ELSEVIER

Tectonophysics 288 (1998) 105–113

TECTONOPHYSICS

Crustal structure of China from deep seismic sounding profiles

Songlin Li [a,b], Walter D. Mooney [a,*]

[a] U.S. Geological Survey, 345 Middlefield Road, MS 977, Menlo Park, CA 94025, USA
[b] Geophysical Prospecting Brigade, Research Center of Exploration Geophysics, State Seismological Bureau, 104 Wenhua Road, ZhengZhou, 450003, China

Accepted 10 November 1997

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 P_n 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 (P_n) 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. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: China; crustal structure; deep seismic imaging; average crustal and P_n 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

* Corresponding author. Fax: +1 650 329 5163; E-mail: mooney@andreas.wr.usgs.gov

PII S0040-1951(97)00287-4

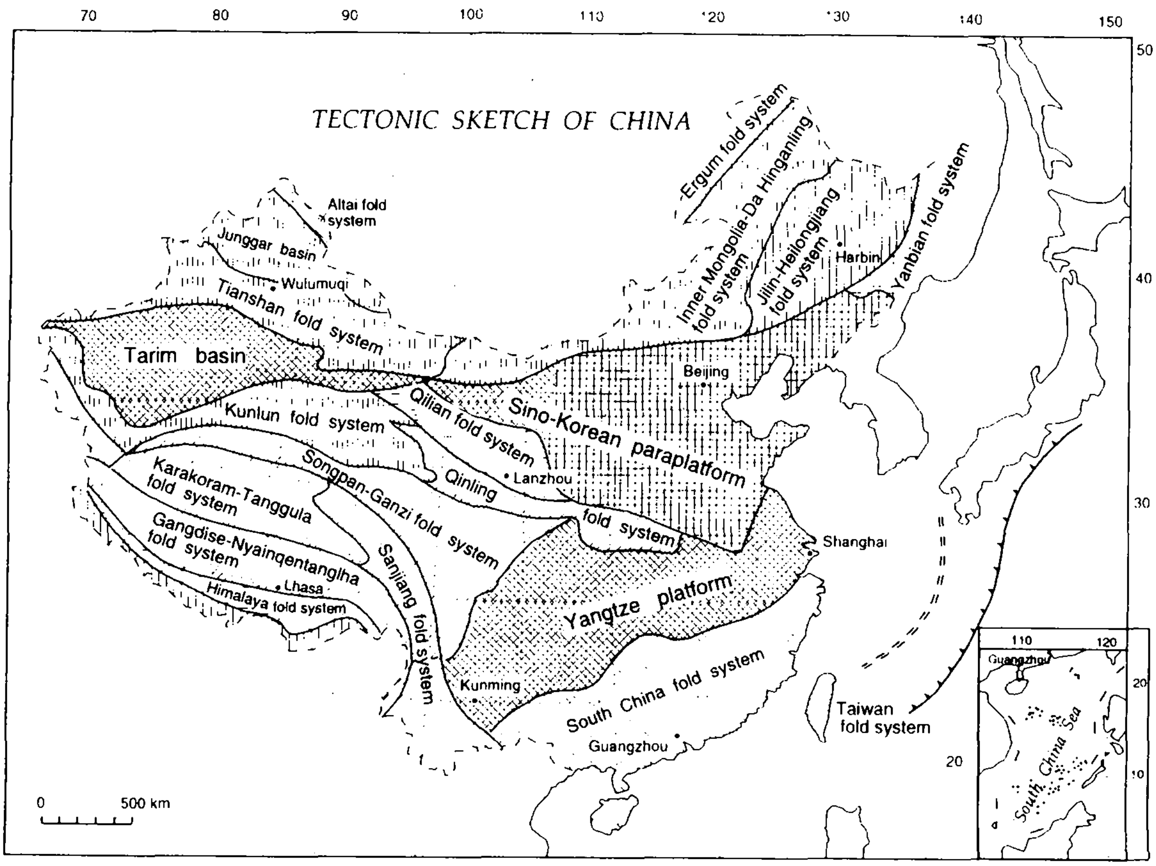

Fig. 1. Tectonic sketch map of China (after Huang et al., 1980). Nearly all geologic provinces have been surveyed with seismic refraction profiles (Fig. 2).

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

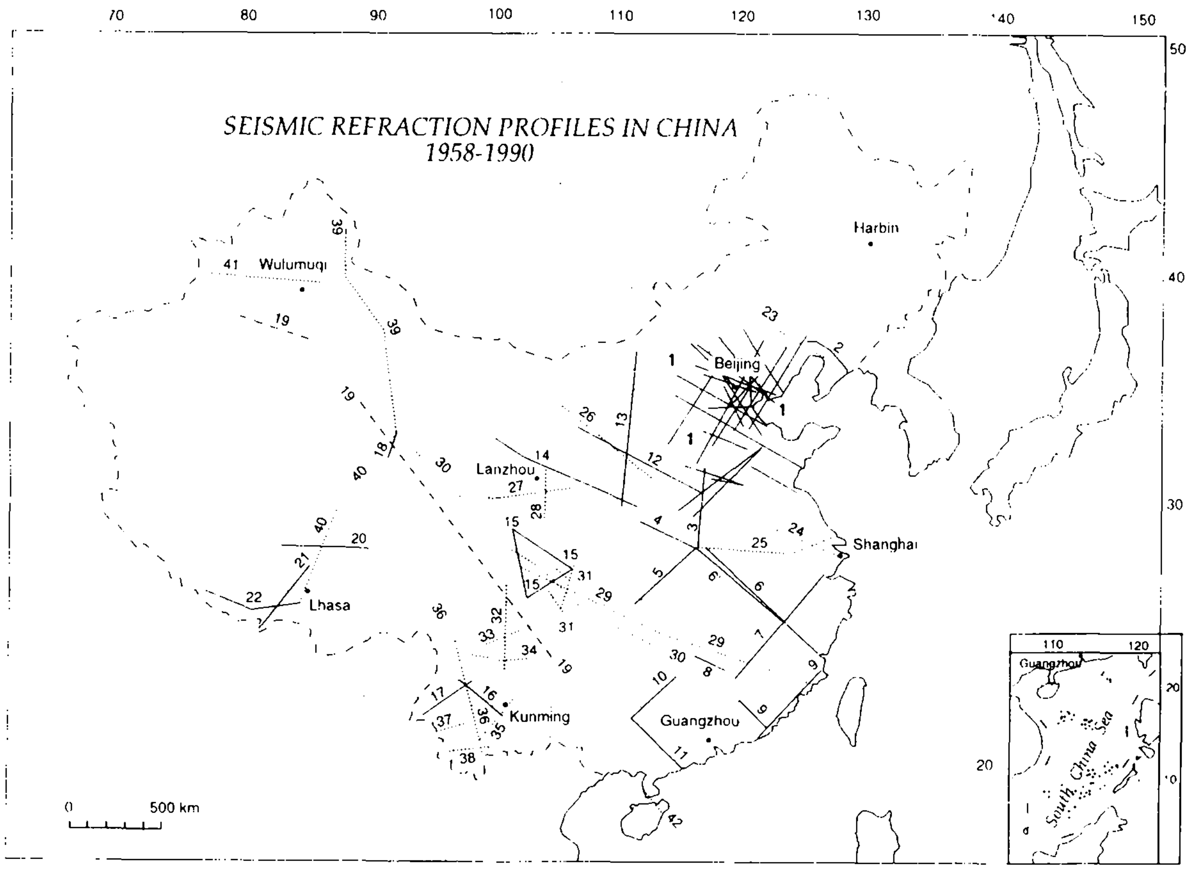

Fig. 2. Location map of the seismic refraction/wide-angle reflection profiles in China (1958–1990). The profile numbers correspond to Table 1. Solid lines: profiles completed from 1958 to 1986. Dotted lines: profiles completed from 1987 to 1990, not yet published. Dashed lines: profile with sparse observational points.

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

Table 1
Brief description of the DSS profiles

Profile number	Region	Reference	Source type [a]	Crustal thickness (km)
1 [b]	North China plain and adjacent regions	Sun et al., 1988	A	30–34
2	Lower Liao River plain	Lu et al., 1988	A	32–35
3	North China plain and Qinling folded region	Hu et al., 1988	B	30–34
4	Qinling folded region	Ding et al., 1988	B	34
5	Qinling folded region and Yangtze quasi-platform	Chen and Gao, 1988	B	34
6	Yangtze quasi-platform and South China folded region	United Observing Group, 1988	B	33
7	South China folded region	United Observing Group, 1988	B	32
8	Hengyang basin, Youxian basin and Chaling–Yongxing basin	Li and Xu, 1988	B	29
9	Southeast coastal fold belt	Liao et al., 1988	A	29
10	Guilin uplift and Yishan uplift	Liuzhou Explosion Research Group, 1988	B	33
11	South China folded region	Liuzhou Explosion Research Group, 1988	B	32
12	Ordos platform	Zhang, pers. commun.	A	–
13	Ordos platform	Zhang, pers. commun.	A	-
14	Qilian, Liupian and Qinling Mts.	Zhang et al., 1988	A	38–60
15	Sichuan basin and Tibet Plateau	Chen et al., 1988	A	40–51
16	Yunnan–Guizhou Plateau	Kan et al., 1988	A	41–46
17	Yunnan–Guizhou Plateau	Kan et al., 1988	A	39–46
18	Qaidam basin	Teng, 1979	A	51
19	Tarim basin	8301 Program Cooperation Group, 1988	B	51
20	Qinghai–Tibet Plateau	Teng, 1987	C	70
21	Qinghai–Tibet Plateau	Institute of Geophysics, 1981	C	45–73
22		Teng et al., 1983	A and C	73–76

[a] A = bore-hole explosion; B = industrial blast; C = explosion in water.
[b] Including 31 DSS profiles.

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-

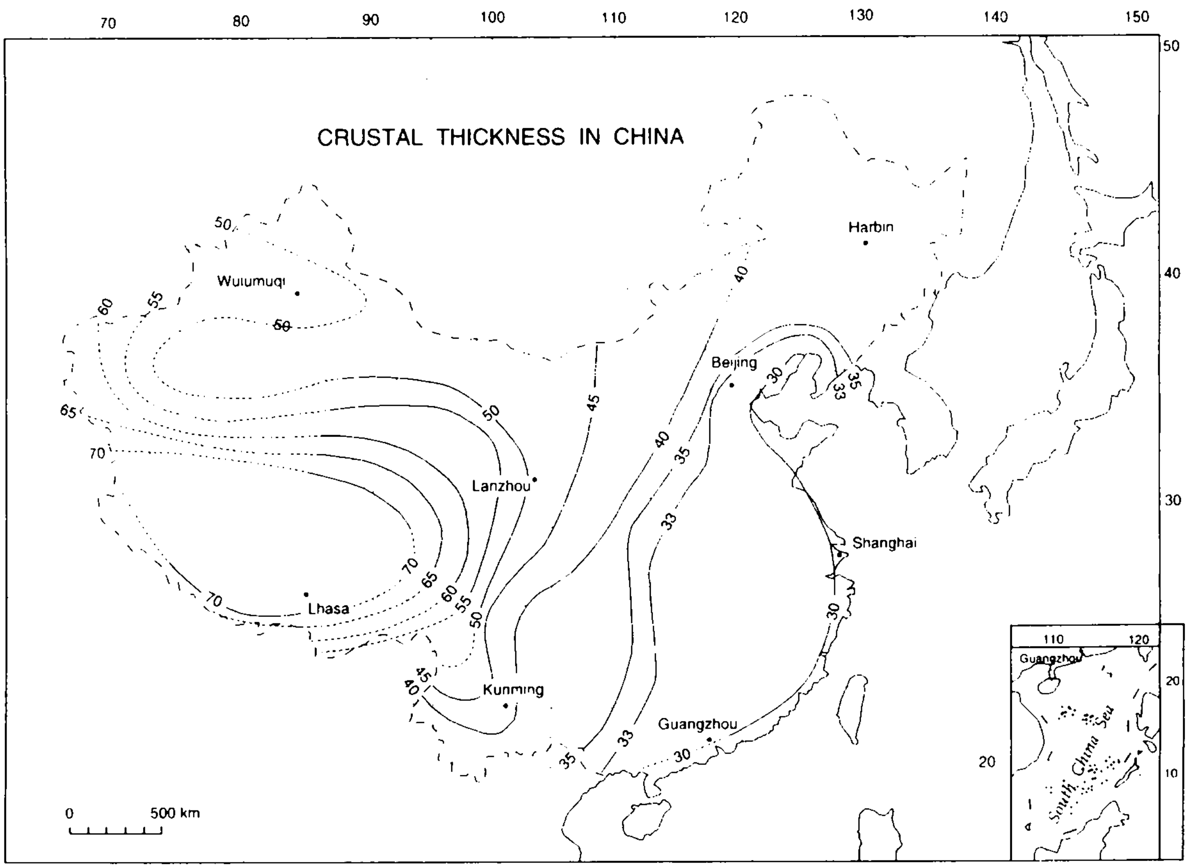

Fig. 3. Crustal thickness obtained primarily from seismic refraction/wide-angle reflection experiments. Solid isolines represent more reliable results. Dashed lines were obtained by considering gravity data. The 45-km contour coincides with the western boundary of the Sino–Korean platform and the Yangtze platform, as well as with the north–south seismic belt.

torial Board for the Lithospheric Dynamics Atlas of the Seismological Bureau, 1996). The contour map clearly divides China into an eastern portion with a crustal thickness of 30–45 km, and a western portion with a thickness of 45–70 km. In western China, crustal thickness is positively correlated with topography. The 70-km-thick crust beneath the Tibetan Plateau constitutes some of the thickest crust in the world (Teng et al., 1974, 1983; Allègre et al., 1984; Hirn et al., 1984a,b; Teng, 1987), along with the central Andes of South America. The strong gradient in crustal thickness in central China (visible in gravity as well as seismic data) is coincident with the north-south-trending seismic belt (105°E). In addition, the east–west-trending fold belts of western China either end at or abruptly change direction when crossing this seismic belt (Fig. 1).

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

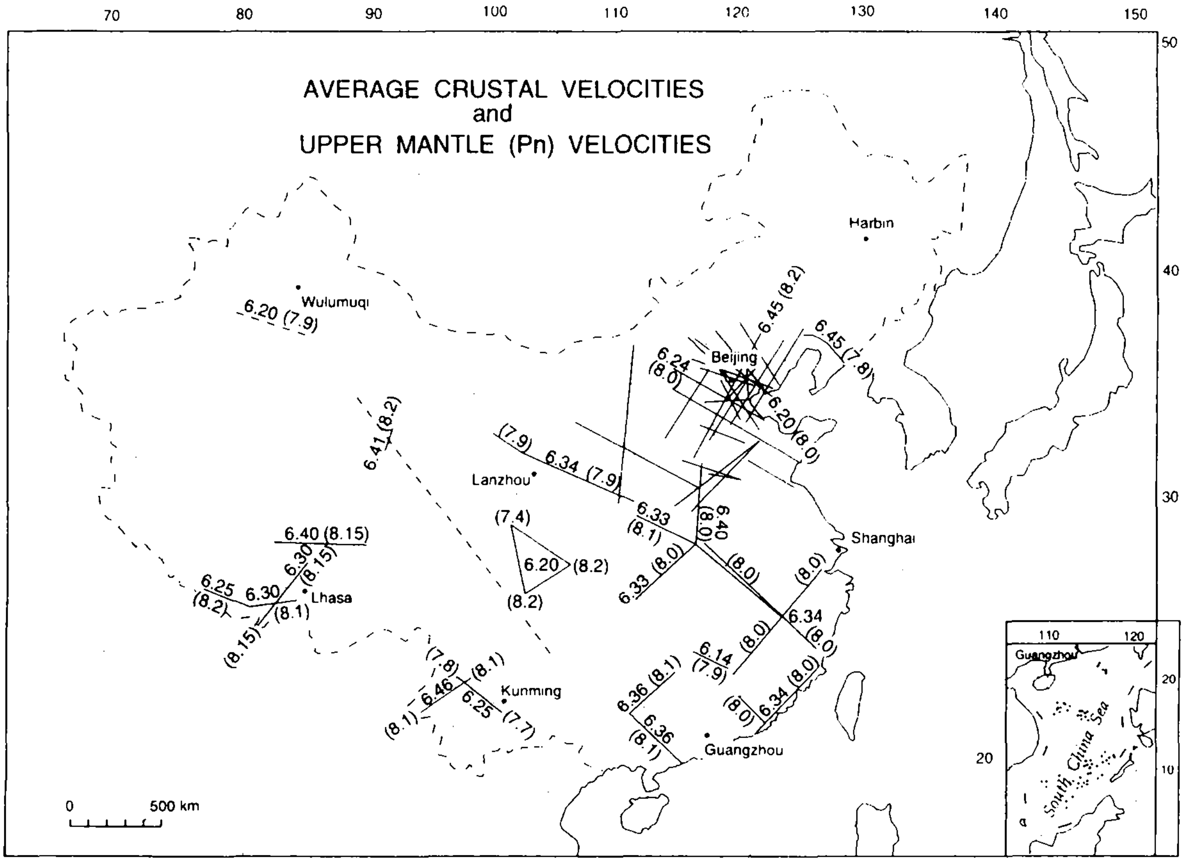

Fig. 4. P_n (upper mantle; in parentheses) and average crustal velocities obtained from seismic refraction profiles in China. P_n velocities are well within the global average of 8.0 ± 0.2 km/s. Average crustal velocities range from 6.14 to 6.45 km/s, corresponding to a felsic to intermediate bulk crustal composition. Average crustal velocities greater than 6.45 km/s, which are commonly reported for the Precambrian of Russia, are not measured in China.

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). The

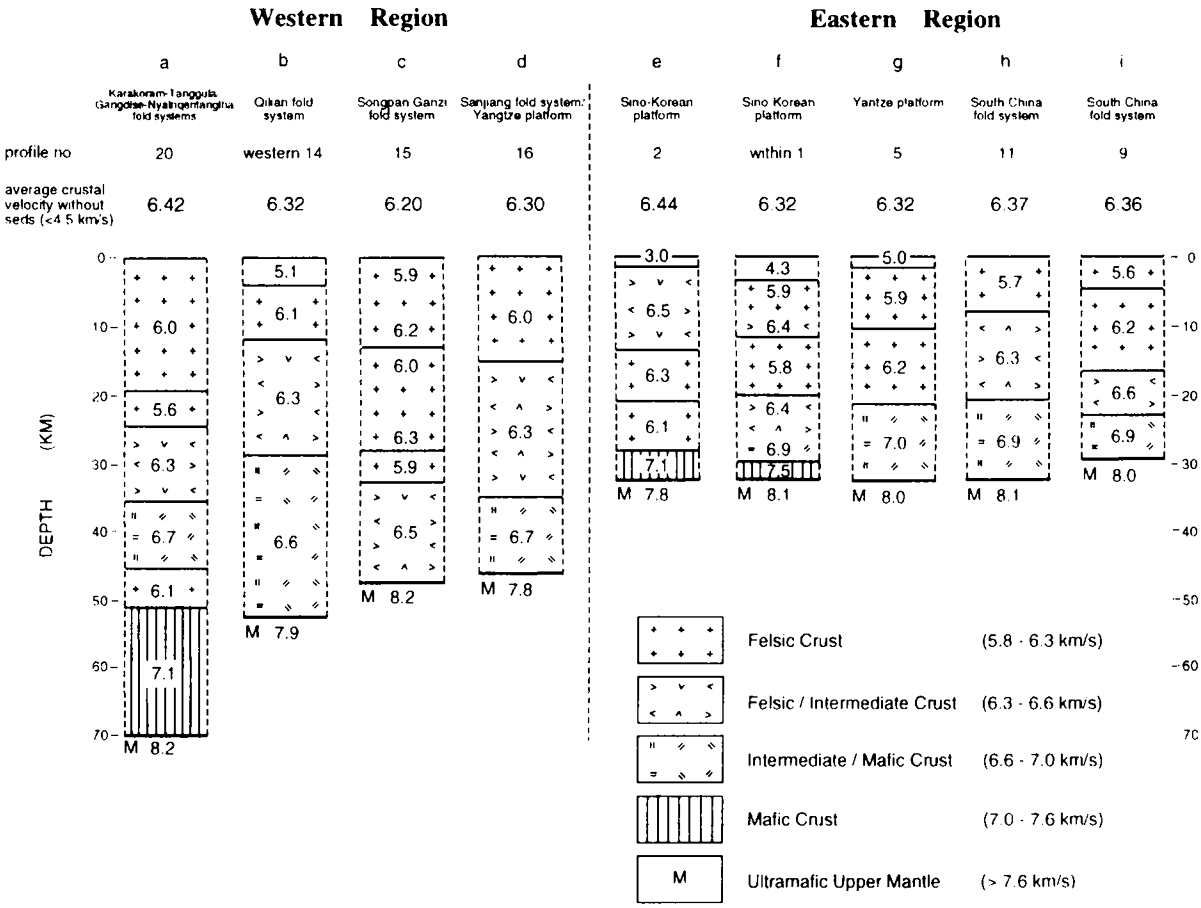

Fig. 5. Representative seismic velocity–depth functions for nine regions of China which can be divided into two parts by the north–south trending seismic belt (105°): western region (a–d) and eastern region (e–i). In the western region, the crustal thickness is greater than 45 km, while it is less than 35 km in the eastern region.

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; Allègre 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.

Acknowledgements

We are grateful to many people for sharing the information that is summarized in this paper. Zhang Xian-Kang, Zeng Rong-Sheng, Wang Chun-Yung, Wang You-Xue, and Yuan Xue-Chung provided data from China, and Katharine Favret and Regina Patzwahl provided helpful comments. Support from the USGS Earthquake Hazards Reduction Program and the Deep Continental Studies Program is gratefully acknowledged.

References

8301 Program Cooperation Group, 1988. Velocity structure of crust and upper mantle at the east margin of the Tarim Basin and the east part of Qinghai–tibet Plateau. In: Developments in the Research of Deep Structures of China's Continent. Geological Publishing House, Beijing, pp. 89–96.

Allègre, C.J., et al., 1984. Structure and evolution of the Himalaya–Tibet orogenic belt. Nature 307, 17–31.

Beckers, J., Schwartz, S.Y., Lay, T., 1994. The velocity of the crust and upper mantle under China from broadband P and PP waveform analysis. Geophys. J. Int. 119, 574–594.

Carroll, A.R., Graham, S.A., Hendrix, M.S., Ying, D., Zhou, D., 1995. Late Paleozoic tectonic amalgamation of northwestern China: sedimentary record of the northern Tarim, northwestern Turpan, and southern Junggar basins. Geol. Soc. Am. Bull. 107, 571–594.

Chen, B., Gao, W., 1988. Crustal structure along the Tiajiwen Shayuan DSS profile. In: Developments in the Research of Deep Structures of China's Continent. Geological Publishing House, Beijing, pp. 152–168.

Chen, X., Wu, Y., Du, P., Li, J., Wu, Y., Jiang, G., Zhao, J., 1988. Crustal velocity structure at the two sides of Longmenshan Tectonic Belt. In: Developments in the Research of Deep Structures of China's Continent. Geological Publishing House, Beijing, pp. 97–113.

Christensen, N.I., Mooney, W.D., 1995. Seismic velocity structure and composition of the continental crust: a global view. J. Geophys. Res. 100 (B7), 9761–9788.

Compiling Group of Results of Deep Exploration, State Seismological Bureau, 1986. Results from Geophysical Exploration of the Crust and Upper Mantle in China. Seismological Press, Beijing, pp. 11–13.

Dewey, J.F., Shackleton, R.M., Chang, C., Sun, Y., 1988. The tectonic evolution of the Tibetan Plateau. Philos. Trans. R. Soc. London 327, 379–413.

Ding, W., Huang, C., Cao, J., Jiang, G., 1988. Crustal structures along Suixian–Xian DSS profile. In: Developments in the Research of Deep Structures of China's Continent. Geological Publishing House, Beijing, pp. 38–47.

Editorial Board for the Lithospheric Dynamics Atlas of the State Seismological Bureau, 1996. Lithospheric Dynamics Atlas of China. China Publishing House, Beijing, 256 pp.

Ekström, G., Tromp, J., Larson, E.W.F., 1997. Measurements and global models of surface wave propagation. J. Geophys. Res. 102, 8137–8157.

Goodwin, A.M., 1996. Principles of Precambrian Geology. Academic Press, San Diego, Calif., 327 pp.

Hirn, A., Lepine, J.-C., Jobert, G., Sapin, M., Wittlinger, G., Xin, X.Z., Yuan, G.E., Jing, W.X., Wen, T.J., Bai, X.S., Pandey, M.R., Tater, J.M., 1984a. Crustal structure and variability of the Himalayan border of Tibet. Nature 307, 23–25.

Hirn, A., Nercessian, A., Sapin, M., Jobert, G., Xin, X.Z., Yuan, G.E., Yuan, L.D., Wen, T.J., 1984b. Lhasa block and bordering sutures — a continuation of a 500-km Moho traverse through Tibet. Nature 307, 25–27.

Hsu, K.J., Li, J.L., Chen, H.H., Wang, Q.C., Sun, S., Sengor, A.M.C., 1990. Tectonics of South China: key to understanding West Pacific geology. Tectonophysics 183, 9–39.

Hu, H., Chen, X., Zhang, B., Song, W., Xiao, Z., He, Z., 1988. Crustal structures along Suixian–Anyang DSS profile. In: Developments in the Research of Deep Structures of China's Continent. Geological Publishing House, Beijing, pp. 48–60.

Huang, T.K., Jen, C., Jiang, C., Chang, Z., Chin, D., 1980. The Geotectonic Evolution of China. Academic Publishing House, Beijing, China, 124 pp.

Institute of Geophysics, Acad. Sci., 1981. Explosion seismic study for velocity distribution and structure of the crust and upper mantle, from Danxung to Yadong of the Xizang Plateau. Acta Geophys. Sin. 24, 155–170.

Kan, R., Hu, H., Zeng, R., Mooney, W.D., McEvilly, T.V., 1988. Crustal structure and evolution of the Yunnan prov., China from seismic refraction profile. In: Developments in the Research of Deep Structures of China's Continent. Geological Publishing House, Beijing, pp. 267–276.

Liao, Q., Wang, Z., Zhu, Z., Wu, X., 1988. Crust and upper-mantle structure in the Quanzhou–Shantou region of China. In: Developments in the Research of Deep Structures of China's Continent. Geological Publishing House, Beijing, pp. 227–235.

Liuzhou Explosion Research Group, 1988. Observation of Liuzhou explosion and the crustal structure in eastern Guangxi. In: Developments in the Research of Deep Structures of China's Continent. Geological Publishing House, Beijing, pp. 246–252.

Lu, Z., Zhang, G., Li, J., Wang, L., Zhao, J., 1988. An explosion-seismology study on the structure of crust and upper mantle in South Liaoning Prov. In: Developments in the Research of Deep Structures of China's Continent. Geological Publishing House, Beijing, pp. 114–128.

Makovsky, Y., Klemperer, S.L., Huang, L.Y., Lu, D.Y., and Project INDEPTH Team, 1996a. Structural elements of the southern Tethyan Himalaya crust from wide-angle seismic data. Tectonics 15, 997–1005.

Makovsky, Y., Klemperer, S.L., Ratschbacher, L., Brown, L.D., Li, M., Zhao, W., Meng, F., 1996b. INDEPTH wide-angle reflection observation of P-wave-to-S-wave conversion from crustal bright spots in Tibet. Science 274, 1690–1691.

McNamara, D.E., Owens, T.J., Silver, P.G., Wu, F.T., 1994. Shear wave anisotropy beneath the Tibetan Plateau. J. Geophys. Res. 99, 13655–13665.

McNamara, D.E., Owens, T.J., Walter, W.R., 1995. Observations of regional phase propagation across the Tibetan Plateau. J. Geophys. Res. 100, 22215–22229.

McNamara, D.E., Owens, T.J., Walter, W.R., 1996. Propagation characteristics of Lg across the Tibetan Plateau. Bull. Seismol. Soc. Am. 86, 457–469.

Mooney, W.D., 1989. Seismic methods for determining earthquake source parameters and lithospheric structure. In: Pakiser, L.C., Mooney, W.D., Geophysical Framework of the Continental United States. Geol. Soc. Am. Mem. 172, 11–34.

Nelson, K.D., and twenty-seven others, 1996. Partially molten middle crust beneath southern Tibet: synthesis of project INDEPTH results. Science 274, 1684–1688.

Rudnik, R.L., Fountain, D.M., 1995. Nature and composition of the continental crust: a lower crustal perspective. Rev. Geophys. 33, 267–309.

Su, W.-J., Woodward, R.L., Dziewonski, A.M., 1994. Degree-12 model of shear velocity heterogeneity in the mantle. J. Geophys. Res. 99, 6945–6980.

Sun, W., Zhu, Z., Zhang, L., Song, S., Zhang, C., Zheng, Y., 1988. Exploration of the crust and upper mantle in North China. In: Developments in the Research of Deep Structures of China's Continent. Geological Publishing House, Beijing, pp. 19–37.

Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R., Cobbold, P., 1982. Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine. Geology 10, 611–616.

Teng, J.-W., 1979. Geophysical investigations of the Earth's crust and upper mantle in China. Acta Geophys. Sin. 22, 346–350.

Teng, J.-W., 1987. Explosion study of the structure and seismic velocity distribution of the crust and upper mantle under the Xizang (Tibet) Plateau. Geophys. J.R. Astron. Soc. 89, 405–414.

Teng, J.-W., et al., 1974. The crustal structure of the Eastern Qaidam Basin from deep reflected waves. Acta Geophys. Sin. 17, 122–135.

Teng, J.-W., Xiong, S., Yin, Z., Xu, Z., Wang, X., Lu, D., 1983. Structures of the crust and upper mantle pattern and velocity distributional characteristics at the northern region of the Himalayan Mountains. Acta Geophys. Sin. 26, 525–540.

United Observing Group of the Yongping Explosion, SSB, 1988. Yongping explosion and deep structure in Southeast China. In: Developments in the Research of Deep Structures of China's Continent. Geological Publishing House, Beijing, pp. 140–153.

Windley, B.F., 1995. The Evolving Continents. Wiley and Sons, Chichester, 526 pp.

Zhang, S. et al., 1988. Interpretation of the Menyuan–Pingliang–Weinan DSS profile in West China. In: Developments in the Research of Deep Structures of China's Continent. Geological Publishing House, Beijing, pp. 61–88.

Zhang, Y. S., Lay, T., 1996. 3-D S-wave velocity variations in the upper mantle. AGU Abstr. 77(46), F482.

Zhang, Z.M., Liou, J.G., Coleman, R.G., 1984. An outline of the plate tectonics of China. Geol. Soc. Am. Bull. 95, 295–312.

Zhao, W.L., Morgan, W.J., 1987. Injection of Indian crust into Tibetan lower crust: a two-dimensional finite element model study. Tectonics 6, 489–504.

Zhao, W., Nelson, K.D., and the Project INDEPTH Team, 1993. Deep seismic reflection evidence for continental underthrusting beneath southern Tibet. Nature 366, 557–559.

Zhao, Z.Y., Windley, B.F., 1990. Cenozoic tectonic extension and inversion of the Jizhong Basin, Hebei, north China. Tectonophysics 185, 83–89.

Zhu, L.-P., Owens, T.J., Randall, G.E., 1995. Lateral variation in crustal structure of the northern Tibetan Plateau inferred from teleseismic receiver functions. Bull. Seismol. Soc. Am. 85, 1531–1540.