation patterns of the crust and the upper mantle do not have to be linked. Interestingly, arguments in favor of both scenarios often depend on observations of directional dependence

---

* Corresponding author. Fax: +1 732 445 5312.
E-mail address: vlevin@rci.rutgers.edu (V. Levin).

0040-1951/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2012.05.013

(anisotropy) of seismic wave speed. Thus, Shapiro et al., 2004 interpret the discrepancy in speeds of vertically and horizontally polarized surface waves as evidence for "flattening" (and hence horizontal flow) of the middle crust of Tibet. On the other hand, Holt, 2000 and Flesch et al., 2001 use similarity between deformation directions predicted by crustal deformation simulations and the direction of fast shear wave speed in the upper mantle as evidence of coherent deformation throughout the lithosphere.

In this paper we focus on the northwestern part of the Tibetan plateau and the border with the Tarim basin (Fig. 1). This area is characterized by significant seismicity, including a recent Mw = 7.2 earthquake. Gravity modeling suggests Tarim lithosphere underthrusting the Tibetan plateau (Lyon-Caen and Molnar, 1984), while teleseismic imaging by Wittlinger et al. (2004) suggests the presence of the Tarim lithosphere in the upper mantle beneath the Tibetan plateau, a configuration consistent with subduction. The sinistral Altyn–Tagh Fault (ATF) is a major tectonic structure in this region. Evidence for an abrupt change in crustal thickness across it was reported by Wittlinger et al. (2004), while the compilation of active-source studies by Zhang et al. (2011) shows a gradual change from Tarim to Tibet. Numerous estimates of the motion rate on the ATF converge on ~10 mm/y (see review in Gold et al., 2011). How this motion is accommodated at depth is significant for the overall arguments on the lithospheric strength. Further east Zhang et al. (2007) combined GPS and geomorphological observations to argue for distributed "strike-slip" deformation in the crust around (primarily — south of) the ATF, while Hilley et al. (2009) used more recent GPS data in conjunction with earthquake cycle models to infer relatively high viscosity in the lower crust and the upper mantle adjacent to the ATF.

In a previously published study (Huang et al., 2011) we identified a number of moderate sized earthquakes beneath this region that have lower-crustal hypocenters. Their focal mechanisms show a mix of normal and strike-slip motion, and suggest an overall NNE–SSW compression in the deep part of the crust. Among nine earthquakes deeper than 40 km found in the region by us and others (Chen and Yang, 2004; Fan and Ni, 1989) only one, at the far eastern edge of the region, shows an oblique thrusting mechanism that would be consistent with subduction of the Tarim lithosphere.

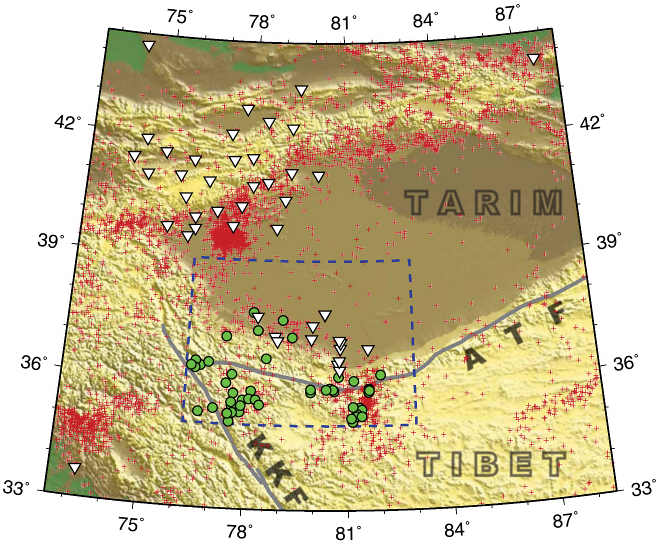

Fig. 1. A map of the study area and seismic stations used by this study. White inverse-triangles show the seismic stations that contributed data used for moment tensor inversion and shear wave splitting analysis. Blue dashed rectangle shows the study area, green circles denote all earthquakes with focal mechanisms, both published and determined in this study. Gray lines show faults: ATF — Altyn–Tagh, KKF — Karakorum. Seismic activity from 1997 to 2008 from the China Earthquake Administration catalog is shown by red crosses.

In this paper we present a compilation of published and newly determined focal mechanisms for northwestern Tibet and the adjacent Tarim basin that, taken together, characterize the stress within the crust and, possibly, the uppermost mantle. We also explore the deformation of the upper mantle using published and newly analyzed measurements of shear wave splitting in teleseismic core-refracted waves. A comparison of these independent measures of deformation in the crust and the mantle provides a means for assessing the degree of coupling between them.

2. Data

We use seismic data from various sources including temporary field deployments (Kao et al., 2001; Roecker et al., 2001; Wittlinger et al., 2004) and permanent seismic networks (the Kyrgyzstan telemetry seismic network— KN, and the Global Seismic Network — GSN). Selection of local earthquakes for focal mechanism analysis is based on the catalog archived by the China Earthquake Administration (CEA). In addition to the network of Kao et al. (2001) in the Tibet–Tarim border region, the seismic network in the Tien-Shan (Roecker et al., 2001) and the GSN station NIL in Pakistan provides good azimuthal constraints for seismic events that are located in our study area but were not recorded by Kao et al. (2001) (Fig. 1). Sites of the network operated by Kao et al. (2001) are listed in the Supplementary Table S1, all others are documented in the IRIS Data Management System archive (www.iris.edu). Events we analyze took place from 1992 to 2008.

To study teleseismic core-refracted shear waves (*PKS* and *SKS* phases) we use data recorded by the temporary network in the Tarim–Tibet border region (Kao et al., 2001). In the discussion we also incorporate previously published results from Levin et al. (2008) that used data from a Sino-French temporary deployment (Wittlinger et al. (2004)).

3. Methods

We perform regional Centroid Moment Tensor Inversion (rCMTI) analysis that uses full waveforms of the vertical, radial and transverse components to invert for earthquake source parameters and determine the focal depth (Huang et al., 2011; Kao et al., 1998). The algorithm involves testing a range of trial CMTs, and comparing resulting synthetic seismograms to selected observations. Azimuthal coverage and a choice of the velocity model influence the solution. While the synthetic seismogram computation technique we use is limited to 1D distributions of velocity, our algorithm allows the use of path-specific velocity models. We can thus accommodate, to a degree, the lateral changes in seismic wave speed within the region of study. Each source–receiver pair in the computation can have a path-specific velocity model. Given what we know about regional variations in wave speed, however, we incorporate only a small number of velocity profiles that reflect major changes in geologic structure.

Errors introduced into rCMTs by potentially mislocated epicenters can be significant (Huang, 2007). As a first step in determining new focal mechanisms we test available published epicenters for each earthquake and compare the inversion results. We use catalogs of CEA, PDE/USGS, the International Seismological Center (ISC), EHB (Engdahl et al., 1998), and the global CMT (Dziewonski et al., 1981; http://www.globalcmt.org). For those rCMTs with published epicenters resulting in a larger waveform misfit, we perform epicentral relocation with additional constraints of wave azimuth in grid search (Uhrhammer et al., 2001). Additional details on this procedure are described in Huang et al. (2011).

We use a basic cross-correlation technique (Levin et al., 1999), and also a group inversion method of Menke and Levin (2003) to perform shear wave splitting analysis. The former method assumes that a shear wave traversing an anisotropic region has been split exactly once, and