Crustal structure of China from deep seismic sounding profiles

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Abstract

More than 36,000 km of Deep Seismic Sounding (DSS) profiles have been collected in China since 1958. However, the results of these profiles are not well known in the West due to the language barrier. In this paper, we summarize the crustal structure of China with a new contour map of crustal thickness, nine representative crustal columns, and maps showing profile locations, average crustal velocity, and Pn velocity. The most remarkable aspect of the crustal structure of China is the well known 70+ km thickness of the crust of the Tibetan Plateau. The thick (45–70 km) crust of western China is separated from the thinner (30–45 km) crust of eastern China by the north–south trending seismic belt (105°E). The average crustal velocity of China ranges from 6.15 to 6.45 km/s, indicating a felsic-to-intermediate bulk crustal composition. Upper mantle (Pn) velocities are 8.0 ± 0.2 km/s, equal to the global continental average. We interpret these results in terms of the most recent thermo-tectonic events that have modified the crust. In much of eastern China, Cenozoic crustal extension has produced a thin crust with a low average crustal velocity, similar to western Europe and the Basin and Range Province, western USA. In western China, Mesozoic and Cenozoic arc-continent and continent-continent collisions have led to crustal growth and thickening. Inferences on the process of crustal thickening are provided by the deep crustal velocity structure as determined by DSS profiles and other seismological studies. A high velocity (7.0–7.4 km/s) lower-crustal layer has been reported in western China only beneath the southernmost Tibetan Plateau. We identify this high-velocity layer as the cold lower crust of the subducting Indian plate. As the Indian crust is injected northward into the Tibetan lower crust, it heats and assimilates by partial melting, a process that results in a reduction in the seismic velocity of the lower crust in the central and northern Tibetan Plateau.

Keywords: China; crustal structure; deep seismic imaging; average crustal and Pn velocity

1. Introduction

The geology of China is highly diverse and records a history of crustal evolution from the Archean core of the Sino–Korean platform to active continent–continent collision in Tibet (Fig. 1).

In addition, China is a country with a large population and high levels of seismic activity. Knowledge of the regional crustal structure is therefore important for the determination of epicentral locations, and for relating seismicity patterns to lateral variations in crustal properties.

Approximately 36,000 km of deep seismic sounding (DSS) profiles have been recorded by several institutions in continental China since 1958, primarily
by the State Seismological Bureau (SSB) of China, the country's main DSS research group. In this paper, we begin with a brief description of the geologic and seismotectonic setting of China, and then summarize the main results of DSS investigations. While some of the results from these DSS profiles are known in the West, much information has not left China due to the language barrier. We provide a broad overview of the crustal structure of China rather than a detailed discussion of each profile.

2. Geology and tectonics of China

Like many other continental regions, the geology of China consists of Precambrian platforms surrounded by accreted terranes and fold belts of various ages. These tectonic elements were first assembled in the Paleozoic Era, but have been further deformed and rearranged in multiple episodes throughout the Mesozoic and Cenozoic. The following geologic summary is based on reviews by Zhang et al. (1984), Dewey et al. (1988), Windley (1995), Carroll et al. (1995), and Goodwin (1996).

There are three Precambrian platforms in China: the Sino–Korean platform, the Yangtze platform, and the Tarim basin (which, despite its common name in Western literature, is referred to as a platform in Chinese literature; Fig. 1). The Sino–Korean platform coalesced in the early Archean through Early Proterozoic; it was largely consolidated by 2.0 Ga. The Yangtze platform contains igneous and metamorphic rocks that range in age from late Archean through Late Proterozoic. This platform was consolidated and stabilized after the Yangtze orogeny (ca. 825 Ma.). The Tarim basin of NW China consists of a nucleus of Archean through Proterozoic age covered
by thick Cenozoic sediments. The Tarim basin and Sino-Korean platform collided with the Siberian craton in the early Paleozoic, creating an east-west arc of fold belts across northern China (Fig. 1) and forming the Paleo-Asian supercontinent. The Yangtze and Sino-Korean platforms, which had been separated by the Paleo-Tethys Ocean, collided in the early Mesozoic to form the Qinling fold system.

The South China fold system of SE China (Fig. 1) is a composite of Late Proterozoic through Mesozoic orogens developed from three continental fragments now joined at two well-defined suture zones. The region was stabilized by the beginning of the Jurassic (Hsu et al., 1990).

South of the Tarim basin, the Kunlun fold system and the Tibetan Plateau (which may be subdivided into five fold systems that become younger to the south; Fig. 1) consist of a series of micro-continental fragments, collapsed ocean basins, accretionary metasedimentary rocks, and volcano-plutonic arcs that assembled at the southern margin of Eurasia after the breakup of Gondwana. The most recent major orogeny in southern Eurasia is the Himalayan collision (commencing ca. 45 Ma), and has been marked by 2000 km of convergence between India and Eurasia.

3. Crustal structure of China

3.1. Profile locations, data acquisition and interpretation

The crustal structure of China has been well investigated with DSS profiles concentrated in regions
of high population density and/or high levels of seismicity (Fig. 2). Table 1 provides a summary of 22 published profiles; in addition, we have used the results from 19 profiles that are not yet published (dotted lines in Fig. 2). Data quality, in terms of signal-to-noise ratio, is generally very good.

A variety of methods have been used to interpret the DSS data reported here. By far the most common method is the interpretation of seismic travel times and amplitudes using either one- or two-dimensional (1D and 2D) modeling methods (cf. Mooney, 1989). In reversed DSS profiles, seismic velocities are directly measured, while depths of refraction (or reflection) horizons are successively calculated from the uppermost layer to the deepest measured horizon (usually the Moho). Thus, seismic velocity determinations generally have lower errors than depth determinations. For the seismic profile data compiled here, seismic velocities are accurate to within 3%, or about ±0.2 km/s. All boundary depths (including the Moho) are accurate to within 10% of the depth.

### 3.2. Maps of crustal parameters

Crustal thickness is a parameter that is well determined by DSS profiles, since both refracted and reflected arrivals are usually observed from the Moho. However, the map of crustal thickness we present (Fig. 3) is the first complete contour map of the crustal thickness of China based primarily on DSS data. Previous maps have been largely based on surface wave, gravity, topography, and geoelectrical data (Compiling Group of Results of Deep Exploration. State Seismological Bureau, 1986; Edi-
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Fig. 3. Crustal thickness obtained primarily from seismic refraction/wide-angle reflection experiments. Solid isolines represent more reliable results. Dashed lines were obtained by considering gravity data. The 45-km contour coincides with the western boundary of the Sino-Korean platform and the Yangtze platform, as well as with the north-south seismic belt.

Worldwide, $P_n$ velocities for continental mantle range from 7.6 km/s to about 8.4 km/s (higher values are occasionally reported; Christensen and Mooney, 1995). Low $P_n$ velocities (7.6-7.8 km/s) are usually restricted to regions of thin (<35 km) crust with moderate to high heat flow, and high $P_n$ velocities correlate with thicker crust (>40 km) with low heat flow (i.e., stable continental interiors).

Fig. 4 shows $P_n$ velocities determined from refraction profiles in China. There is a weak tendency for northeast-southwest refraction profiles to show higher P-wave velocity values (8.1-8.2 km/s), and for northwest-southeast profiles to show lower values (7.7-8.0 km/s). This indicates possible seismic anisotropy in the uppermost mantle of about 4°.

Average crustal velocity, a parameter well determined from DSS data, is of interest because it is
directly related to bulk crustal composition, assuming that the measured velocity has not been strongly reduced by anomalously high crustal temperatures or high pore pressure. A low average crustal velocity (6.0–6.3 km/s) is indicative of a dominantly felsic composition, and a higher average velocity (6.5–6.8 km/s) indicates a significantly more mafic crustal composition (Christensen and Mooney, 1995; Rudnik and Fountain, 1995). Fig. 4 summarizes the average crustal velocity for the profiles in China from which we were able to make reliable calculations. Significantly, most values are less than or equal to the global average of 6.44 km/s (Christensen and Mooney, 1995). We interpret this to indicate a dominantly felsic to intermediate bulk crustal composition, whereas ‘typical’ (i.e., platform and shield) crust has a significantly more mafic composition. This raises the question of why much of the crust of China is ‘atypical’ in terms of its composition.

4. Crustal evolution

Crustal velocity columns (Fig. 5) provide insights into the evolution of the crust of China. The five crustal columns for eastern China all indicate a relatively thin (29–33 km) crust, close to the continental global average for extended crust (30.5 km), but significantly thinner than the global average of 39 km (Christensen and Mooney, 1995). This observation, along with geologic evidence, is consistent with Cenozoic crustal extension in eastern China (Hsu et al., 1990; Zhao and Windley, 1990).
low average crustal velocity (Fig. 4) and uppermost mantle velocity (7.8–8.2 km/s) are consistent with this inference, as are global tomographic models that indicate low shear-wave velocities in the upper mantle (i.e., thin lithosphere) of eastern China south of 42°N (Su et al., 1994; Zhang and Lay, 1996). Northeastern China (above 42°N) has no crustal refraction data, but global tomographic models (Ekström et al., 1997) provide evidence for a thick lithospheric root, and geologic evidence does not indicate significant Cenozoic crustal extension.

The crustal columns for western China (Fig. 5) show thick crust that is characteristic of young orogenic belts. Three of the four columns differ from the thick crust of shields in that they lack a high-velocity (7.0–7.6 km/s) lower crustal layer (Christensen and Mooney, 1995). These three crustal columns are best considered in light of recent seismological studies in western China that define crustal and upper-mantle properties on both a regional scale (McNamara et al., 1994, 1995, 1996; Beckers et al., 1994; Zhu et al., 1995) and locally for the southern Tibetan Plateau (Fig. 1: Allegre et al., 1984; Hirn et al., 1984a,b; Zhao et al., 1993; Nelson et al., 1996; Makovsky et al., 1996a,b). These data are consistent with a model for the evolution of western China that is based on the concepts proposed by Zhao and Morgan (1987) and Nelson et al. (1996). The key concept of this model is that the middle and lower crust of the Tibetan Plateau is a fluid-like layer, and the crust of India is injected into the Tibetan crust as an initially cold slab, but is heated and partially melted after
moving 200–300 km northward. Thus, the crust of India is assimilated into the crust of Tibet, and the surface of the Plateau is raised by the increasing crustal volume. We interpret column (a) (Fig. 5) to show the high-velocity (7.1 km/s) lower crust of the Indian shield prior to its heating and assimilation into the lower crust of Tibet. Such a high-velocity lower crustal layer appears to be missing beneath the central and northern Plateau. Bordering the Plateau, the thick crust of Sichuan Province (column c) and Western Yunnan Province (column d) appears to reflect the eastward extrusion (‘escape’) of this crust from the Tibetan Plateau (Tapponnier et al., 1982).

In summary, the crustal structure of China closely reflects the most recent thermo-tectonic event that has modified the crust. The most recent processes that have dominated crustal evolution are continent–continent collision (western China) and crustal extension (eastern China). Despite the long history of crustal evolution, very little stable continental crust with ‘typical’ seismic properties has been formed to date in China.

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References


