Progress in deep lithospheric exploration of the continental China: A review of the SinoProbe

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Abstract

The SinoProbe, deep exploration in China, is a multidisciplinary earth science research program that aims at revealing the composition, structure and evolution of the continental lithosphere in China. The SinoProbe (2008–2012) has successfully conducted research and field experiments on determining the crustal and mantle structures using new deep seismic and magnetotelluric (MT) exploration. This has allowed the accumulation of new exciting data that have significantly accelerated China’s development on deep lithospheric exploration. The new data also led to new understandings on the Mesozoic and Cenozoic geological evolution of the continental China. The main results of the SinoProbe so far include (1) a collection of ca.6000 km long seismic reflection profile data, (2) a nation-wide geochemical baseline, (3) a nation-wide 4° × 4° MT array and regional 1° × 1° MT arrays in the North China and the Qinghai–Tibet Plateau, (4) three dimensional (3-D) exploration of ore districts in the eastern China, (5) several continental scientific drilling holes, (6) regional in-situ stress monitoring networks, (7) geodynamic modeling of the lithosphere underneath the continental China, and (8) instrumentation development for deep exploration in China, etc. For the first time, the SinoProbe has obtained deep seismic reflection evidence for the Moho surface below the thick crust of the central Qinghai–Tibet Plateau. It also reveals dipping fabrics in the lithospheric mantle beneath the northeastern China. The preliminary results from MT array observation of the SinoProbe show an abnormal electric-conductivity structure of the lithosphere beneath the Ordos basin, providing important evidence for the evolution mechanism of the North China craton (NCC). Generally, the SinoProbe has conducted successfully during its initial phase (2008–2012), which has settled a foundation for the next phase of the SinoProbe in the future.

1. Introduction

Our understanding of the deep lithospheric structure of the Earth depends on integrated analysis of the data acquired using deep exploration techniques. The continental China occupies a large region of the central and eastern Asia (Fig. 1). It has a complicated geophysical structure of the lithosphere (Li, 2010). The thickness of the consolidated crust in China is between ca.10 and 85 km, following a pattern of gradual thickening from east to west (Li, 2010; Teng et al., 2013; Zhang et al., 2011d, 2013a; Zhao et al., 1996). The lithosphere rheology structure can be described by jelly sandwich model in the eastern China, and crème brulee models with weak and strong lower crust in the western China (Zhang et al., 2013a). Most of the tectonic systems in China appear to be isostatically compensated except the Qinghai–Tibet Plateau (Zhang et al., 2011d).

The continental China holds some keys to resolving several first-order problems in earth sciences. To list a few, they include: 1) Does continental lithosphere deform fundamentally in a plate-like or fluid-like fashion during continent–continent collision? 2) How did the uplift of the Qinghai–Tibet plateau control the regional and global climate change and biological evolution? 3) Was indentation from India or slab rollback from the Western Pacific a main driver in initiating the > 3500-km long back-arc basin system along the eastern margin of Asia? 4) Did the development of the Paleo-Tethys, the Neo-Tethys and the Paleo-Asia Oceans contribute to significant Phanerozoic production of continental crust in the Earth’s history? and 5) What is the dynamic cause (i.e., plate boundary conditions vs. deep-mantle processes) for rejuvenating ancient crystalline basement such as the North China craton (NCC), in which numerous devastating earthquakes had occurred in the past few millenniums?

In order to resolve some of the problems mentioned above, the program SinoProbe – Deep Exploration in China, which is a Chinese government-funded major program of unprecedented scope and...
scientific ambition on geosciences, has been taking a multi-disciplinary approach to study the composition, structure and evolution of the continental lithosphere in China at all scales (Dong and Li, 2009; Dong et al., 2010, 2011a, 2012b). The initial phase of the SinoProbe, from 2008 to 2012, was carried out using the state-of-the-art techniques and methods, including the up-to-date geophysical technologies for real time data acquisition on deep crust and mantle structures. The data achieved by the SinoProbe program, along with advanced computation and modeling, will enable scientists to address some of the outstanding questions about the deep structure, composition distribution and evolution of the continental lithosphere in China, provide the vital information for the exploration of energy and mineral resources, assessing of potential geological disasters and mitigating the damages associated with these geological issues. The SinoProbe 2008–2012 has created a comprehensive new perspective on deep exploration of the continental China.

2. Mesozoic and Cenozoic tectonic setting of the continental China

The continental China (Figs. 1 and 2) is the key to resolve some first-order problems in earth sciences. It belongs to the tectonic transitional zone between the Gondwana and the Laurasia continents, with complicated geological and tectonic characteristics. It has stable Precambrian North China craton (NCC), which is older than 3.8 Ga, and several different Eoarchean to Paleoarchean continental nuclei (Liu et al., 2007). It outcrops widespread high and ultra-high pressure metamorphic rocks, the most extensive and diffusive tectonic deformation domains in the world, the densely distributed ophiolite mélanges (suture zones), the wide range of magmatic arcs, the abundant and specific paleobiocenoses, the characteristic crustal and mantle geochemical compositions in the transitional regions (Zhang et al., 2002, 2011a), and the thinnest continental lithosphere in eastern China (Li, 2006). Meanwhile, China is also a typical seismic region with neo-tectonic activities. The making of the continental China has resulted from multi-phase collisions of major and microplates, through the North–South China collision in the Triassic (250–220 Ma), the multi-direction convergence of the East Asia in the Late Jurassic (since 165 ± 5 Ma) to the Early Cretaceous (Fig. 1), and the India–Asia collision in the Cenozoic (Dong et al., 2000, 2008a; Ren, 1994; Yin, 2010; Yin and Harrison, 2000; Zhang et al., 2004).

The giant Central China Orogenic Belt (CCOB), extending more than 5000 km and characterized by the connection and transition of the Qinling, the Qilian, and the Kunlun Mountains and the

![Fig. 1. Multi-directional convergent tectonic model of the Eastern Asia in the Late Jurassic–Early Cretaceous. Modified from the geological map of the Eastern, Northern and Central Asia and adjacent areas in a scale of 1:2500000 (edited by Li et al., 2012b). NCC, the North China craton; SCB, the South China block; YZMB, the middle and lower Yangtze metallogenic belt; LMSFZ, the Longmen Shan fault zone.](image-url)
Songpan–Ganzi block, records two times of collisional orogeny in the Devonian and the Triassic, respectively, and intra-continental orogeny since the Cretaceous (Zhang et al., 2002, 2004, 2011a; Xu et al., 2006a; Yang et al., 2010). During the Triassic collisional orogeny, dextral strike slip faulting is developed in the south margin of the CCOB, and in the South China block. For example, metamorphic rocks in the Wuyishan, southeastern China, have suffered from dextral strike-slip shearing at the time span between 239 Ma and 230 Ma (Xu et al., 2011a). The closing of the Paleo-Tethys ocean and the collision of a number of microplates from the Late Triassic to the Middle Jurassic, shape the giant T-shaped compound Indosinian orogenic system in the east Asia, with a mountain root composed of the Dabie–Jiangsu–Shandong high and ultra-high pressure metamorphic belt (Dong et al., 2008b; Xu et al., 2012). Large basins with extensional tectonic environment and giant oil and gas fields formed in western China from the Late Triassic to the Early Jurassic.

The subduction of dominantly eclogitized mafic crust of northern south China in the Triassic might provide the driving force for continued convergence between north and south China until the Late Jurassic at ca.165 Ma (Dong et al., 2013). Due to the spreading of the mid-Atlantic, the mid-Pacific and the mid-Indian Ocean ridges, the breaking off and northward drifting of the Indian sub-continent from the Australian plate, the southward movement of the Siberian plate, and the closing of the Tethys Ocean and the Mongolia–Okhotsk Ocean (it was argued to be with ~3000 km width in its eastern part at ca.155 Ma; Pei et al., 2011), the East Asia convergence since the Late Jurassic (165 ± 5 Ma) initiates the classical Yanshan Movement in the NCC and significant intra-continental orogeny in the South China, resulting in characteristic intra-continental deformation and large scale mineralization in the eastern China (Dong et al., 2008a). The relatively stable Ordos and Sichuan blocks compose the two rigid continental cores in the East Asia convergence tectonic system, with the Late Jurassic to the Early Cretaceous multi-direction compressional deformation and foreland basins formed around them (Li et al., 2012a; Shi et al., 2012; Zhang et al., 2011c). The East Asia Convergence in the Mesozoic, gave rise to the large-scale metallogenesis in eastern China (Mao et al., 2005), the evolvement of the terrestrial Jehol Biota in northeastern China (Ji, 2002), the destruction and lithosphere thinning of the North China craton (160–150 Ma), and the collapse of mountain roots and tectonic seesawing of the East Asia continent (Dong et al., 2000).

In the Late Jurassic, westwards subduction of the paleo-Pacific plate formed the NNE-trending Neocathaysian trench-arc-basin tectonic system bounded by the west Pacific Ocean in the East Asia. A highly metamorphosed ophiolitic mélange, deformed during 190–135 Ma, has been identified within the north-eastern margin of the NCC along the Songjiang River in Jilin, which is helpful to define the tectonic nature of the NCC’s easternmost boundary. Accretionary complexes in Wandashan, Heilongjiang, developed on the east margin of the Bureya–Jiamusi block, formed in the Permo-Jurassic and back-thrust over pre-Jurassic arc assemblages, which tells the tectonic nature of the westernmost boundary of West Pacific accretionary orogen.

The East Asia had undergone the transition from compressive structure to extensional faulting in the Early Cretaceous. In the North China, the major extensional ductile shearing along the detachment zones of the Hohhot metamorphic core complex took place at ca. 142 Ma at depth and during ca. 140–132 Ma at shallow. In the South China, the formation of the Hengshan metamorphic core complex, shows the transition of deformation from compressional collision orogeny in the Triassic.
3.1.1. Methodological study and instrumental development of the SinoProbe

3.1. Methodological study

3.1.1. Deep seismic reflection and refraction profiling and seismic tomography

As one of the currently most advanced technologies, the near-vertical deep seismic reflection profiling is used to probe the detailed structures of the crust, to reveal the crustal deformation and continental geodynamics (Gao et al., 2011; Mooney and Brocher, 1987; Wang et al., 2011). Seismic tomography has opened a window for probing into the deep earth structure. Seismic tomography using P/S wave disturbance yielded relatively accurate velocity structure of the mantle, providing new geophysical constraints for mantle flow and dynamics (Yang and Yu, 2011).

The SinoProbe has developed joint collecting and simultaneous acquisition technique of common-source deep seismic near-vertical and wide-angle reflection together with seismic refraction, and realized simultaneous acquisition of low- and high-frequency signals. It has applied rapid hole-boring, deep-well (e.g., 50 m), large amount of dynamite, and super-long recording for high resolution deep seismic reflection exploration, which is suitable for hard rock areas (Wang et al., 2012). It has developed a series of special procedures for data processing of deep seismic reflection profiling, including statics correction of ray-free seismic tomography, pre-stack time migration of surface topography, non-stretch dynamic correction of long-array profiling, frequency-variant denoising of seismic data. A station-pair double-difference location technique has been developed to determine absolute tremors (Zhang et al., 2010a). SKS shear wave splitting measurements are used to investigate upper mantle anisotropy beneath the eastern China (Zhao et al., 2013b). A rapid calculation of relative travel time residual of teleseism has been suggested and applied to the processing of teleseismic waveform data with poor signal-to-noise ratio in the lower-middle reaches of the Yangtze River (Jiang et al., 2012).

3.1.2. MT array survey

The SinoProbe has applied magnetotelluric (MT) sounding methods, to develop a series of techniques on standard continental MT array survey, including the key issue of establishing a continental scale MT array standard grid, and the integration of gravity and magnetic data, to reveal the conductivity and thermal structures and rheologic characteristics of the crust and mantle underneath the continental China (Wei et al., 2009, 2010).

The SinoProbe has established a nationwide standard electrical structure model of the crust and upper mantle by 4° × 4° framework, and two regional standard models by 1° × 1° denser networks in the North China and the Tibetan Plateau. It has applied a standard method of grid MT survey for the establishment of standard models. By this method, a standard grid node (an ‘area element’) with 11 MT sounding sites in the two cross lines is placed at every grid of the 4° × 4° (or 1° × 1°) framework. And with the data from these stations, rock resistivity (conductivity) parameters (to a depth of upper mantle) were acquired from processing and inversion routines, including data processing based on S-transform (Jing et al., 2012), multiple-station far-referential data processing, and resolution of impedance tensor based on genetic algorithm. It has integrated one, two, and three dimensional (1-D, 2-D and 3-D, respectively) inversion techniques of MT sounding, dealt with the applicability of the 2-D inversion technique to solve complicated electric structure (Dong et al., 2012a), and established 3-D ‘standard model’ of conductivity structure of the continental lithosphere by inversion method for ‘area element’ data set of the continental MT ‘standard grid’. Through 1-D and 2-D MT inversion experiments, the validity of the model of convolution degeneration and the efficiency of the algorithm for enhanced blind deconvolution have been verified (Zuo et al., 2012).

Through forward modeling, the impact of shore effect including depth of sea water and topographic(al) change of seabed in offshore area (e.g., Bohai sea region) on continental MT aberration has been analyzed and summarized (Zhang et al., 2012a).

3.1.3. Gravity and magnetic data processing and inversion

The precise processing of satellite gravity and magnetic anomalies, multi-dimensional separation of anomalies, acquisition and enhancement of the tectonic information, and 3-D analytic continuation and inversion of geophysical potential field data based on relative imaging and GPU parallel algorithm, have been applied and developed by the SinoProbe, based on EGM2008 model. Significant practical progress has been made on reduction to the pole of magnetic anomalies at low or variant latitude, and potential field separation based on preferential wave filtering method (Chen et al., 2012a; Gao et al., 2011a, 2011b).

An inverse interpolation method is used for the gridding of aeromagnetic data based on Tikhonov’s regularization theory (Guo et al., 2012b). Preferential filtering method for gravity anomaly separation based on Green equivalent-layer and Wiener filter is also developed (Guo et al., 2013). It has established resolving, editing and examining technique for satellite gravity and magnetic data, realized rapid calculation method of 3-D inversion of GPU parallel gravity and gravity gradient (Chen et al., 2012b), brought up the processing method of upward continuation noise-elimination by means of gravity anomaly separation aiming at inherent high-frequency noise of the EGM2008 (Guo et al., 2011a), and systematically conducted collecting, trimming and processing of gravity and magnetic data in the Central and Eastern Asia. An iterative method to inverse the susceptibility based on inversion of the source distribution in a purely probabilistic sense is proposed (Liu et al., 2012b).

3.1.4. Continental scientific drilling

Continental scientific drilling (CSD), which is deemed as a telescope to the interior of the Earth, is an efficient technique for directly obtaining information from the Earth’s surface to the deep in the crust. Along with geological and geophysical investigations, it will help to reveal the composition and structure of the continental crust, and verify the results of geophysical explorations and establish standards for deep geophysical
exploration. It provides information on the Earth’s fluid systems, the potential distribution of geothermal energy and earthquake mechanisms. It provides fine and high-resolution geological records for the research of ‘deep time’ as well (Sun and Wang, 2009). It may be also helpful for monitoring global climate and environmental changes and microbial distribution in the deep earth.

3.1.5. Petrophysical property and in situ stress measurement

Extrapolation of the surface rock data to depth may result in substantial underestimates in seismic velocities. The intrinsic pressure derivatives obtained from the V_p-pressure relations for the core samples are more suitable for the determination of in situ velocities at great depth than those derived from measurements on rocks exposed at the surface (Sun et al., 2012a).

The change of the regional stress field is the reflection of the ‘pulse’ of the crustal activity such as earthquake. The present crustal stress field of the continental China is a result of long time evolution of the viscous-elastic crust, and closely related to the out-of-sequence distribution of active faults, tectonic geomorphology, and crustal structures under the control of plate tectonics (Fan et al., 2012). In order to monitor the change of the active regional stress field across the continental China, the SinoProbe is implementing regional networks of in situ stress measurement and monitoring stations. Hydraulic fracturing and over-coring methods are adopted for in situ stress measurement. Capacitive strain and piezomagnetic stress meters are applied for strain and stress monitoring respectively.

3.1.6. Geodynamic modeling and simulation

Modeling and simulation have become the third kind of the method of scientific research. Deep process controls the responses in the surface and shallow crust, and brings up topographical features of the continent (Cloetingh et al., 2009), through profound influence of gravity potential and tectonics on stress state. The estimation of lithospheric equivalent viscosity is a basic of continental dynamics (Shi and Cao, 2008), and instantaneous or short-term adjustments of stress field, resulting from earthquake faulting, can refer to analytical results of perfect elasticity (Fan et al., 2012). Initial temperatures transferred from seismic tomography are applied in the calculation of the global convection model. Four-dimensional (4-D) quantitative modeling is a direct response to the need for the reconstruction and forecasting of the complex processes in the Solid Earth (Cloetingh et al., 2011).

The SinoProbe has applied a high-performance calculation and simulation platform and a software package, to resolve 3-D geodynamic problems in global, regional, and local scales. The parallel computing platform has considered stress changes of the Earth’s crust and coupling problems in global, regional, and local scales. The parallel computing (Fan et al., 2012). Initial temperatures transferred from seismic tomography are applied in the calculation of the global convection model. 

3.1.7. Deep exploration of ore districts

There is great potential for discoveries of large and ultra-large ore deposits in the so-called ‘second space’ with a depth of 500–2000 m. Metallic ore exploration depends mainly on gravity, magnetic and electrical surveys, and separation, edge detection, and 3-D inversion of regional gravity and magnetic potential fields. With a depth up to 1000 m and more, high-resolution seismic reflection method becomes the most promising technique for metallic ore exploration, due to its superiority in revelation of ore-controlling structures, tracing of ore-bearing layers, and discovery of ore-bodies in the depth (Lu et al., 2010a,b).

3.2. Instrumental development

The SinoProbe has developed a series of key equipments for deep exploration, including the cable-free self-positioning seismic exploration system, the surface electromagnetic probe (SEP) system, the unmanned aerial vehicle (UAV) aeromagnetic system, the super-deep (up to 10 km) continental scientific drilling (CSD) equipments, and the all-in-one software for moving platform exploration and integration (Huang et al., 2012). They are so-called a real picture of China’s ambition in deep lithospheric exploration, represented by the SinoProbe. Currently, a great deal of testing experiment has been carried out and significant breakthrough has been made for robust performance of the instruments and all-in-one software in real exploration in the future. 

For the purpose of the early warning of geological hazards, the SinoProbe has also developed new-type piezomagnetic stress relieving measuring system and stress–strain monitoring system for in situ stress measurement and monitoring in deep holes, with the deepest installation and measuring depth up to 213 m.

3.3. Field observation and experimentation

During the past five years, the SinoProbe (Fig. 3) has completed some nation-wide geological, geophysical and geochemical surveys in China. It has established a nation-wide geophysical baseline framework with a cell size in 160 km × 160 km and 78 crustal elements covered. It has conducted nation-wide 4° × 4° MT array observations, and dense 1° × 1° MT array observations in the North China and the Qinghai–Tibetan Plateau, using ‘standard grid’ method developed by the SinoProbe. In respect of research on regional electromagnetic potential field, it has gridded and put together satellite 1° × 1° gravity, 30° × 30° remote sensing topographic, and 3’ × 3’ magnetic anomaly data, based on EGM2008.

It has collected deep seismic reflection profiles with a total length of ca. 6000 km, crossing major orogens and basins in the Qinghai–Tibetan Plateau, the South China, the North China, and the Northeastern China (Fig. 3). Each profile is surveyed by combined deep seismic reflection and refraction profiling, broadband seismic survey with a space of 10 to 30 km, MT sounding, and geochemical corridor investigation. The deep seismic reflection profiling length accounts ca.1000 km more than that had been conducted before the beginning of the SinoProbe program in China, letting the total length of the deep seismic reflection profiles in China to be ca.11,000 km in the present time.

The SinoProbe has carried out 3-D deep exploration in the Luijiang–Zongyang (Lu-Zong) and the Tongling ore districts in the middle and lower reaches of the Yangtze River and the Yudu–Ganxian ore district in the Nanling (South Range) metallogenic belts in the eastern China (Fig. 3), based on multi-disciplinary exploration of seismic reflection, MT/AMT, CSAMT, SIP, TEM surveys, and scientific drilling (Gao et al., 2010; Lu et al., 2010a, 2010b, 2013a). It has finished several pre-pilot continental scientific drilling holes with a depth in 2000–3000 m, including two holes at the Luobusa chromite deposit in the Indus–Tsangpo suture, one hole in the Tengchong active volcano–geothermal tectonic system in Yunnan, one hole at Jinchuan Cu–Ni sulfide deposit in Gansu, two holes at the Yudu–Ganxian poly-metallic deposit in the Nanling metallogenic belt (Chen and Wang, 2012), and two holes at the Lu-Zong and two holes at the Tongling polymetallic ore districts in the middle and lower reaches of the Yangtze River (Fig. 4).

It has systematically set up two regional in-situ stress measurement and monitoring networks. The one is in the southeastern margin of the Qinghai–Tibetan Plateau, where the Wenchuan 5.12 big earthquake (Mw7.9) and the Lushan 4.20 earthquake (Mw6.6) had happened in 2008 and 2013, respectively. Total 16 boreholes with depths of 300 m to 1000 m have been deployed in this area. Another network is in the surrounding area of the capital Beijing, including a comparison experimental station for stress and strain monitoring. The results revealed preliminarily the change law of in situ stress with depth, due to the interaction between stress field and active fault.

Several earthquakes, such as the Kunlun Earthquake in 2001 (Yan et al., 2012), the 12 May 2008 Wenchuan Earthquake (Yan et al.,
Fig. 3. Deployment map of the initial phase of the SinoProbe during 2008–2012, showing the deployment of deep seismic reflection and refraction profiles with broad band observations, geochemical corridors, MT arrays (in 4° × 4°), 3-D deep exploration of ore districts, in situ stress monitoring region, and several scientific drilling holes. Profiles: NECP, the Northeastern China profile; NCP, the North China profile; SCCP, the South and Central China profile; QTP, the Qinghai–Tibet profile. Ore districts: LZ, the Lu-Zong ore district; TL, the Tongling ore district; NL, the Nanling (Yudu–Ganxian) ore district.

Fig. 4. Locations of pilot holes of continental scientific drilling and experiments of the SinoProbe during 2008–2012. NCC, the North China craton; SCB, the South China block. Scientific drilling holes at: JC, the Jinchuan Cu–Ni-sulfide deposit; LBS, the Luobusha ultramafic block Cr-bearing along the Indus–Tsangpo suture; TC, the Tengchong active volcanic–geothermal system; LY, the Laiyang basin at the boundary of the North and the South China blocks (proposed to drill in future); NL, the Nanling (Yudu–Ganxian) poly-metallic ore district; TL, the Tongling ore district; LZ, the Lu-Zong ore district.

4.1. Deep lithospheric exploration in the Qinghai–Tibetan Plateau

4.1.1. Deep seismic reflection and refraction profiling and seismic tomography

The Qinghai–Tibetan Plateau is characterized by super-thick crust with complicated structure and changed Moho surface (Gao et al., 2009; Zhang et al., 2013a; Zhao et al., 1996, 2008). The crustal fine structure of the Qinghai–Tibetan Plateau is the key to testify uplift dynamic mechanism of the Plateau. The deep seismic profiling of TIB-1 under the INDEPTH-1 revealed the strong reflection belt in the middle crust in the South Tibet, reflecting subduction of the lower crust of the India plate underneath the South Tibet with the Moho depth of 72–75 km (Zhao et al., 1996).

The SinoProbe Himalayan–Tibetan profiles consist of the HKT profile in the southwestern Tibet and the Qiangtang profile in the central Qinghai–Tibetan Plateau, with a total length of ca. 520 km. They traverse the Himalayan, the Karakoram fault, the Indus–Tsangpo (Yarlung-Zangbo) suture zone, the Lhasa terrane and the Gangdese batholithic belt, the Bangong–Nujiang suture zone, the Qiangtang terrane in the hinterland of the Qinghai–Tibetan Plateau, and the Jinsha suture zone.

The HKT profile shows Moho reflectors at 24 s (T.W.T; about 72 km in depth), north-dipping reflectors in the lower crust, flower structure in the shallow part of the upper crust in the Karakoram strike-slip fault zone, and strong reflections at the bottom of the Gangdese magmatic belt. The Qiangtang profile has acquired strong reflection of the Moho surface of the Qiangtang terrane at ca. 20 s (T.W.T: about 60 km in depth), which is ca. 10 km lower than the Moho depths of the terranes on both sides. On the Qiangtang profile, the north-dipping reflectors in the lower crust of the super-thick crust, indicate possible northward subduction of the Lhasa terrane in early time. The results of teleseismic tomography show that the Indian lithospheric mantle has subducted beneath the Qiangtang terrane at 34°N (He et al., 2010).

Migrated receiver function images from passive seismic profiling across the Yadong-Gulu Rise, reveal highly asymmetric lithospheric structure in the South Tibet, suggesting whole-crust extension controlled by a simple/general shear rifting mechanism (Zhang et al., 2013c).

The northeastern Tibetan plate results from the superposition of the Caledonian Qilian orogenic belt and the Cenozoic reactivation following continental collision between the Indian and the Asian plates (Zhang et al., 2013b). Detailed processing of the previously collected deep seismic reflection profile in the west Qinling orogen, reveals the detailed structure of the deformed crust in the northeastern margin of the Qinghai–Tibetan Plateau (Wang et al., 2011). The profile provides evidence for the subduction of the lower crust of the Ruogai Basin (with Moho depth of ~50 km) underneath the west Qinling orogen. Meanwhile, the profile with duplex in the upper crust, near horizontal detachment in the lower crust, and Moho-involved imbricate thrust and duplex (Fig. 5; Wang et al., 2011), challenges the popular channel detachment in the lower crust, and Moho-involved imbricate thrust (Zhang et al., 2013b).

Seismic reflection/wide-angle reflection profile from Moba to Guide in the eastern Qinghai–Tibetan Plateau, reveals the crustal thicknesses of ca. 62 km under the Songpan–Ganzi terrane, 62–64 km under the South Kunlun, and 60 km under the Middle Kunlun block, and a remarkable W-to-E change in the Moho topography across the Kunlun fault system (15–20 km Moho step at 95°E, but only 2–5 km along the profile at 100°E) (Zhang et al., 2011f).
Seismic tomography reveals convergence of the Indian and Eurasian plates under the eastern Qinghai–Tibetan Plateau. The Indian lithospheric mantle underthrusts sub-horizontally under the eastern Qinghai–Tibet Plateau below the Moho, and the extent of the northward advancing Indian lithosphere decreases from west to east (Zhang et al., 2012b). In the north, the Asian lithospheric mantle is detected under the vicinity of the Qaidam Basin (Zhang et al., 2012b).

4.1.2. MT array survey and profiling, and satellite gravity and magnetic inversion

Results from previous INDEPTH-MT survey on six super-broad band MT sounding profiles in the Himalayan and the South Tibet, suggested the existence of ‘molten mass’ and ‘hot fluid’ in the super-thick crust of the Qinghai–Tibetan Plateau (Wei et al., 2010; Zhao et al., 2008). The SinoProbe-MT experimentation of 1” × 1” ‘standard grid’ gives the overall characteristics of the electrical structure underneath the Qinghai–Tibetan Plateau. In the Indus–Tsangpo suture zone, the result reveals low-resistance bodies in the shallow zone within 20 km depth in the south, and in the lower zone below 20 km depth with no continuity in the north. Therefore, low-resistance bodies might be relevant to the N–S rifting. Large-scale low-resistance bodies have not been found in different depths to the east of E94°, which contradicts the general opinion of ‘channel flow’ in the lower crust in the Qinghai–Tibetan Plateau. In the central and northern Qinghai–Tibetan Plateau, 2-D nonlinear conjugated gradient inversion of the MT profile from Wudaxi to the Lücao Mountain, achieved a 2-D electrical model with inferred main faults (Xie et al., 2012).

MT profiling across the eastern margin of the Qinghai–Tibetan Plateau and the Sichuan Basin, reveals an electrical transfer between the low-resistance in the middle and lower crust of the Qinghai–Tibetan Plateau and the high-resistance in that of the Yangtze craton (Zhang et al., 2012d), supporting that the crustal flow is blocked in the eastern margin of the Qinghai–Tibetan Plateau (Zhao et al., 2012). In the north-eastern margin of the plateau, MT profile from Hezuo to Dajing, revealed the prevalence of high-conductivity layers in the middle and lower crust, which is characterized by longitudinal layering and horizontal blocking (Jin et al., 2012). 3-D density inversion based on Bouguer gravity anomally, revealed a rigid block with high-density in the lower crust of the Liupanshan region, southwestern Ordos basin, which might obstruct the channel flow in the lower-crust in the northeastern margin of the Qinghai–Tibetan Plateau (Meng et al., 2012).

4.1.3. Scientific drilling

The scientific drilling of the Luobusha ophiolite along 1400-km-long Yarlung–Zangbo suture zone, aims to reveal the formational condition of the ophiolitic peridotites and associated podiform chromitites. Deep mantle minerals, such as micro-diamonds, moissanites and many high pressure minerals, have been found in the Luobusha ophiolite and chromite deposit (Yang et al., 2007; Yang et al., 2011a), and also in the Pulan, the Dongbo, the Danqiong, the Shigatse, the Zêtang, and the Myitkyina (Myanmar) ophiolites in the Yarlung–Zangbo suture zone (Yang et al., 2011b, 2012a). Nitrogen oxide and natural metal inclusions in massive chromitizes, indicate that they had formed under the environment of ultra-high temperature and pressure (>10 GPa with more than 300 km depth) and very low O2, which provides a window for the study of the deep mantle and the distribution of nitrogen within the Earth.

Geochronological results suggest that the Luobusha MOR and the Myitkyina (Myanmar) SSZ ophiolites formed at ca. 170 Ma in the Middle Jurassic, while the Pulan and the Dongbo MOR and the Luobusha SSZ ophiolites formed at ca. 130 Ma in the Early Cretaceous (Xu et al., 2011b; Yang et al., 2012a). Massive chromite ores had been found in the Pulan and the Dongbo ophiolites, implying a good future for the prospecting of large scale chromite deposits along the Yarlung–Zangbo suture zone, especially in its western part (Yang et al., 2011b). Meanwhile, a third genetic type of diamond, i.e., ophiolite-type diamond, was bringing up (Yang et al., 2011a).

4.2. Deep lithospheric exploration in the North and Northeastern China

4.2.1. Deep seismic reflection and refraction profiling and seismic tomography

4.2.1.1. The North China craton. The Precambrian North China craton (NCC) is a part of the pre-Rodinia supercontinent Columbia (Zhang et al., 2012e). The subduction of ocean plate, and convergence and crustal accretion of continental plates along the Solonker suture zone have attracted a lot of interests from the geologists. However, due to the lack of fine lithospheric structure data, the understanding of the deep processes varies greatly for a long period of time.

Joint seismic exploration of high-resolution and high-accuracy simple component deep seismic reflection, tri-component wide-angle reflection and refraction profiling by the SinoProbe in the north margin of the NCC, provides reliable deep lithospheric information for the tectonic evolution of the Paleo-Asian Ocean and the deep resource exploration. The N–S-trending North China profile extends from the capital Beijing in south to the China–Mongolia border in north, with a total length of ca.710 km. It traverses many tectonic units and boundary faults, such as the traditional boundary between the North China platform and the Inner Mongolian geosyncline (the Central Asian Orogenic Belt), the Permo-Triassic Yanshan orogenic belt, the Solonker suture zone, the north margin of the highly extended early Paleogene North China basin (with crust and lithosphere thicknesses of ~31 km and 70 km, respectively; Zhang et al., 2011e), and the enigmatic Mesozoic intra-continental Yanshan fold-thrust belt (with crust and lithosphere thicknesses of ~36 km and 180 km, respectively; Zhang et al., 2011e).

The North China deep seismic reflection profile reveals fine structure of the lithosphere, including transparent reflections of widespread granitoids in the upper crust, and north-dipping strong reflections in the lower crust and the upper mantle, indicating the multiple northward subductions of the NCC in the Late Paleozoic. It may track the whole course processes including plate convergence, crustal extension, magmatic intrusion, over-thrusting, and crustal accretion since the Late Paleozoic. The Moho surface undulates acutely on the profile. The deepest Moho occurs in the Yanshan fold-thrust belt, with locally superposed Moho reflectors. The shallowest one occurs in the granite-outcropped Huade area.

The North China profiling of wide-angle seismic reflection and refraction experiment, reveals that thicker crust appears beneath the Yinshan–Yanshan belt and was probably generated by compression in the Early Jurassic and modified during the craton’s destabilization and extension, and the flat and relatively shallow Moho in the Central Asian Orogenic Belt may be attributed to the extension (Li et al., 2013).

The ambient noise tomography shows distinct variations of the crustal shear wave velocity structure beneath the NCC (Cheng et al., 2013). The Bohai Bay Basin in the eastern NCC is underlain by a thin crust (~30 km) which may have resulted from the widespread tectonic extension and intensive magmatism in this region since late Mesozoic. Beneath the Ordos Basin in the western NCC, the crust is relatively thicker (~40 km) and well stratified, and presents a large-scale low velocity zone in the middle to lower crust and overall weak radial anisotropy except for a localized lower crust anomaly. The overall structural features of this region resemble those of typical Precambrian shields, in agreement with the long-term stability of the region. The crustal structure under the Trans North China orogen (TNCO, central NCC) is more complicated, re

Processing of teleseismic body waves recorded by permanent stations, reveals the change of the Moho depths in the southeastern
margin of the Ordos block, i.e., from Moho depth of 33.4–45 km in the east, to that of 31 to 53.1 km in the south, and ca. 53 km in the Qinling orogen (Ren et al., 2012). To the north, the Moho depth is getting deeper and deeper in the north part of the Ordos block (Teng et al., 2010).

Deep seismic reflection profile, in the western part of the junction belt of the South Tian Shan and the Tarim Basin, reveals the current lithospheric-scale tectonic relationship between the structures from the top to the deep, reflecting the coupled mountain–basin relationship of intra-continental subduction under compressive system (Hou et al., 2012).

4.2.1.2. The Northeastern China block. The main target of the Northeastern China deep seismic reflection profiling, with a length of ca. 1500 km, is to address the poorly known geological and geophysical settings of the oil-bearing Songliao Basin. With application of deep-well, high-energy excitation and super-long recording (up to 50 s), the profile has acquired clear reflections in the lithosphere. It reveals strong variation of the lower crust, overlapping of the Moho discontinuity, and west-dipping continuous reflections up to 39 s (ca. 100 km in depth) in the upper mantle. Though possible mantle reflections beneath the Montana Great Plains had been mentioned by Best (1991), the continuous mantle reflection beneath the Songliao Basin, down to the bottom of the upper mantle, is still exciting. The reflections in the upper mantle could be fragments of the lower crust (Cook and Vasudevan, 2003), or mantle faults/shear zones resulted from deformation of the lithosphere (Vaucuez et al., 2012). The profile reveals a westward subducted oceanic crust into the asthenosphere at a low angle between the Zhaoguangcui Range and the Kiamusze block, supporting the existence of the long controversial Paleo-Pacific Plate in the Northeastern China.

The crust and uppermost mantle structure beneath the northeastern China is imaged with fundamental mode Rayleigh waves recorded by 125 broad-band stations in the region. The results show that obvious low velocities exist in the uppermost mantle beneath the Changbaishan volcanic region due to asthenospheric upwelling. The thin lithosphere in the lower crust of the Songliao Basin implies that the lithosphere mantle beneath NE China is partly removed (Li et al., 2012c).

4.2.2. MT array survey and inversion

A regional 3-D electrical conductivity model of the North China is obtained through 2-D and 3-D inversion of the SinoProbe-MT 1° × 1° ‘standard grid’ data, showing a significantly different conductivity structure between the east and the west parts of the North China. The current North China lithosphere could be roughly divided into 6 blocks, such as the Shandong–Liaoning high and the Huang-Huai-Hai low resistance blocks in the east, the Taihang–Luliang high resistance block in the central, the Ordos low resistance block in the west, and the Yanshan and the Inner Mongol high resistance blocks in the north. High-resistance blocks approximately correspond with orogenic and fold-thrust belts of ‘rigid’ lithosphere, and low-resistance blocks tally with basins of relatively ‘plastic’ lithosphere. Contrary to the thinned lithosphere and high surface heat flow, relatively high resistive structures are revealed in the east part of the North China craton.

3-D MT inversion reveals an abnormal conductivity structure for the lithosphere of the Ordos block, with relatively high conductivity in general. There are many large-scale conductive bodies in the crust and the mantle, and several groups of steep dipping high-conductivity channels in the upper mantle. The Ordos block could be divided into two blocks by latitude 37.5°N, with the conductivity of the northern block higher than that of the southern block obviously. The low-resistance of the Ordos block, especially in the north, is not consistent with the nature of an old stable craton. Therefore, it is highly possible that there are quantities of deep thermal fluid, which could be the result or the cause of the ongoing thinning and delamination of the Ordos lithosphere.

4.3. Deep lithospheric exploration in the South China

The deep seismic reflection profiling in the South China by the SinoProbe, from east coast to the eastern margin of the Tibetan Plateau, is the longest one in the mainland China with a total length up to ca. 2500 km. It crosses the following important tectonic features: 1) the eastern continental margin of Asia at Taiwan Strait, 2) the early Paleozoic suture zone between the Cathaysian block to the east and the Yangtze block to the west (Zhang et al., 2012f), 3) the Mesozoic Xuefengshan thrust belt along the eastern edge of the Sichuan Basin, 4) the oil-and-gas bearing Sichuan basin, 5) the Cenozoic Longmen Shan fault zone that marks the boundary between the relatively stable Sichuan Basin and the active Qinghai–Tibetan Plateau, and 6) the Triassic Songpan–Ganzi flysch complex.

Preliminary data processing of the South China deep seismic reflection profile reveals an eastward inclining of the Moho surface underneath the eastern Sichuan Basin in the core area of the Yangtze block, implying possible relics of an ancient subduction zone, which is similar to that in Canada discovered by Cook and Vasudevan (2003) and van der Velden and Cook (2005). Information from detailed processing of the profile will offer new and crucial deep structure evidence for the reconstruction of the South China continent.

Deep seismic reflection profiling across the Daba Shan, northeast Sichuan Basin, reveals detailed structure of the Daba Shan thrust belt and some Neoproterozoic rift basins developed at 800–700 Ma, in the northern margin of the South China block. The deformation pattern on the profile suggests continued convergence between the North and the South China blocks lasted ~50 Ma after the Triassic closure of their intervening oceans (Dong et al., 2013).

The broadband seismic survey and teleseismic tomography in the South China show northwestward radial thinning from the coast to the inland and lateral adjusting of the crust and the upper mantle (Zhao et al., 2013b), and collisional tectonics between the Eurasian and Philippine Sea plates (Zheng et al., 2013). In the Sichuan–Yunnan and adjacent regions, 2.5-dimensional tomographic models of the uppermost mantle provide more evidence for the subduction of the Indian plate beneath the Myanmar–Yunnan region and the existence of the hot material upwelling beneath the Hainan region (Lü et al., 2013b).

4.4. Deep exploration of ore districts in the middle and lower Yangtze metallogenic belt

4.4.1. The middle and lower Yangtze metallogenic belt

The middle and lower Yangtze metallogenic belt (YMB) lies in the middle and lower reaches of the Yangtze River between the North China craton and the South China block. Deep seismic reflection profiling reveals thrust-fold structures in the upper crust, detachment between the upper and the lower crust, and nappes in the Tan-Lu fault zone and the Zhabgaling uplift. Receiver function profiling and teleseismic tomography (in 2-D and 3-D) display significantly seismic anisotropy (Lü et al., 2011), existence of mantle uplift, crustal extension, and multi-level magma system, and an abnormal low velocity asthenosphere beneath the YMB, implying delamination of the lithosphere, upwelling of the asthenosphere, and underplating of mantle-derived magma during the Mesozoic ore-forming process (Jiang et al., 2013; Shi et al., 2013).

In boundary areas between the North China craton and the South China block, fast directions trend in a NW–SE direction that is inconsistent with the strike of known surface features, and the strikes of the Qinling–Dabie and Sulu orogenic belt may result from the subduction of the Yangtze lithosphere beneath the North China craton (Zhao et al., 2013b). Integrated geophysical and geochemical constraints suggest that the Tan-Lu fault belt probably served as a channel for melt and fluid percolation, and exerted a significant control on the lithosphere evolution in the Eastern China (Deng et al., 2012a, 2012b).
4.4.2. The Lu-Zong ore district

The Lu-Zong Fe–Cu ore district is a volcanic basin, with crust thickness of 30 km and volcanic strata of average 800–1000 m in thickness (Dong et al., 2010, 2011b; Lü et al., 2011, 2013a). Five intersecting reflection seismic profiles reveal the transformation between the compression in the Late Jurassic and the extension in the Late Cretaceous, and support the delamination of the lower crust and underplating of mantle-derived magma (Lü et al., 2011, 2013a). Joint exploration of deep seismic reflection profiling, MT and high-precision gravity and magnetic measurement, fine processing and tectonic analysis by the SinoProbe, reveals a 3-D structural framework with multi-layer magma intrusion, ore-conducting and ore-bearing structures, and high magnetic and/or high density bodies, in depth up to 10 km (Gao et al., 2010; Lü et al., 2010a, 2010b, 2013a). Separation of gravity anomaly from background is applied for shaping of the ore-body in the Nihe Fe deposit (Liu et al., 2012d). First arrival wave tomography of seismic reflection profiling, yields a velocity structure in depth up to 1200 m, which accurately reveals the spatial distribution of concealed intrusive bodies (Liu et al., 2012e). The upwelling and eruption channel of mantle fluid and magma down to the Moho surface in the west part of the basin, certifies that the Lu-Zong basin is an asymmetric graben with master faults on both the east and north flanks (Lü et al., 2013a), and denies the possibility of the existence of the other half volcanic basin under the red bed in the west (Dong et al., 2010; Gao et al., 2010; Lü et al., 2010b). The northern part of the Lu-Zong basin is suggested to be an exploration target for deep porphyry and skarn deposits (Lü et al., 2013a).

4.4.3. The Tongling skarn copper deposit district

Deep seismic reflection and MT profiling, and source parameter inversion of gravitational and magnetic field in depth of 0–5 km in an area of 1800 km², reveal the spatial distribution of magmatic and high density bodies in the Tongling skarn copper deposit district. Integrated geophysical models for several typical deposits, such as the Shujadian porphyry copper and the Yaojialing hydrothermal lead–zinc–copper deposits, are established for the deep mineral exploration.

4.4.4. The Jiurui and Ning-Wu ore districts

Reprocessing of gravity and magnetic data gives the spatial distribution of ore controlling fault system, stratigraphic system, and mineralization related magmatic bodies in the Jiurui ore district (Deng et al., 2012a, 2012b). In the Ning-Wu ore district and its western margin, MT survey along two profiles reveals electrical structure of the upper crust with depth less than 10 km (Yang et al., 2012b).

4.5. Petrophysical property measurement, in situ stress monitoring and numerical modeling

4.5.1. The Longmen Shan fault zone

The key to determine the cause of strong earthquake lies in the material, the environment, and the dynamic process in the deep (Teng et al., 2009). The northeast-trending Longmen Shan fault zone in the eastern margin of the Tibetan plateau, where the 2008 Wenchuan Earthquake and aftershocks occurred, is located to the east of a giant gravity horizontal gradient belt (Zhang et al., 2010b). The comparison of petrophysical property with previous in-situ seismic data reveals four-layer crust of the Longmen Shan fault zone from the surface to the Moho, and suggests that channel flow is unlikely to occur beneath this fault zone (Sun et al., 2012b).

In situ stress measurement and monitoring network of the SinoProbe have given the basic image of the present stress field and the change of magnitudes and directions of horizontal principal stresses along the Longmen Shan fault zone in the eastern margin of the Qinghai–Tibetan Plateau. One year after the Wenchuan Earthquake, the principal horizontal stress decreased considerably, and the preferential direction of tectonic stress field in the shallow crust has changed to be NE-ENE, which is ca.39° counterclockwise than that before the earthquake, in the fault zone in Beichuan and Jiangyou regions (Wu et al., 2009).

Based on focal mechanism solutions of the Wenchuan Earthquake sequence, a deformation model is given for the Longmen Shan fault zone (Cui et al., 2011; Hu et al., 2012). The results indicate that, structural characteristics and stress state are in favor of reverse fault activity within the northeastern segment of the Longmen Shan fault zone, and the concentrated energy has not been released in spite of the occurrence of the Wenchuan Earthquake and aftershocks (Chen et al., 2012a).

It has modified an approximation method for the calculation of shear stress variation along slipping direction on earthquake rupture plane (Shi and Cao, 2010), and applied it in 3-D simulation of geodynamic problems with different scales, such as the 12 May 2008 Wenchuan Earthquake (Yan et al., 2012), and stress change after reservoir filling in the Longmen Shan fault zone (Sun et al., 2012b).

4.5.2. The North China craton

Hydrofracturing stress measurements by the SinoProbe acquire the magnitude, direction, and distribution of the current stresses from 13 deep holes drilled in the south and the north margins of the Shansi Basin in the North China craton (Chen et al., 2010). The stress monitoring station in Pinggu, Beijing, has successfully recorded continuous changing of stress and underground water-level before and after the Japan Earthquake (Ms 9.0) on March 11, 2011. The relationship between spatial distribution of history earthquakes and speed of tectonic stress accumulating in the North China basin, is simulated based on 3-D visco-elasticity model of rheological layered crust (Liu et al., 2012a).

Water rock interactions occurring in the crust will cause strong leaching of Si, breakage of silicate framework structures, rock collapse, and further lead to the generation of increased rock porosity and also drive fluid flow. These hydrothermal events have a significant role in enhancing the conductivity of rocks in the mid-crust (Zhang et al., 2011b).

5. Conclusion and perspective

In the last five years (2008–2012), the program SinoProbe—Deep Exploration in China, a multidisciplinary earth science research program, has created a new episode for the development of geosciences in China. It will integrate geological, geophysical, geochemical, and modern exploration technology to examine the deep earth structures and their evolution in China. The results will undoubtedly contribute to the improvement of our current understanding of the Eurasia continent in particular and the Earth in general.

The SinoProbe 2008–2012 is expected to lead to the full launch of China’s ambitious initiative of crust and lithospheric exploration in the soon future. A wide range of scientific studies are getting underway, including more detailed exploration of crustal and lithospheric structures, component and activity of the continental China, super-deep continental scientific drilling and long-term observation, 3-D exploration of the deep-sited energy and mineral resources, exploration and utilizing of underground space and deep-level high temperature geothermal, industrializing of deep exploration instruments, and construction of a super-earth simulator, etc.

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