Research Article

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The Cretaceous stratigraphy, Songliao Basin, Northeast China: Constrains from drillings and geophysics

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Abstract: The Cretaceous nonmarine sedimentary strata are widespread in Songliao Basin, Northeast China. As the largest oil producer in China, an abundance of data has been generated by the petroleum industry, including sedimentology, seismology, geochemistry, and geochronology in the Songliao Basin. This article reviews the achievements in China Cretaceous Continental Scientific Drilling SK and presents the new results of the China Continental Geothermal Drilling SR1 in stratigraphy and geophysics. The results allow us to establish the relationships among SK-1, SK-2, and SR1, provide some constrains on the tectonic setting of Songliao Basin, and interpret the sedimentary facies and environmental evolution. After stratigraphic correlation of SK and SR boreholes, the result indicates that the geological boundary between the late Cretaceous Mingshui formation and the Paleogene Yi'an formation is at the depth of 115 m. The magnetotelluric sounding anomaly areas are corresponding with the unconformities, which are equivalent to seismic horizon T03, T1, T2, and T3, respectively. In addition, the typical "steer's-head" geometry in the magnetotellurics indicates that the SLB has experienced five evolution stages.

Keywords: Songliao Basin, the Cretaceous, the SK1, SK2 and SR1 borehole, magnetotelluric sounding, stratigraphic correlation

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1 Introduction

As the last period of Mesozoic, the Cretaceous (145–66 Ma) has been established as a representative international stratigraphic scale based on the well development of marine strata in the world and formed a two series, twelve stages partition succession [1–5]. The facts that global volcanism, massive oceanic crust generation, rapid rise of the sea level, extreme climatic events, and mass extinction occurred in the Cretaceous have been verified by the palaeogeography, palaeoclimatology, and palaeoecology [6,7].

Stratigraphic correlation is a significant tool to investigate the regularity of the distribution and the characteristics of sedimentary strata in vertical and horizontal directions and can better understand the basin's paleogeography, paleoclimate, and paleoecology evolution [8]. It plays a critical role in deciphering the earth system dynamics and in solving current socio-economic problems faced by humans. Recently, driven by International Geological comparison program and Songliao Basin Scientific Drilling (SK), great progresses have been made in Cretaceous strata in China [9]. This scientific drilling includes two stages, the SK-1 and SK-2. The SK-1 includes drilling and coring of early Paleogene to Late Cretaceous strata in two boreholes (north and south holes), which can be correlated through a regional marker bed of black shale, while the SK-2, including drilling through the whole Cretaceous strata and coring of Early Cretaceous strata and early Mesozoic to Paleozoic basement of the Songliao Basin, consists of two boreholes, the east hole and the west hole. Two stages, i.e., four boreholes, have drilled more than 10,000 m and covered almost 2,800 m cores [10,11].

The SK-1 and SK-2 boreholes enabled the scientists to establish the continuous continental Cretaceous stratigraphic scale, which provide a ruler for carrying out the correlation of continental Cretaceous strata and laying a solid foundation for further study about the palaeoclimate change in Paleogene [12]. Moreover, other achievements such as accurate dating for terrestrial deposits from Turonian to Paleocene, identification marine transgression events, and improving our understanding of modern global warming have been obtained [13].

However, except for the Albian, most of the gold nails (Global Boundary Stratotype Section and Points [GSSP]) have not been determined on the account of the Cretaceous stages that are mainly determined by marine fossils [14–17]. Compared with the marine strata, the research level in the continent is still relatively low, and little attention has been paid on geophysics [18]. Geophysics, especially the magnetotelluric sounding method (MT), has its predominance in detecting the spatial distribution of geological bodies and imaging the fluids beneath the subsurface, because the resistivity of the lithosphere is mainly determined by the fluid content rather than lithology combination [19,20].

In this article, we present the results of latest drilling SLB Geotherm No. 1 (SR1), with the aim to carry out stratigraphic correlation with the SK-1 and SK-2. In addition, we present the MT profile that elucidates the subsurface structure, spatial distribution of the geological bodies, and the change of SLB sedimentary paleoenvironments. The combined results provide new constraints on the sedimentary facies and environmental evolution of the Songliao Basin (SLB). The workflow of this article was shown in Figure 1.

2 Geological background

The SLB is located in the eastern margin of Eurasia, surrounded by Erguna Block in the northwest, Jiamusi Block in the east, and North China Craton in the south [21] (Figure 2a). In Mesozoic, it was sandwiched between the Mongolia Okhotsk suture zone and the subduction zone of Pacific plate and deposited up to 10,000 m Cretaceous volcanic sedimentary sequence [22–25]. In the early Cretaceous, under interaction of two active continental margin zones (the Mongolia Okhotsk and Sikhote-Alin), the SLB developed a series of rift basins, which was dominated by volcanic

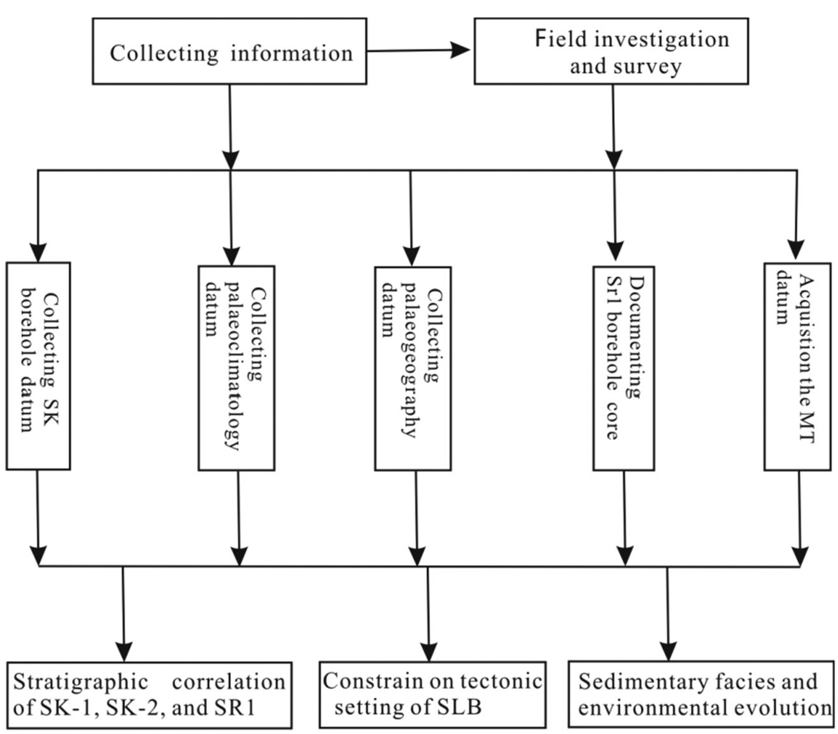

Figure 1: The workflow diagram of this article.

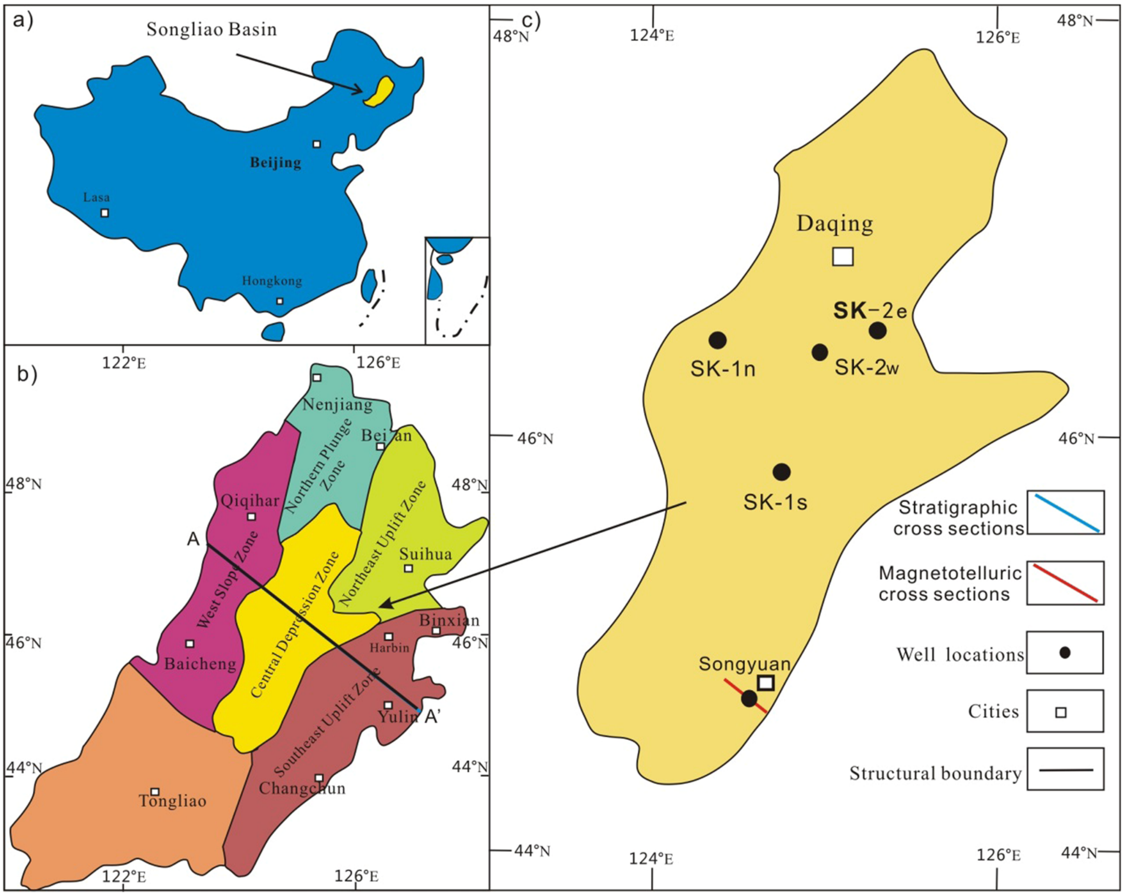

Figure 2: Map showing the location of the SK-1n, SK-1s, SK-2w, SK-2e, SR-1 borehole, stratigraphic cross section, magnetotelluric cross section, and tectonic units of Songliao basin. (a) Songliao basin is located in northeast China. (b) Distribution of six first-order tectonic units. (c) The location of SK-1s, SK-1n, SK-2w, SK-2e, the newly completed in 2019 SR-1 boreholes, and the magnetotelluric cross section.

sedimentary sequence. In the late Cretaceous, driven by the subduction of the Pacific slab, the SLB began to receive the rapid deposited sediments, which was deposited up to 6,000 m in the upper Cretaceous sediments [26,27]. According to the basement properties and regional geological characteristics of the sediments, the SLB can be further divided into six first-order structural units, the western slope zone, the southwest uplift zone, the central depression zone, the northeast uplift zone, and the northern plunging zone [28] (Figure 2b).

The locations of SK-1n, SK-1s, SK-2e, and SK-2w were at E 124°16′26″, N 46°12′50″; E 124°39′08″, N 45°34′11″; E 125°21′47.3″, N 46°14′26.9″; and E 124°40′50″, N 46°04′26″, respectively (Figure 2c). The cretaceous strata can be divided into two series and nine formations, the lower Cretaceous including Huoshiling Formation (Berriasian), Shahezi Formation (Valanginian), Yingchengzi Formation (Hauterivian), Denglouku Formation (Aptain-Barremian) and Quantou Formation (Albain), the upper Cretaceous including Qingbaikou Formation (Cenomanian-Turonian), Yaojia Formation (Coniacian-Santonian), Nenjiang Formation (Campanian), and Sifangtai-Mingshui Formation (Maastrichtian) [29,30] (Figure 3).

To better understand the following inference, we briefly introduce the main stratum lithology. The Donglouku Formation (K_1d) was developed in the rift-depression transformation stage and can be divided into two units [31]. The Quantou Formation (K_1q) was developed in the early depression stage, and it was in parallel unconformity contact with Denglouku Formation. The down-warping stage developed Qingshankou, Yaojia, and Nenjiang Formations. The shrinkage and the regional compression stage developed the Mingshui Formation [32–35]. The lithology of these formations was presented in Table 1.

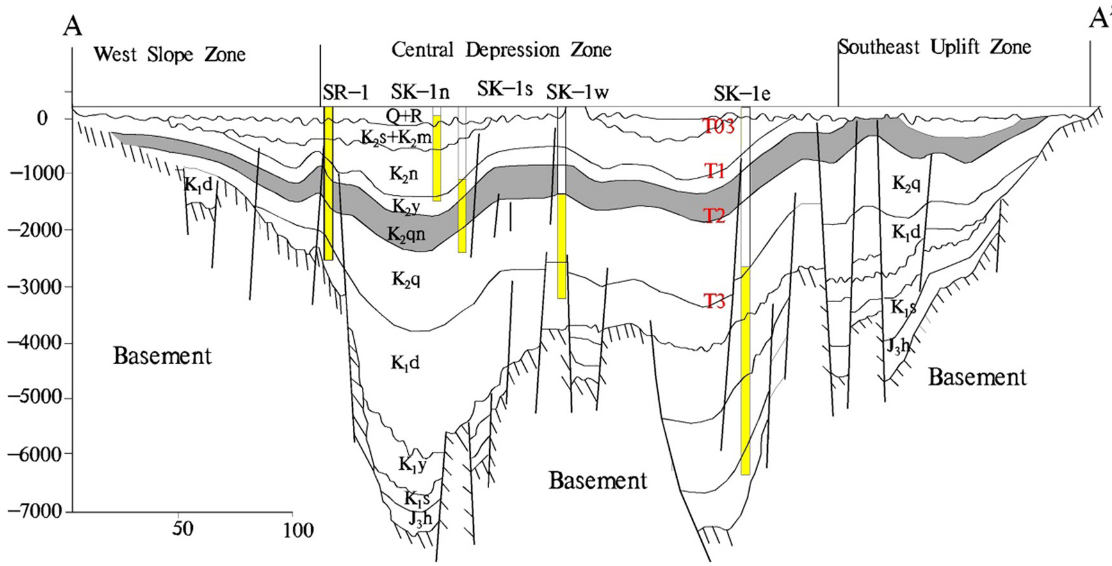

Figure 3: Structural cross section across the central part of the Songliao Basin based on regional seismic analyses; lithologies and formations derived from geophysical logs and cores tied to seismic sections. Q-Ey, Quaternary/Neogene; K_2s, Sifangtai Formation; K_2m, Mingshui Formation; K_2n, Nenjiang Formation; K_2y, Yaojia Formation; K_2qn, Qingshankou Formation; K_1q, Quantou Formation; K_1d, Denglouku Formation; K_1yc,Yingcheng Formation; K_1sh, Shahezi Formation; K_1h, Houshigou Formation; T03-T3, seismic horizons. The yellow bars in SK-In, SK-Is, SK-2w, SK-2e, and SR1 are coring intervals, and the white bars are un-cored intervals.

Table 1: Stratigraphic histogram of SLB

Stage	Formation	Description of the cores
K_2m	Mingshui	Greyish-green, grayish-black mudstone. Interbedded with gray, greyish-green sandstone and argillaceous sandstone
K_2n	Nenjiang	Black, grayish-black mudstone. Shale with intercalation of oil shale
K_2y	Yaojia	Purplish-red, reddish-brown, and greyish-green mudstone. Interbedded with greyish-white sandstone
K_2qn	Qingshankou	Purplish-red, greyish-green, greyish-white mudstone. Intercalation of oil shale
K_1q	Quantou	Purple grey, gray white glutenite. Interbedded with dark purple mudstone
K_1d	Denglouku (2)	Gray green and gray brown mudstone. Interbedded with motley glutenite
	Denglouku (1)	Grayish white conglomerate with grayish green. Purplish red mudstone with some tuff

3 Analytical methods

3.1 Drilling technology of SR1

The SR1 adopts hydraulic vertical spindle core drill instrument type XY-5, which is produced by the Lianyungang drilling machinery factory, Lianyungang, China. The bit adopts diamond bit with a diameter of 127 mm. During the rope core drilling, the inner drill pipe is designed with single action, core blocking alarm, and straightened technology, which can guarantee the core integrity and the rock samples recovery rate [36].

3.2 Magnetotelluric method

At a 8 km northwest to southeast, 500 m dot pitch magnetotelluric (MT) profile comprising 40 (0.001–10 s) stations across southern SLB (location shown in Figure 4) was surveyed to image the two dimensional resistivity distribution of the Cretaceous sedimentary. Magnetotelluric field data were collected by the American crystal earth company instrument Aether type, and the data were processed using prMT software, which could eliminate the serious interference data in the original time series. To get higher quality impedance tensor and apparent resistivity, the time field signal was converted

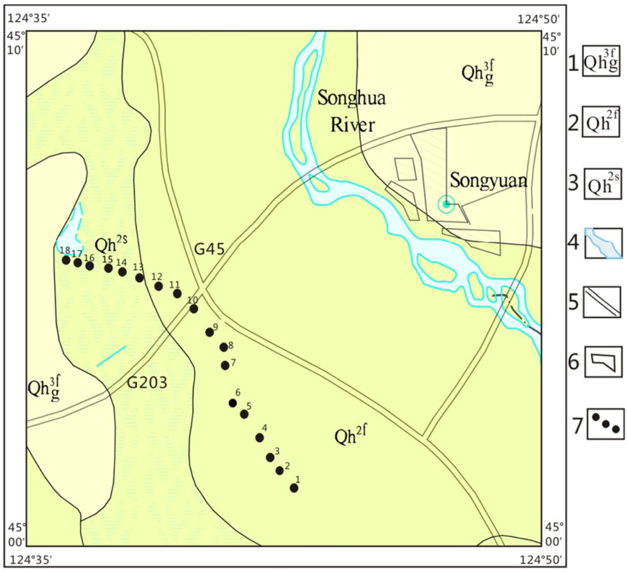

Figure 4: Simplified geologic map of the southern Songliao Basin. (1) Holocence series low washland-riverbed alluvium; (2) Holocence series high washland-riverbed alluvium; (3) Holocence series big deposit; (4). River; (5) Highroad; (6) City; and (7) MT site locations.

to the frequency domain data by the Fast Fourier transform and selective iteration technology. The signal-to-noise ratio of the electromagnetic signal determines whether the correct response of the magnetotelluric sounding can be obtained [37]. Figure 5 shows the apparent resistivity and phase curves of some magnetotelluric sounding points. From these few examples, it can be seen that the quality of the magnetotelluric sounding data obtained in field was good and the near-field interference did not exist in the data. Then, the data adopt the two-dimensional nonlinear conjugate gradient inversion algorithm to obtain the apparent resistivity of different geological bodies in tensor electricity (TE) and tensor magnetism (TM) models by using different inversion parameters [38]. Since the actual dimensions of geological bodies are three-dimensional structures, the TE model is susceptible to induce the magnetotelluric sounding data distortion. Therefore, in this article, we adopt the TM model and the regularization factor τ is 10, which not only takes into account the smoothness of the model but also has a good fitting relationship with the original magnetotelluric sounding data [19]. Initial

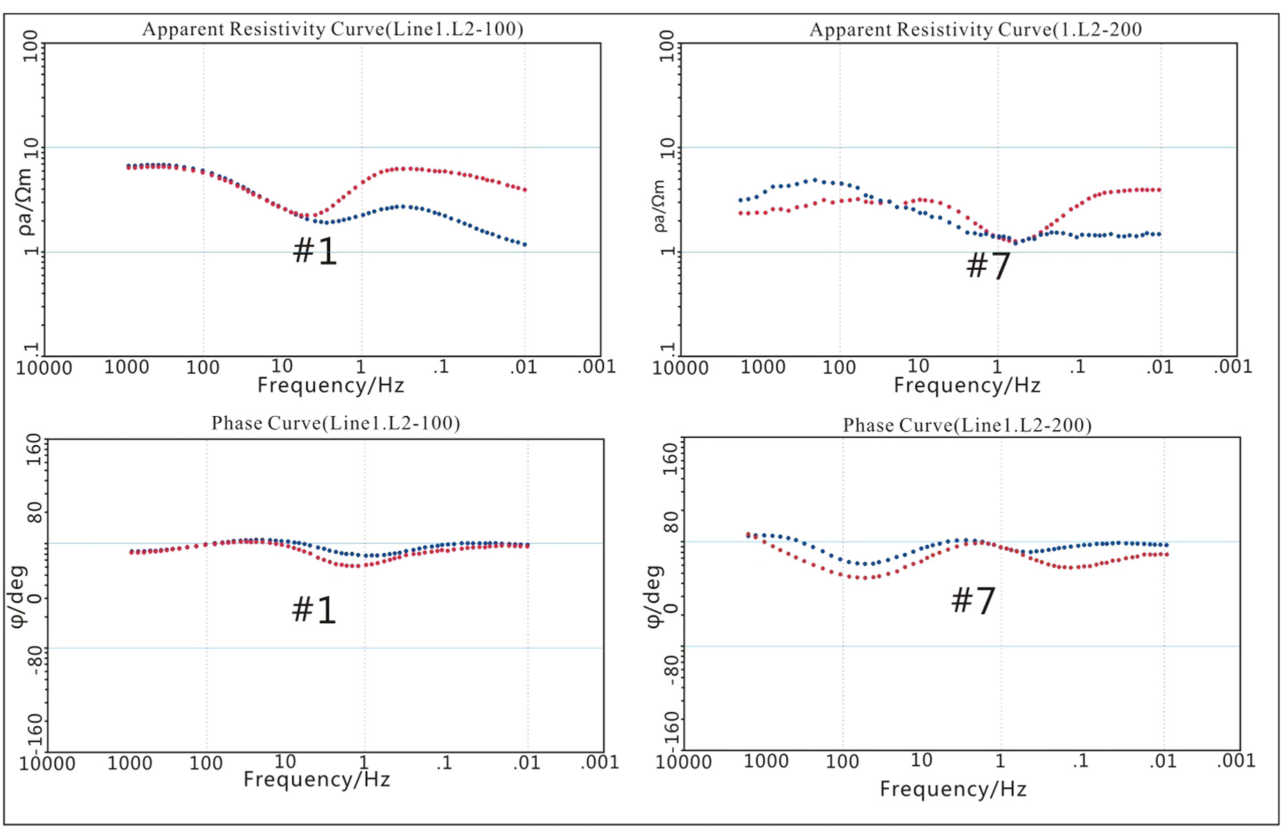

Figure 5: The MT apparent resistivity and impedance phase curve of #1 and #7 points. The blue dot is the tensor electricity model, and the red dot is the tensor magnetism model.

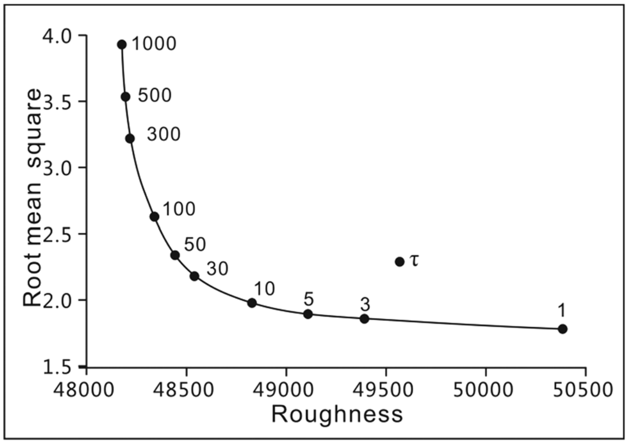

Figure 6: Relationship between RMS versus roughness in L-curve. In this graph, $\tau = 10$ is the compromise parameter.

model resistivity is set to 100 Ωm. The error value of apparent resistivity and impedance phase are 10% and 5%, respectively. The horizontal and vertical smoothness ratio is 1 and the number of iterations is 500 times. The final root mean square (RMS) fitting difference is reduced to 1.7%, which proves the reliability of the inversion result (Figure 6).

4 Results

4.1 The SR1 results

The SR1 program has some research purposes: (1) to study the stratigraphic correlation among the SK-1, SK-2, and SR1 boreholes; (2) to provide some constrains on the tectonic setting of SLB; (3) to understand the sedimentary facies and palaeoclimatology evolution. The SR1 project consists of drilling and coring of Quaternary to Cretaceous strata [35,36]. The drilling depths of 2,010 m were completed, and core samples of 1,895 m were recovered. The detailed description on the SR1 core are some changes of environment within sedimentary microfacies, such as the change of colors, contents, water cut evaluation, and structure. Table 2 presents the columnar section of the SR1.

Table 2: Detailed description of the SR1 core (depth: 0–2,010 m; thickness: 2,010 m)

Formatiom (unit)	Interval (m)	Description of the cores
Qh	0–115	Silty fine sand, subclay, mudstones
Mingshui	115–142	Siltstone
Sifangtaizi	142–160	Mudstone
Nenjiang (4)	160–260	Gray mudstone, with some thin-layered sandstone. Muddy composition, horizontal bedding, poor diagenesis, and waterproof
Nenjiang (3)	260–352	Grayish black mudstone. Muddy composition, horizontal bedding, poor diagenesis, and waterproof
Nenjiang (2)	352–392	Black shale. Muddy composition, lamellar structure, and poor diagenesis
Nenjiang (1)	392–427	Black shale. Muddy composition, lamellar structure, and poor diagenesis. The notable features are oily gloss and the oil shale
Yihe (3)	427–492	Maroon mudstone. Muddy composition, horizontal bedding. Poor diagenesis. Partially sandwiched within layered silty mudstone
Yihe (2)	492–507	Purplish-red argillaceous siltstone. Muddy composition, horizontal bedding. Poor diagenesis
Yihe (1)	507–525	Maroon mudstone. Muddy composition, horizontal bedding. Poor diagenesis
Qingshankou (2)	525–624	Grayish-black, greyish-green, with some maroon mudstone. Muddy composition, horizontal bedding. Good diagenesis, good water content. Silty mudstone is sandwiched at 603.3–624.2 m
Qingshankou (1)	624–671	Black oil shale. Muddy composition, lamellar structure. Good diagenesis. The notable features of this unit are oily gloss, oil smell
Quantou (4)	671–908	Brownish red, partial gray black argillaceous siltstone. Silt composition, good water content
Quantou (3)	908–1,473	Brownish red to white mudstone. Silt composition, horizontal bedding, good water content, good diagenesis
Quantou (2)	1,473–1,553	Dark purple mudstone. Silt composition. Horizontal bedding. Good diagenesis. Six layers sandstone are sandwiched
Quantou (1)	1,553–1,612	Gray green, dark purple mudstone interbedded with siltstone. Silt composition. Horizontal bedding. Good diagenesis
Denglouku (2)	1,713–1,786	Grayish black, partial purlish-red mudstone. Silt composition. horizontal bedding. Good water content. Good diagenesis
Denglouku (1)	1,786–1,903	Grayish-black mudstone. Silt composition. Horizontal bedding
γ5	1,903–2,010	Pale red granite. Coarse grain texture. Fracture development

4.2 MT results

The MT is one of the effective methods that have been widely used to study the lithospheric structure and tectonic evolution history in various terranes of the world [19]. In this article, the variation in the MT resistivity has successfully reflected the change of SLB sedimentary paleoenvironments. The shape of MT resistivity curve is the "high-low-high" H-type. Figure 5 shows the resistivity and the impedance phase curve of #1 and #7 points.

Within the MT profile, overall apart from the top 0–100 m, the MT resistance value is 10^3 Ωm, which indicated that the geological body is Quaternary silt. Sites from #1 to #7 in the shallow (100–800 m), the range of low resistance (10^{-1}–10^1 Ωm), from northwest to southeast gradually expanding can be associated with the thickening of upper Cretaceous sedimentary strata and the range of high resistance (10^2–10^3 Ωm) gradually narrowing can be associated with the thinning of lower Cretaceous sedimentary strata. In the sites from #8 to #18, the MT results show a reverse trend. Thus, both the thickest sediment of the upper Cretaceous and the thinnest of the lower Cretaceous position are in #7 sites.

On the basis of the SR1 results on the #7 point, we may reasonably draw the conclusion of the MT profile that 0–100 m horizontal highest resistance is the Quaternary silt, the 100–140 m horizontal high resistance is the Mingshui formation siltstone, the 140–160 m horizontal high to middle resistance is the Sifangtaizi formation mudstone, 160–260 m horizontal middle resistance is the 4 unit of the Nenjiang formation mudstone, which is the waterproof layer, the 260–430 m horizontal low to middle resistance is the 3 to 1 unit of the Nenjiang formation black shale, the 430–530 m horizontal low resistance is the Yihe formation argillaceous siltstone, the 530–670 m horizontal low to middle resistance is the Qingshankou formation mudstone with a small amount of black shale, the 670–1,710 m the horizontal middle to high resistance is the Quantou formation argillaceous siltstone and mudstone, the 1,710–1,900 m horizontal middle resistance is the Denglouku formation mudstone interbedded with siltstone, and the 1,900–2,010 m is the Indosinian coarse grain texture granite (Figure 7).

5 Discussion

5.1 Stratigraphic correlation

On the basis of SK1n and SK2e results, we present the stratigraphic correlation with the SR1 and the MT section located in the south central depression. The stratigraphy in SR1 is basically consistent with that in SK1n and SK2e; however, there have some differences in definition the geological boundary between of the late Cretaceous Mingshui formation and the Paleogene Yi'an formation. The Paleogene Yi'an formation is at the depth of 318 m [11,13] while in SR1, the depth is 115 m. What is more, the sedimentary sequences of SK1n, SR1 in the Nenjiang formation show some differences: the maker layer lacustrine black shale was found at the depth interval of 1,586–1,800 m in the SK2n borehole, while that was at the depth interval of 352–427 m in SR1 (Figure 3a and b). The total length of Nenjiang formation unit 1 and 2 in SK1n borehole is 214 m, while that in the SR1 borehole is

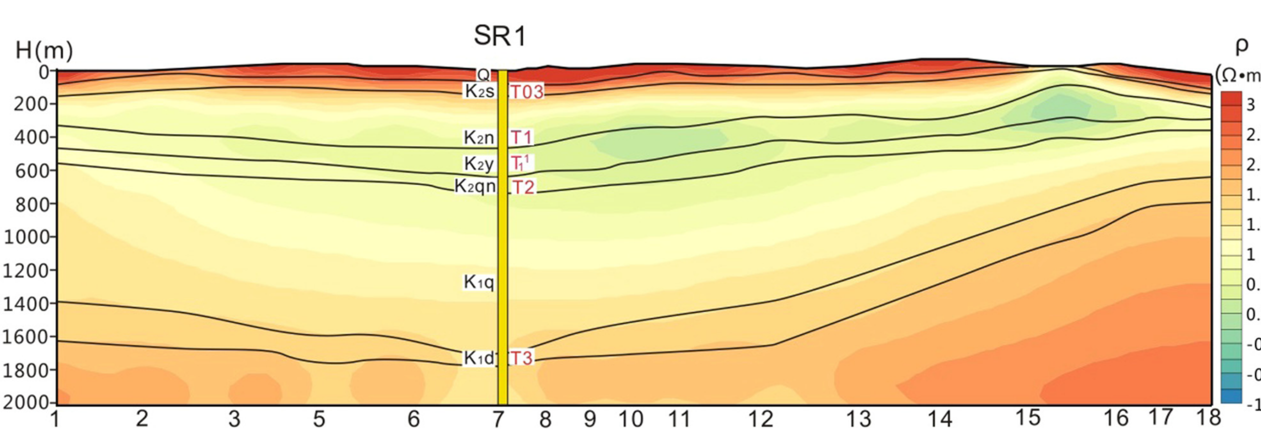

Figure 7: The magnetotellurics nonlinear conjugate gradient inversion results. The yellow bar in SR1 is coring intervals; SR1, China Cretaceous Continental Scientific Drilling Project; T03-T3, seismic horizons.

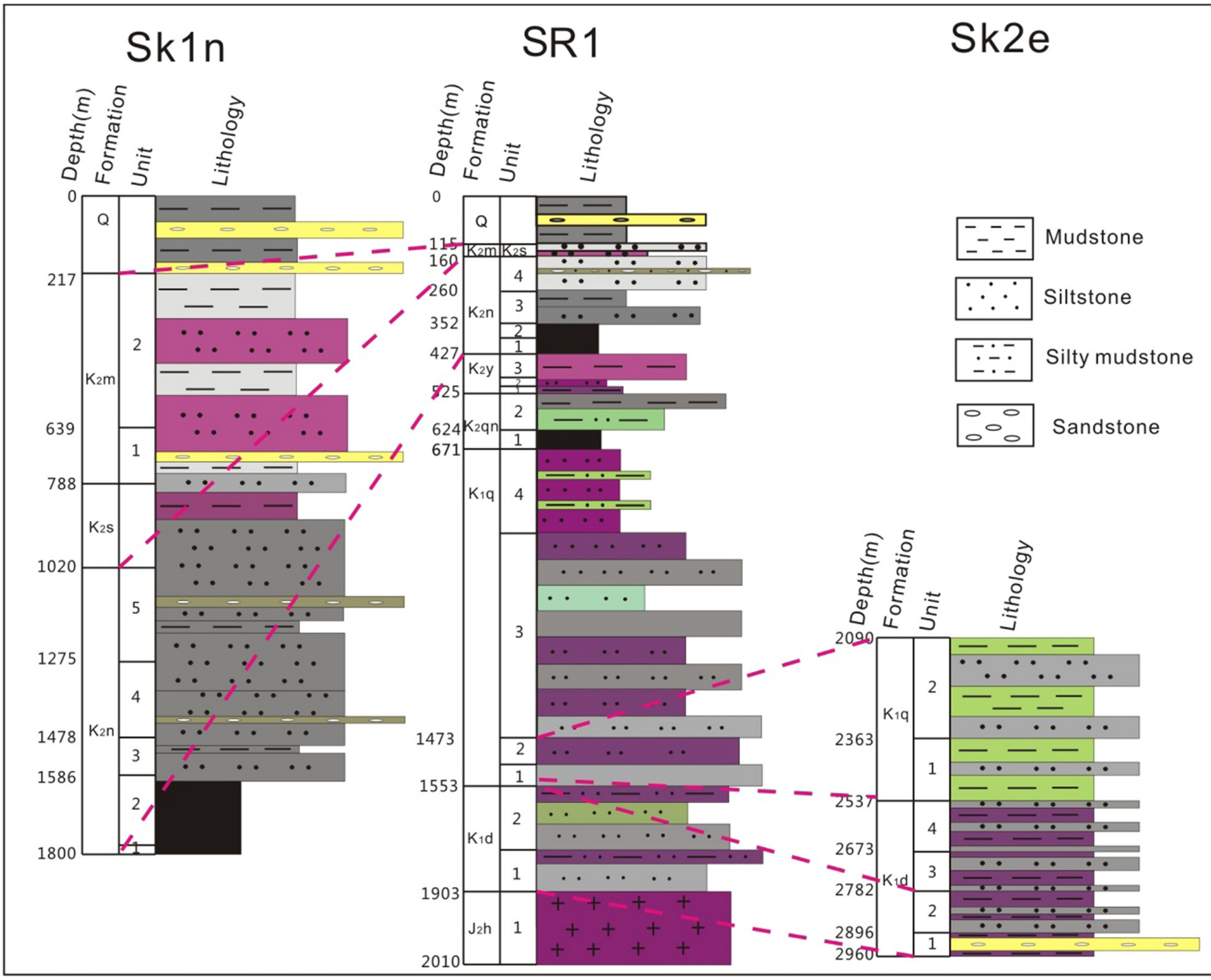

Figure 8: Stratigraphy of the north borehole of the Cretaceous Continental Scientific Drilling SK1n, east borehole SK2e, and the geothermal borehole SR1.

75 m, implying that the depositional thickness is thinner in SR1 (Figure 8).

In addition, this trend can be found in the Quantou Formations: the maker layer mudstone was found at the depth interval of 1,473–1,553 m in SK2e, while that was at the depth interval of 2,090–2,537 m in SR1. The total length of Nenjiang Formation unit 1 and 2 is 80 m in SK1n borehole, while that is 447 m in the SK2e borehole. These results indicate that the depositional thickness is thinner in SR1 than that in SK2e [35].

5.2 Constrain on the tectonic setting of SLB

The nature and the geotectonic setting of SLB have divided the geologists for many years. Some believe that SLB was a back arc basin during Late Jurassic to Cretaceous [24,26]. Opponents of this view argued that SLB was an intracratonic compound rift basin. The data presented in this article as well as the data published in different disciplines such as geothermics, sedimentology, and tectonic are consistent with the second view [39]. Based on the previous achievements, we conclude that the evolution of the SLB consists five stages: (1) mantle uplift stage: during the late Permian to Triassic, the Eurasian plate collides with the paleo-Pacific plate and triggered large-scale folds. (2) Early rift-depression stage: during the middle to late Jurassic, the initial continental tension formed different scales rift basins. (3) Late rift-depression stage: during the late Jurassic to early Cretaceous, the continuous intensive tension caused SLB rift enlarged and developed the Huoshiling, Shahezi, and Yingcheng Formations. (4) Down-warping stage: during the early to late Cretaceous, the thermal subsidence driven SLB integral settlement and developed the Denglouku, Quantou, Qingshankou, Yaojia, and Nenjiang Formations. (5) SLB shrinkage and regional compression stage: during the late Cretaceous to Quaternary, regional stress became compressional and developed the Sifangtaizi and Mingshui formations (Figure 9).

The MT cross section across the south central depression area reveals that the subsurface resistance image is the typical "steer's-head" geometry, which coincides with petroleum industry seismic inference. The Denglouku formation was deposited in the downwarping stage overlap on the graben basins and in the successor extensive overlap. A regional unconformity occurs near the base of the Upper Cretaceous strata, equivalent to seismic horizon T2. This unconformity divides the thermal subsidence tectonostratigraphic unit into two parts, each with distinct architecture and depositional features [31]. The Denglouku Formation, which began to form at the beginning of the Early Cretaceous, is related to left-lateral movement of the Paleo-Pacific plate along the Paleo-Asian continental margin.

Specifically, the MT resistivity anomaly areas are corresponding with the unconformities, such as the unconformities between Mingshui and Sifangtai Formation at the depth of 140 m, the Nenjiang and Yaojia Formation at the depth of 430 m, the Qingshankou and Quantou Formation at the depth of 670 m, and the Quantou and Denglou formation at the depth of 1,710 m, which is equivalent to seismic horizon T03, T1, T2, and T3, respectively [13].

5.3 Sedimentary facies and environmental evolution

The Cretaceous continental sedimentary records of SLB enable us to understand how the terrestrial geologic and ecologic systems responded to past climate fluctuations [6]. The Sk1e, SK1n, SK2e, SK2w, and SR1 boreholes provide significant rock records of global climate changes under the conditions of greenhouse climate.

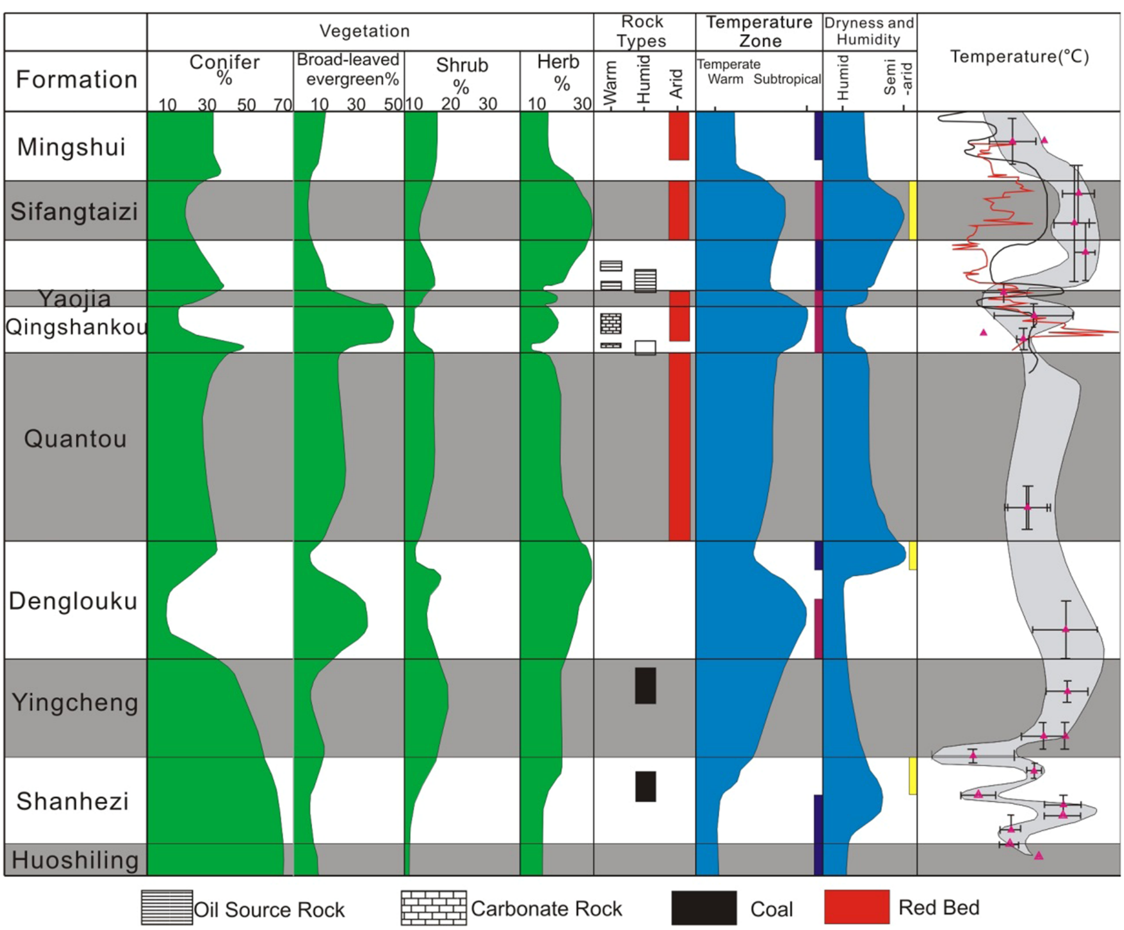

Figure 9: Cretaceous paleoclimate evolution of the Songliao Basin [7].

The occurrence of terrestrial red beds indicates that the climate changed rapidly, and the red beds would be the indication of climates that are warm and dry or seasonal with respect to rainfall [40,41]. Combining with the data of the spore/pollen relative abundances, we argue that the red siltstone intermittently appeared in the Mingshui, Sifangtaizi, Yaojia, Qingshankou, and Quantou Formations in the borehole of SK1n, SK1s, and SR1 indicate that the climates during the middle Cretaceous to the Late Cretaceous were warm and dry or seasonal with respect to rainfall [42,43]. In addition, according to the oxygen isotope data, and the broad-leaved evergreen forest widely spread in SLB and Far East, some experts argued that the temperature is generally above 5°C and the highest more than 25°C [7]. Thus, we argue that the Mingshui, Nenjiang, and Yaojia Formations indicate a semi-humid monsoon warm environment, the Sifangtaizi and Quantou Formation indicate a semi-humid subtropical environment, and the Qingshankou formation indicate a humid subtropical-tropical environment. The absent of red siltstones in Denglouku Formation indicates the climate did not change rapidly or sharply, and the environment was semi-arid semi-humid subtropical [43].

In addition, coal is distributed in Huoshiling–Yingcheng Formation of SLB in Lower Cretaceous, indicating a relatively well-developed plant ecosystem, while, in the SR1 borehole, the coal is virtually absent in the deepest stratigraphic units, implying a less humid climate and less-developed plant ecosystem [42]. Moreover, the main terrestrial petroleum reservoirs in the Qingshankou formation unit 1 and the Nenjiang formation units 1 and 2 indicate different climate zones. The climate zones were shifted from tropical-southern subtropical zone to the northern subtropical zone.

The atmospheric temperature of SLB in Cretaceous changed rapid and can be divided into four cooling events and three warming events. In detail, the cooling events were the Shahezi Formation units 1 and 2, the Denglouku Formation unit 4, and the Nenjiang Formation and the Mingshui Formation unit 2. The warming events were the Denglouku Formation unit 1 and 2, the Qingshankou and Yaojia Formations, and the Sifangtai Formation.

Based on the aforementioned information and the fact that the SLB has the same trends with the Far East in the spore/pollen data, oxygen isotope data, and the Sikhote-Alin orogenic belt in the isotopic data [43], we infer that the paleoclimate and paleoecology of SLB was in humid to semi-humid subtropical environments in the Cretaceous (Figure 9).

6 Conclusion

On the basis of SR1 borehole and magnetotelluric sounding results, we obtain the following conclusion on the SLB.

1. Through stratigraphic correlation with SK boreholes, we inclined that the core samples in SR1 borehole can be subdivided into the Paleogene Yi'an formation, upper Cretaceous Sifangtaizi, Mingshui, Nenjiang, Yaojia, Qingshankou formation, and the lower Cretaceous Quantou Denglouku formations.
2. The magnetotelluric sounding anomaly areas are corresponding with the unconformities, including the unconformities between Mingshui and Sifangtai formation, the Nenjiang and Yaojia formation, the Qingshankou and Quantou formation, and the Quantou and Denglou formation, which are equivalent to seismic horizon T03, T1, T2, and T3, respectively.
3. The typical "steer's-head" geometry of the magnetotelluric sounding resistance image indicate that the SLB has experienced five evolution stages: the mantle uplift stage, the early rift-depression stage, the late rift-depression stage, the down-warping stage, and the shrinkage and regional compression stage.

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References

[1] Schlanger SO, Jenkyns HC. Cretaceous oceanic anoxic events cause and consequence. Geol Mijinbouw. 1976;55:179–84.
[2] Cronin M, Tauxe L, Constable C, Selkin P, Pick T. Noise in the quite zone. Earth Planet Sci Lett. 2001;190:13–30. doi: 10.1016/S0012-821X(01)00354-5.
[3] Haggart JW, Matsukawa M, Ito M. Paleogeographic and paleoclimatic setting of Lower Cretaceous basins of East Asia and western North America, with reference to the nonmarine strata. Cretaceous Res. 2006;27:149–67. doi: 10.1016/j.cretres.2005.11.008.
[4] Wang PJ, Chen FK, Chen SM, Siebel W, Satir M. Geochemical and Nd–Sr–Pb isotopic composition of Mesozoic volcanic rocks in the Songliao basin, NE China. Geochem J. 2006; 40(2):149–59. doi: 10.2343/geochemj.40.149.

[5] Meng FC, Liu JQ, Li M, Liu X, Yin CH, Lu JM, et al. Geochemistry and tectonic implications of rhyolites from Yingcheng Formation in Xujiaweizi, Songliao Basin. Acta Petrol Sin. 2010;26:227–41 (in Chinese with English abstract).
[6] Skelton PW, Spicer RA, Kelley SP, Gilmour I. The Cretaceous World. Cambridge, UK: Cambridge University Press; 2003.
[7] Wang CS, Feng ZQ, Zhang LM, Huang YJ, Cao K, Wang PJ, et al. Cretaceous paleogeography and paleoclimate and the setting of SKI borehole sites in Songliao Basin, northeast China. Palaeogeograph Palaeoclimatol Palaeoecol. 2012;385:17–30. doi: 10.1016/j.palaeo.2012.01.030.
[8] Yang Q, Mizutani S, Nagai H. Biostratigraphic correlation between the Nadanhada Terrane of NE China and Mino Terrane of Central Japan. J Earth Planet Sci Nagoya Univ. 1993;40:27–43.
[9] Gao YF, Qu XJ, Jiang LJ, Wang SX, Wang PJ. Lithology and stratigraphic interfaces prediction of the Continental Scientific Drilling Project of Cretaceous Songliao Basin (SK2). Earth Sci Front. 2017;24:242–56 (in Chinese, with English abstract).
[10] Wang CS, Feng ZQ, Wu HY, Wang PJ, Kong FJ, Feng ZH, et al. Preliminary achievement of the Chinese Cretaceous Continental Scientific Drilling Project-SK-I. Acta Geol Sin. 2008;82:9–20 (in Chinese with English abstract).
[11] Deng CL, He HY, Pan YX. Chronology of the terrestrial Upper Cretaceous in the Songliao Basin, northeast Asia. Palaeogeograph Palaeoclimatol Palaeoecol. 2013;385:44–54. doi: 10.1016/j.palaeo.2012.07.028.
[12] Feng ZQ, Wang CS, Graham S, Koeberl C, Dong HL, Huang YJ, et al. Continental scientific drilling project of Cretaceous Songliao Basin: scientific objectives and drilling technology. Palaeogeograph Palaeoclimatol Palaeoecol. 2012;385:6–16. doi: 10.1016/j.palaeo.2012.03.016.
[13] Wang GD, Cheng RH, Wang PJ. High resolution continuous sedimentary records of Upper Cretaceous obtained from the continental drilling (SK-1) borehole in Songliao Basin: Sifangtai and Mingshui Formations. Geosci Front. 2015;6:895–912.
[14] Hasegawa T. Cenomanian–Turonian carbon isotope events recorded in terrestrial organic matter from northern Japan. Palaeogeograph Palaeoclimatol Palaeoecol. 1997;130: 251–73. doi: 10.1016/S0031-0182(96)00129-0.
[15] Hasegawa T. Cretaceous terrestrial paleoenvironments of northeastern Asia suggested from carbon isotope stratigraphy: increased atmospheric pCO_2-induced climate. J Asian Earth Sci. 2003;21:849–59. doi: 10.1016/S1367-9120(02)00109-8.
[16] Gröcke DR, Hesselbo SP, Jenkyns HC. Carbon isotope composition of Lower Cretaceous fossil wood: ocean–atmosphere chemistry and relation to sea level change. Geology. 1999;27:155–8.
[17] Heimhofer U, Hochuli PA, Burla S. Timing of early Cretaceous angiosperm diversification and possible links to major paleoenvironmental change. Geology. 2005;33:141–4. doi: 10.1130/G21053.1.
[18] Haq BU, Hardenbol J, Vail PR. Chronology of fluctuating sea levels since the Triassic. Science. 1987;235:1156–67. doi: 10.1126/science.235.4793.1156.
[19] Jones A, Ferguson I, Chave A, Evans RL, McNeice G. Electric lithosphere of the Slave Craton. Geology. 2001;29:423–6.
[20] Selway K, Hand M, Heinson G, Payne J. Magnetotelluric constraints on subduction polarity: reversing reconstruction models for proterozoic australia. Geology. 2009;37(9):799–802. doi: 10.1130/G30175A.1.
[21] Wu FY, Sun DY, Li HM, Wang XL. The nature of basement beneath the Songliao Basin in NE China: geochemical and isotopic constraints. Phys Chem Earth. 2001;26:793–803. doi: 10.1016/S1464-1895(01)00128-4.
[22] Şengör AMC, Natal'in BA. Palaeotectonics of Asia: fragments of a synthesis. In: Yin A, Harrison TM, editors. The Tectonic Evolution of Asia. Cambridge: Cambridge University Press; 1996. p. 486–640.
[23] Hendrix MS, Davis GA. Paleozoic and Mesozoic tectonic evolution of central and eastern Asia: from continental assembly to intracontinental deformation. Geol Soc Am Memoir. 2001;194:1–25. doi: 10.1130/MEM194.
[24] Ren J, Tamaki K, Li S, Zhang J. Late Mesozoic and Cenozoic rifting and its dynamic setting in Eastern China and adjacent areas. Tectonophysics. 2002;344:175–205. doi: 10.1016/S0040-1951(01)00271-2.
[25] Wei HH, Liu JL, Meng QR. Structural and sedimentary evolution of the southern Songliao Basin, northeast China, and implications for hydrocarbon prospectivity. AAPG Bull. 2010;94:533–66. doi: 10.1306/09080909060.
[26] Graham SA, Hendrix MS, Badarch G, Badamgarav D. Sedimentary record of transition from contractile to extensional tectonism, Mesozoic, southern Mongolia. Geol Soc Am Abstr Progr. 1996;28:A-68.
[27] Khanchuk AI, Kemkin IV, Kruk NN. The Sikhote-Alin orogenic belt, Russian South East: Terranes and the formation of continental lithosphere based on geological and isotopic data. J Asian Earth Sci. 2016;120(Apr.15):117–38. doi: 10.1016/j.jseaes.2015.10.023.
[28] Gao RQ, Zhang Y, Cui TC. Cretaceous petroleum bearing strata in the Songliao Basin. Beijing (China): Petroleum Industry Press; 1994. p. 333 (in Chinese).
[29] Sha JG. Cretaceous stratigraphy of northeast China: non-marine and marine correlation. Cretac Res. 2007;28:146–70. doi: 10.1016/j.cretres.2006.12.002.
[30] Gao RQ, Qiao XY, He CQ. Cretaceous microphytoplankton from the Songliao Basin and its depositional environment. Acta Micropalaeontol Sin. 1992;9(2):111–26 (in Chinese with English abstract).
[31] Feng ZQ, Jia CZ, Xie XN, Zhang S, Feng ZH, Timothy AC. Tectonostratigraphic units and stratigraphic sequences of the nonmarine Songliao basin, northeast China. Basin Res. 2010;22:79–95. doi: 10.1111/j.1365-2117.2009.00445.x.
[32] Li G, Chen PJ, Wan XQ, Jiang JH, Liu JC, Yin DS, et al. Stratotype of the basal boundary of the Nenjiang stage, Cretaceous. J Stratigraph. 2004;28:297–300 (in Chinese with English abstract).
[33] Li G, Wan XQ, Batten DJ, Bengtson P, Xi DP, Wang PJ. Spinicaudatans from the Upper Cretaceous Nenjiang Formation of the Songliao Basin, northeast China: taxonomy and biostratigraphy. Cretaceous Res. 2009;30:687–98. doi: 10.1016/j.cretres.2008.12.008.
[34] Xi DP, Li G, Wan XQ, Jing X, Li S. Yaojia-Lower Nenjiang Formations and lake evolution of southeastern Songliao Basin, NE China. Acta Paleontol Sin. 2009;48:556–68 (in Chinese with English abstract).

[35] Lin F, Luan H, Zeng Y. Some new correlations of *Q*-value with rock mechanics parameters in underground oil storage caverns. Civil Eng J. 2017;3(8):537–46.
[36] Dormishi A, Ataei M, Mikaeil R. Relations between texture coefficient and energy consumption of gang saws in carbonate rock cutting process. Civil Eng J. 2018;4(2):413.
[37] Wang JY. New progress of magnetotelluric sounding research in China. J Geophys. 1997;S1:206–16 (in Chinese).
[38] Rodi W, Mackie RL. Nonlinear conjugate gradients algorithm for 2D magnetotelluric inversion. Geophysics. 2001;66: 174–87. doi: 10.1190/1.1444893.
[39] Khudololey AK, Sokolov SD. Structural evolution of the northeast Asia continental margin: an example from the western Koryak fold and thrust belt (northeast Russia). Geol Mag. 1998;135:311–30. doi: 10.1017/S0016756898008747.
[40] Parrish JT. Interpreting pre-Quaternary climate from the rock record. New York: Columbia University Press; 1998.
[41] Chamberlain CP, Wan X, Graham SA, Carroll AR, Doebbert AC, Sageman BB, et al. Stable isotopic evidence for climate and basin evolution of the Late Cretaceous Songliao basin, China. Palaeogeograph Palaeoclimatol Palaeoecol. 2013;385:106–24. doi: 106-124.10.1016/j.palaeo.2012.03.020.
[42] Gao RQ, Zhao CB, Qiao XY, Zheng YL, Yan FY, Wan CB. Cretaceous oil strata Palynology from Songliao Basin. Beijing: Geological Publishing House; 1999 (in Chinese).
[43] Zakharov YD, Boriskina NG, Ignatyev AV, Tanabe K, Shigeta Y, Popov AM, et al. Palaeotemperature curve for the Late Cretaceous of the northwestern circum-Pacific. Cretaceous Res. 1999;20:685–97. doi: 10.1006/cres.1999.0175.