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Seismic structure and rheology of the crust under mainland China

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ABSTRACT

The crust and upper mantle in mainland China were relatively densely probed with wide-angle seismic profiling since 1958, and the data have provided constraints on the amalgamation and lithosphere deformation of the continent. Based on the collection and digitization of crustal P-wave velocity models along related wide-angle seismic profiles, we construct several crustal transects across major tectonic units in mainland China. In our study, we analyzed the seismic activity, and seismic energy releases during 1970 and 2010 along them. We present seismogenic layer distribution and calculate the yield stress envelopes of the lithosphere along the transects, yielding a better understanding of the lithosphere rheology strength beneath mainland China. Our results demonstrate that the crustal thicknesses of different tectonic provinces are distinctively different in mainland China. The average crustal thickness is greater than 65 km beneath the Tibetan Plateau, about 35 km beneath South China, and about 36–38 km beneath North China and Northeastern China. For the basins, the thickness is ~55 km beneath Qaidam, ~50 km beneath Tarim, ~40 km beneath Sichuan and ~35 km beneath Songliao. Our study also shows that the average seismic P-wave velocity is usually slower than the global average, equivalent with a more felsic composition of crust beneath the four tectonic blocks of mainland China resulting from the complex process of lithospheric evolution during Triassic and Cenozoic continent–continent and Mesozoic ocean–continent collisions. We identify characteristically different patterns of seismic activity distribution in different tectonic blocks, with bi-, or even tri-peak distribution of seismic concentration in South Tibet, which may suggest that crustal architecture and composition exert important control role in lithosphere deformation. The calculated yield stress envelopes of lithosphere in mainland China can be divided into three groups. The results indicate that the lithosphere rheology structure can be described by jelly sandwich model in eastern China, and crème brulee models with weak and strong lower crust corresponding to lithosphere beneath the western China and Kunlun orogenic belts, respectively. The spatial distribution of lithospheric rheology structure may provide important constraints on understanding of intra- or inter-plate deformation mechanism, and more studies are needed to further understand the tectonic process(es) accompanying different lithosphere rheology structures.

1. Introduction

Mainland China was mainly amalgamated by the Triassic collision between the South China and North China Craton along the central orogenic belt, reactivated by the Mesozoic subduction of the Pacific plate from the west, and the Cenozoic orogeny from the collision between Indian and Eurasia plates (Zhang et al., 1984; Ma, 1986). These tectonic events should pose their imprints upon seismic architecture, composition and rheology strength in the crust and upper mantle (Teng et al., 2003). The strength and rheology of the lithosphere play the fundamental control roles on its deformation (Panza, 1980), and can provide key information on understanding crustal deformation from the Triassic amalgamation and later reactivation by the Indian–Eurasia plate collision and Pacific subduction. Since the discovery of Moho discontinuity more than a century ago, seismic methods have played an important role in the geophysical exploration of the Earth's interior (Teng et al., 2003). Seismic structure of the crust and its physical properties, and imaging by deep seismic experiments deepen our understanding of the tectonics and kinematics of the complex continents (Christensen and Mooney, 1995). In China, pioneering experiments using deep seismic profiling has been carried out in the Qaidam Basin, to the north of Tibet, principally investigated by R.S. Zeng and J.W. Teng (Tseng and Kan, 1961; Tseng et al., 1961; Tseng, 1962; Tseng et al., 1965; Teng, 1979). These experiments were carried out in 1958 and were jointly sponsored by the Chinese Academy of Sciences and the Chinese Petroleum Ministry. During the same years, geophysical investigations were carried out in Karakorum (Marussi, 1964). Later on, and particularly

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from 1980 onwards, numerous wide-angle seismic profiles were obtained in China, especially following the occurrence of the disastrous 1966 Xingtai and 1976 Tangshan earthquakes. Standard processing and interpretative schemes were applied to deep seismic dataset of all these profiles even though these surveys were conducted under the auspices of various international programs, such as the 'International Geophysics Year' of the 1950s, the 'Crust and Upper Mantle Project' of the 1960s, the 'Geodynamics Project' of the 1970s, the 'International Geological Correlation Program', also of the 1970s, the 'International Lithosphere Program' of the 1980s, and the 'Continental and Ocean Drilling Program' of the 1980s and 1990s. To date, more than 80,000 km of wide-angle seismic profiles and about 10,000 km of reflection seismic profiles have been obtained (Su et al., 1984; Kan et al., 1986; Kan et al., 1988; Alsdorf et al., 1988; Program-8301 Cooperation Group, 1988; Hu et al., 1988; Li et al., 1991; Sun et al., 1988; Wu et al., 1991; Wang et al., 1993; Wang et al., 1997; Wang et al., 2001; Wang et al., 2002; Teng et al., 1997; Li and Mooney, 1998; Li et al., 2006; Gao et al., 1999; Gao et al., 2001; Kong et al., 1999; Wang and Qian, 2000; Kao et al., 2001; Yan et al., 2001; Zhao et al., 2001b, 2003b; Wang et al., 2000; Wang et al., 2003a,b; Jiang et al., 2006; Zhang et al., 2000a,b; Zhang et al., 2002b, 2002c, 2002d; Zhang et al., 2003b; Zhang and Klemperer, 2005; Zhang and Klemperer, 2010; Zhang et al., 2005a, 2005b, 2005c; Zhang et al., 2008a, 2008b; Zhang and Wang, 2007). Most of the interpretative results have been published in Chinese journals, Chinese books or project reports (SSB, 1986; CAGS, 1988; SSB, 1988a,b), in addition to a few publications in English in international journals. The database has grown with the acquisition of additional data sets supplied by gravity data inversion and Rayleigh wave seismic tomography applied to the continental and adjacent marine areas of China (Hirn et al., 1984a,b; Zhang et al., 1984; Zhao and Morgan, 1987; Dewey et al., 1988; Zhao and Windley, 1990; Beckers et al., 1994; McNamara et al., 1994; McNamara et al., 1995; McNamara et al., 1996; Carroll et al., 1995; Makovsky et al., 1996a,b; Nelson et al., 1996; Yuan, 1996; Yuan, 1997; Ekström et al., 1997; Zhu et al., 1997; Zhang et al., 2011a,b,c). Our understanding of Earth is principally from the geology at or near the Earth surface. However, crustal structure provides important information on crustal growth and deformation, and seismic images of the Earth's crust offer valuable information about deeper geological structures and tectonic processes that shape the lithosphere and the modern landscapes. Therefore, knowledge on the lithosphere–asthenosphere system is relevant for natural resource exploration, the distribution and management of ground-water resources, and the study and mitigation of natural hazards such as earthquakes. They also define the large-scale processes that control the evolution of the landscape and soils. Transects aided by data from crustal-scale active seismic studies offer a synoptic view of the Earth's crust structure, from a few kilometers of the upper crust to the Moho and of seismic activity distribution.

In this paper, we construct crustal transects across several important tectonic blocks in mainland China, such as South China, North China, Tibetan Plateau and northeastern China (Fig. 1a) by taking advantage of the relatively dense coverage of wide-angle seismic profiles, except in northeastern China where data are not so rich. In addition, we construct several crustal-scale transects in order to discuss crustal structure beneath several orogenic belts. Along the related transect, both crustal P-wave velocity model and lithosphere strength structures (featured with seismogenic layer thickness and yield stress envelopes) are integrated. After the brief description of the data used in this study, we summarize crustal structure along several crustal-scale transects imaged by relatively dense wide-angle seismic profiles. For definition and analysis of the spatial distribution of the seismogenic layer in the above tectonic blocks, we collected the earthquake activity catalogue of the events occurred from 1980 to 2010 in China continent, and analyzed the spatial variation of seismogenic layer beneath different tectonic blocks, which may provide strong constraints on lithosphere rheology. Finally, we analyze the spatial distribution of crustal structure and lithosphere rheology pattern in mainland China and discuss the implications on geodynamic processes that shape the lithosphere.

2. Data description

The data used in this study consists of two types: (1) crustal P-wave velocity distribution dataset from wide-angle seismic profiling, and (2) data describing lithosphere strength features, such as seismic activity data during the time period from 1980 to 2010 for seismogenic layer and heat flow dataset and density structure for the calculation of yield stress envelopes (YSE). In the following, we will briefly summarize the dataset resources from wide-angle seismic profiling with high resolution in both vertical and horizontal directions. Then, we will brief the dataset used to display seismogenic layer in the tectonic blocks and orogenic belts of our interest. In the next section related to the yield stress envelopes, we summarize the calculation scheme of the YSEs. The rheology structure is mainly controlled by the architecture of the crust, while the main boundaries, such as the bottom of upper, middle, lower crust and the lithosphere, and the contribution of physical properties to the YSEs are limited. The lateral variation of density in the lithospheric mantle is not considered in this study, even though we recognize significant regional variations from previous seismological studies in the lithospheric structure of China, although in recent years, more attention is being paid to the lateral heterogeneity for the lithospheric mantle from interpretation of the Bouguer anomaly dataset (Brandmayr et al., 2010; Brandmayr et al., 2011; Mooney and Kaban, 2010; Zhang et al., 2012a; Zhang et al., submitted for publication).

2.1. Crustal P-wave velocity models from wide-angle seismic profiles

Numerous wide-angle seismic profiles in mainland China and surrounding oceans were carried out (Figs. 1, 2a) and crustal P-wave velocity models have been obtained (Li and Mooney, 1998; Teng et al., 2003; Li et al., 2006; Zhang and Klemperer, 2010; Teng et al., submitted for publication). The available interpretations so far are highly qualitative as all these profiles were synthesized based on standard schemes and most of the results are published in Chinese journals, Chinese books or project reports (Chinese State Seismological Bureau (CSB), 1986), in addition to a few publications in English (Hirn et al., 1984a,b; Zhang et al., 1984; Zhao and Morgan, 1987; Dewey et al., 1988; Lu et al., 1989; Zhao and Windley, 1990; Wu et al., 1993; Xiong and Liu, 1997; Zhao et al., 2006; Beckers et al., 1994; Carroll et al., 1995; McNamara et al., 1994; McNamara et al., 1995; McNamara et al., 1996; Makovsky et al., 1996a,b; Nelson et al., 1996; Yuan, 1996; Ekström et al., 1997; Teng et al., 1985a,b; Teng et al., 1999; Teng et al., 2010; Zhang et al., 2010b; Zhang and Klemperer, 2010; Zhang et al., 2011a, 2011b, 2011c, 2011d). In this study, we do not make a reinterpretation of these deep seismic sounding datasets, but attempt to construct several crust scale transects in order to understand seismic structure of the crust across several important tectonic blocks with a compilation of crustal velocity models of the related profiles. Because of the relatively dense ray coverage, there is less uncertainty in the crustal models. We zoom on the large-scale (first-order) feature of the crustal structure in this paper; for smaller scale or detailed features of crustal velocity variations, we refer to the readers to the corresponding publications of the specific wide-angle seismic profiles. Our assumption minimizes the drawback due to the lack of information about the uncertainty in the 2-D models. In fact, these uncertainties depend on the shotpoint distance, the recorder's density and the identification of the various phases, and were reduced with the improvement of the deep seismic sounding observation procedure since the 1980s (Teng et al., 2003). Because of different reasons, the digitized interpretational results such as crustal velocity models are not available for further studies. We digitized (or re-sampled) crustal P-wave velocity models of wide-angle seismic profiles for a total length of more than