3-D magnetotelluric inversion reveals the superposition of tectonic systems in the northern Songliao Block, NE China

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Summary

The Songliao Block is located in the eastern part of the Central Asian Orogenic Belt. Its creation and evolution are believed to be related to the closure of the Paleo-Asian and Mongol-Okhotsk oceans, and to the subduction of the Paleo-Pacific Ocean. The deep seismic reflection profiles showed that there are sloping mantle reflections below the Songliao Block, which are suspected to be the result of the convergence of three tectonic domains. However, it is still not clear the current structural form of the Songliao Block is caused by the direct action or not of the tectonic systems. This work used 138 broadband magnetotelluric stations to obtain a three-dimensional electrical structural model of the northern Songliao Block. The results showed there are orthogonal network fault systems, faulted basins, igneous rocks. And the Lindian fault depression is the center of the asthenospheric upwelling, the shallowest up to 45 km. Combined with evidence from seismic studies, we proposed that the superposition of tectonic systems may have produced weak tectonic zones. These zones provided channels for the later upward movement of fluids and melt, likely due to hydrous upwellings caused by the subduction of the Paleo-Pacific system.

1 Introduction

The Songliao Block, Northeast (NE) China, is located in the eastern part of the Central Asian Orogenic Belt (CAOB). During the Paleozoic era, NE China experienced a complex history characterized by multiple stages of accumulation and collision. With the closure of the Paleo-Asian Ocean, many micro-continent blocks in NE China were combined into a composite landmass (Xiao et al., 2003; Miao et al., 2008; Jian et al., 2008). In the late Mesozoic, NE China experienced extensive volcanic activity and expansion, which may be related to the subduction of the Paleo-Pacific slab in the east and the closure of the Mongolia-Okhotsk Ocean in the north (Lei and Zhao, 2005; Chen and Pei, 2010). At about 157 Ma, the Paleo-Pacific Ocean began to roll back and cause extension, forming some Mesozoic basins, including the Songliao Basin (Meng, 2013).

Previous geophysical studies (Yang et al., 2004; Liu et al., 2011) in this area were mostly conducted on 2-D profiles, making it difficult to conduct a comprehensive study of large structures across the entire basin. Furthermore, there has been a lack of high-resolution electrical data. In contrast, in this study, using an array of 138 MT sites, we generate a 3-D resistivity model of the northern Songliao Block and determine the electrical structure of the crust and upper mantle. This is done for the first time and gives an unprecedented view into the subsurface of the region. Here we explain the characteristics of the lithosphere under the superposition and transformation of the multi-stage tectonic system.

2 Data collection

The research area is located at an expanse of 120,000 square kilometers in NE China in NE China (Figure 1). MTU-5 MT instruments, manufactured by Phoenix Geophysics of Canada, were used for field collection of MT data. This study used a total of 138 broadband MT sites: 107 sites recorded in the frequency band 0.00073–320 Hz, and 31 MT sites recorded in the frequency band 0.00042–320 Hz. The poles were arranged according to the tensor measurement method. Each MT station measured 5 components, 3 of them were components of magnetic field, while the other 2 were components of mutually orthogonal horizontal electric field. The signal acquisition time was about 1 day, and the average site spacing was 10 km.

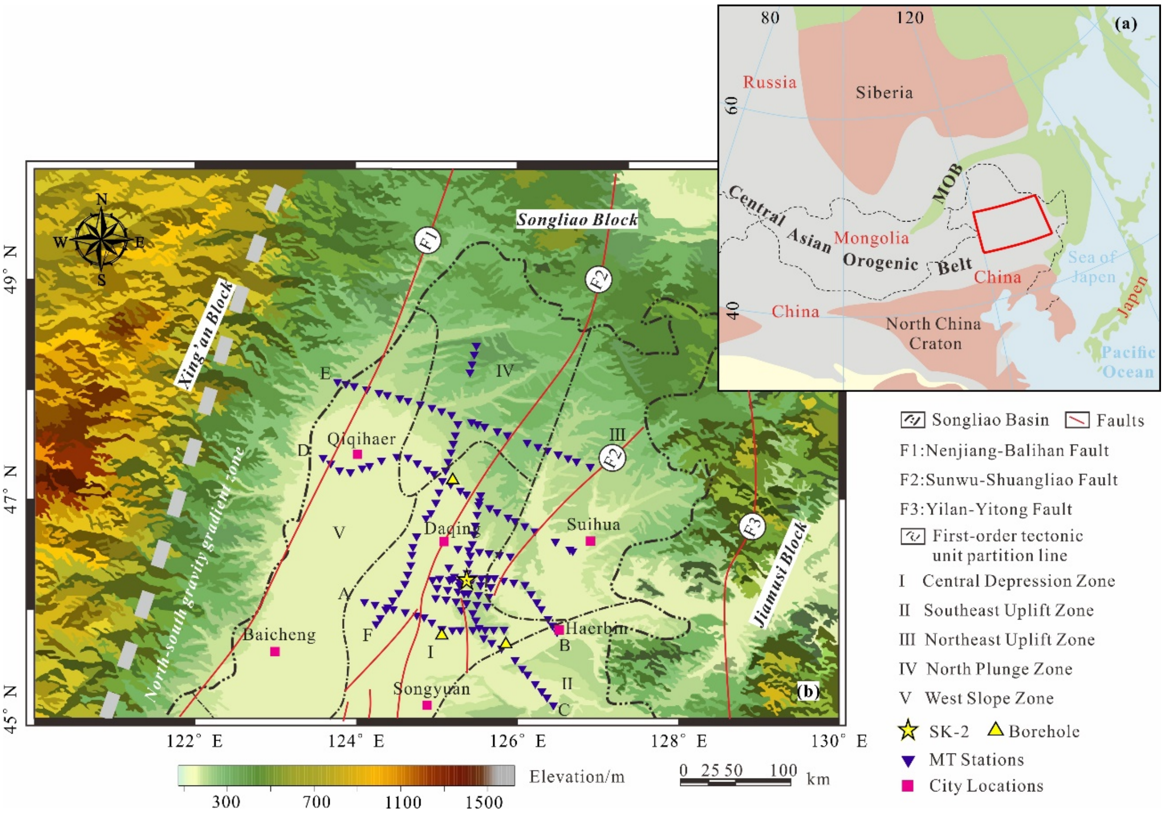

Figure 1. (a) The location illustration of the research area (modified after Safonova and Santosh, 2014). SK-2 is a drilling through the whole Cretaceous sequence of the Songliao Basin, to obtain continuous high resolution continental geological records. (b) The location map of the MT profiles in the north of the Songliao Block. MOB is Mongolia-Okhotsk belt.

3 Electrical resistivity model

The ModEM inversion algorithm (Egbert and Kelbert, 2012; Kelbert et al., 2014) was adopted in this study. The grid dimensions were 5 km in both horizontal directions, covering an area of 310 km by 415 km (excluding the padding which extended an additional ~800 km in both directions). In the vertical direction, the cell dimensions started at 30 m and increased geometrically with a factor of 1.15 to a maximum depth of 220 km. This discretization resulted in a grid with 62×83×55 cells (x, y, z). No topography was included. We imposed error floors of 5% of $|ZxyZyx|^{1/2}$ to full-impedance components. The initial trade-off parameter λ was 100. A total of 87 iterations were performed until convergence, and the normalized root mean square (nRMS) misfit decreased from 41.26 to 2.36.

4 Model features

In Figure 2 and Figure 3, the final 3-D electrical resistivity model is displayed as horizontal and vertical slices. It can be observed that localized low resistivity anomalies are distributed throughout the mid-upper crust (e.g., C1, C5) and the mid-lower crust (e.g., C3, C4, C6), whereas broad low resistivity regions are found in the upper mantle (e.g., C7). What is noticeable is that there is a big piece of high-conductivity anomaly C7 under 30 km with raised centers, two sides are connected with the conductors C3–C6 in the lower crust. The resistivity value more than 10 Ω·m.

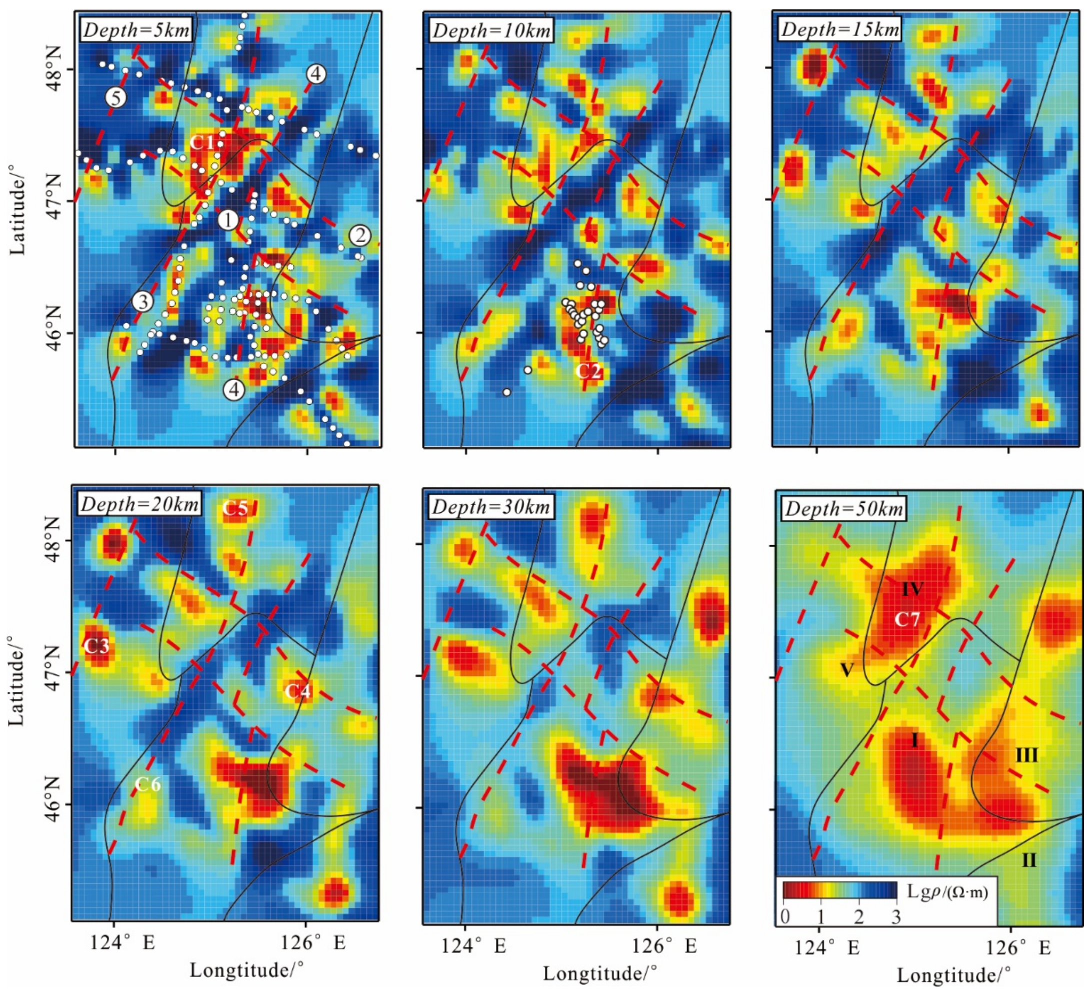

Figure 2. Horizontal slice of the 3-D electrical structure in the north of the Songliao Block. The white circle is the location of the MT stations in the 5km slice. The white circle is the location of the boreholes that encountered CO_2 (according to Zhang et al., 2010) in the 10 km slice. The

black dotted line demarcates the boundary of the structural unit. The red dense line is fault zone ① Binzhou fault zone ② Nehe-Suihua fault zone ③ Yi'an-Tongyu fault zone ④ Sunwu-Shuangliao fault zone ⑤ Nenjiang-Balihan fault zone.

The southern end of the high conductivity feature C1 corresponds to the Binzhou fault zone, and the location of C1 is consistent with the location of the Lindian fault depression on the surface (see Figure 3). At this location the seismic profile is in agreement with the electrical model, showing that the fault depression extends to a depth of 10 km, and is deep in the middle and shallower on the sides. The low resistivity anomaly C2 (visible on the horizontal slice at a depth of 10km, Figure 2) is located at the exact location where a borehole is drilled and where CO_2 is detected (Zhang et al., 2010) (see Figure 2). Thus, it is inferred that feature C2 is a crustal fault system and that it may provide a channel for the upward migration of CO_2.

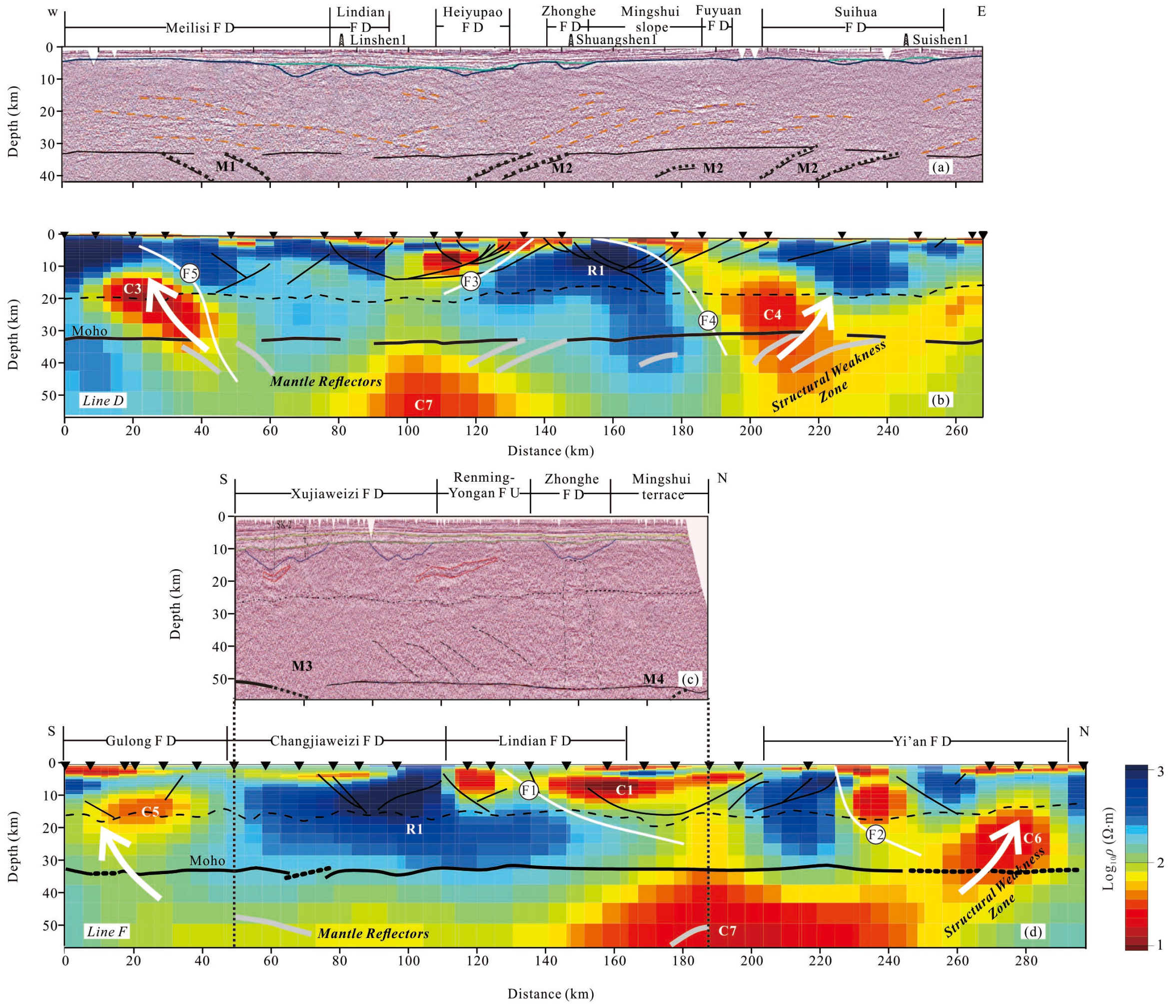

Figure 3. Comparison of the deep reflection seismic profile of Fu et al. (2019) and vertical slices of the 3-D electrical resistivity model in the north of Songliao Block. (a) coincides with the position of (b). (c) is parallel to (d), but offset by approximately 40 km. The thick black line is the depth of Moho (crust-mantle boundary; according to Fu et al., 2019; Sun, 2019). The dashed black line is the middle-lower crust interface identified from seismic data (according to Wang, 2010). The thin solid black line is fault (Wang, 2010). The white line is fault zone according to MT results: F1. Binzhou fault zone; F2. Nehe-Suihua fault zone; F3. Yi'an-Tongyu fault zone; F4. Sunwu-Shuangliao fault zone; F5. Nenjiang-Balihan fault zone. Label F.D.

marks a fault depression and F.U. marks a fault uplift. The label M designates various upper-mantle reflectors interpreted by Fu et al. (2019).

Combined with the residual traces of the tectonic system revealed by the deep seismic reflection profile (Figure 3) and the compressional events in the late Paleozoic and late-middle Jurassic (Chi, 2002). We propose that C3–C6 observed at the edges of the Songliao Block were tectonic weak zones caused by the collision and suturing caused by the closure of the Paleo-Asian Ocean. In addition, then under the strong compressional orogeny of the Mongol-Okhotsk tectonic system and the westward subduction of the Paleo-Pacific Ocean, the weak zones at the edge of the Songliao block developed further.

The lithosphere of the Songliao Block is thinner than the average thickness of the continental lithosphere (Ren et al., 2002; Meng., 2003; Guo et al., 2014). Previous studies have defined the boundary of the lithosphere and the asthenosphere (LAB) as 100–120 km (Zhang et al., 2014), 80km (Guo et al., 2014), and 45–90km (Wang et al., 2018) in the Songliao Block. This conductive zone C7 is assumed to be related to the thin lithosphere and upwelling asthenosphere established at this location.

5 Conclusions

In this work, the full-impedance magnetotelluric 3-D inversion of the MT profile was carried out in the northern Songliao Block, and a 3-D electrical model was established. Based on seismic data and petrophysical methods, electrical structures are used to identify the existence of orthogonal grid fault systems, fault depression, and igneous rocks. The results show that the most prominent area of asthenospheric upwelling is located at the junction of the central depression and the northern plunge area (under the Lindian fault depression), with a buried depth of 45 km in the Songliao Block. The deep electrical structure is analyzed in combination with the residual traces of the tectonic system revealed by the deep seismic reflection profile. It is found that the roots of the lower crustal symmetrical conductors at the edge of the Songliao Block all has distribution of are connected with materials in the mantle. The reason of the broken tectonic weak zone may be the collision welding cooperation between blocks caused by the closure of the Paleo-Asian Ocean or the strong compression orogeny caused by the closure of the Mongolia-Okhotsk Ocean, which provide the tectonic basis for the upward movement of the later partial melting. The upwelling and partial melting of the asthenosphere caused by the subduction of the Paleo-Pacific tectonic system is the direct cause of influencing the crust-mantle structure of the Songliao Block.

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