Late Cretaceous marine fossils and seawater incursion events in the Songliao Basin, NE China

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Abstract

The Songliao Basin is the largest non-marine oil-bearing basin in China. Because of the absence of substantial evidence, the hypothesis of seawater incursion events into the Songliao Basin remains controversial. The presence of marine fossils could provide direct proof to support this supposition. Here, we report new discoveries of foraminifera, calcareous nannofossils, brackish dinoflagellates, and other marine and brackish-water fossils to support the suggestion of seawater incursion events in the Songliao Basin. Relatively abundant benthic and planktonic foraminifera, calcareous nannofossils, marine and brackish-water dinoflagellates, fish, and bivalves have been discovered in Members 1 and 2 of the Nenjiang Formation, a few foraminifera and brackish-water dinoflagellates have been found in the lower Qingshankou Formation, and just a few brackish-water bivalves have been found in the uppermost Qingshankou Fm. Based on the presence of marine molecular fossils and other evidence, we suggest that relatively large seawater incursion events occurred during the sedimentation of the lower Nenjiang Fm., relatively smaller seawater incursions occurred during the deposition of the lower Qingshankou Fm., and possibly a very small seawater incursion occurred during the sedimentation of the uppermost Qingshankou Fm. These seawater incursion events in the Songliao Basin were controlled by regional tectonic activity, evolution of the palaeo Songliao Lake, and global sea level change. These periodic seawater incursions brought marine biota into the palaeo Songliao Lake.

1. Introduction

The Cretaceous represents the warmest periods in the Mesozoic, with high sea level and oceanic anoxic events (Sclater and Jenkyns, 1976; Haq et al., 1987; Skelton, 2003; Jenkyns, 2010; Hu et al., 2012; Haq, 2014). However, our knowledge of Cretaceous terrestrial climatic change remains weak, which is largely because of the fragmentary nature of the continental stratigraphic record (Wu et al., 2009, 2014). The Songliao Basin in northeast China is one of the largest Cretaceous continental rift basins in the world. The palaeo Songliao Lake was at its greatest extent in the Late Cretaceous, depositing continuous lacustrine sediments, which provide a unique opportunity to study the Cretaceous terrestrial biota, palaeoenvironment, and palaeoclimate. Two large transgressions occurred during the late Turonian (lower Qingshankou Formation) and late Santonian–early Campanian (lower Nenjiang Formation), depositing suites of dark mudstone, black shale, and oil shale (Huang et al., 1998; Feng et al., 2011). During the Late Cretaceous, the palaeo Songliao Lake was a large lake, which was not far from the western Pacific Ocean (Gao et al., 1992; Wang et al., 2013). Thus, it is possible that the Songliao Basin experienced seawater incursion events during these periods (Wang et al., 2001; Xi et al., 2011a, 2011b; Wang et al., 2013; Hu et al., 2015).

Since the 1950s, researchers have proposed that seawater incursion events occurred frequently in the palaeo Songliao Lake.
and that such events were closely related to the development of the oil-source rocks found within the basin (Hu et al., 2015). Evidence of seawater incursion events includes marine and brackish-water fish, bivalves, dinoflagellates, shark teeth, calcareous nannofossils, foraminifera (Gu, 1976; Zhang et al., 1977; Gao et al., 1992; Ye and Wei, 1996; Xi et al., 2011a), biological marker dinoflagellate steranes, 24-n-propyl and 24-isopropyl cholestanes (Hou et al., 2000; Feng et al., 2011; Hu et al., 2015), and stable sulphur isotopes and elements (Wang et al., 2001; Huang et al., 2013). However, fossil evidence supporting the hypothesis of seawater incursions remains poorly studied, and it is difficult to use geochemical parameters to distinguish non-marine and marine environments directly. Consequently, any suggestion regarding the occurrence of marine water incursions is doubted (Huang et al., 1999; Li et al., 2000; Zhang et al., 2014).

The Cretaceous Continental Scientific Drilling project in the Songliao Basin (CCSD-SKI) offers a unique opportunity to investigate the nature of the non-marine Upper Cretaceous palaeoenvironment (Gao et al., 2008, 2009b; Wang, 2013). The sedimentary sequence has been studied in two boreholes (SKI south and north): the lower 959.55 m from the south core (SKI(s)), and the upper 1636.72 m from the north core (SKI(n)) (Fig. 1). The south core comprises the upper Quantou (K2q), Qingshankou (K2qn), Yaojia (K2y), and lower Nenjiang formations (K2n), while the north core comprises the middle to upper Nenjiang (K2n), Sifangtai (K2s), and Mingshui formations (K2m). Since the first discovery of foraminifera in the Lower K2n SKI(s) (Xi et al., 2011), relatively abundant foraminifera, calcareous nannofossils, and brackish-water dinoflagellates have been found more recently in the SKI(s) and SKI(n).

In this study, based on the first report of foraminifera in the Lower K2n of SKI(s) (Xi et al., 2011), we report new discoveries of foraminifera, calcareous nannofossils, brackish-water dinoflagellates, and other brackish-water fossils, together with previously discovered marine and brackish-water fossils, to discuss the likelihood of seawater incursion events of the Songliao Basin. This
will help us better understand the seawater incursion events, palaeoenvironment, and formation of the hydrocarbon source rocks within this basin.

2. Geological setting

The Songliao Basin is a Mesozoic–Cenozoic intracratonic basin in northeastern China. The modern fault-bounded Songliao Basin is about 750-km long and 300–370-km wide, with a total area of 26 \times 10^6 km². It is one of China’s most prolific oil- and gas-producing sedimentary basins and it contains a complete Cretaceous sequence of terrestrial sediments (Gao et al., 1994; Huang et al., 1998; Wan et al., 2013). The Sk1 boreholes are situated in the Qiài-Gulong Depression, which is one of the major depositional centres within the basin (Gao et al., 2008, 2009a; Fig. 1).

The Lower Cretaceous Huoshiling (K1h), Shahezi (K1s), Yingcheng (K1y), and Denglouku (K1d) formations are composed of volcanic–volcanoclastic rocks and alluvial–lacustrine sedimentary rocks, while the upper Cretaceous consists of the Quantou (K2q), Qingshankou (K2qn), Yaojia (K2y), Nenjiang (K2n), Sifangtai (K2s), and Mingshu (K2m) formations, which are composed of lacustrine, deltaic, and alluvial sedimentary rocks (Wang et al., 2007; Wang and Chen, 2013). The chronostratigraphic framework of Sk1 is constrained by high-quality SIM–Pb zircon radiometric ages, magnetostratigraphy, and astronomical time scales (He et al., 2012; Deng et al., 2013; Wu et al., 2013, 2014). The age of the upper K2n1 is Turonian, the K2qn is Turonian to early Coniacian, the K2q is late Coniacian to early Santonian, and the lower K2n1 is late Santonian to middle Campanian (Wang et al., 2013; Wang et al., 2013). The Cretaceous biota of the Songliao Basin includes ostracods, spores and pollen, dinoflagellates, foraminifera, spinicaudatans, gastropods, bivalves, ostracods, spores, and pollen, dinoflagellates, foraminifera, spinicaudatans, gastropods, bivalves, and di-nosaurs (Gao et al., 1994; Huang et al., 1998; Wan et al., 2013). Detailed lithostratigraphic and sedimentary facies descriptions have been undertaken in detail for these formations (Cheng et al., 2009, 2011; Gao et al., 2009b, 2011; Wang et al., 2009, 2011a, 2011c). Abundant ostracods, spores and pollen, dinoflagellates, foraminifera, spinicaudatans, and gastropods have been identified from the cores of Sk1 (Gao et al., 2008, 2009a; Li et al., 2010; Wan et al., 2013).

3. Studied material

Samples for the study of the foraminifera and ostracods were collected on average at 1-m intervals. Samples of 100 g dry weight were dissolved in deionised water for several weeks prior to sieving through a 200–μm sieve. Foraminifera were picked from the samples under a low-power binocular microscope and stored on microscope slides. Scanning electron microscope images of the foraminifera were taken at the China University of Geosciences (Beijing).

Samples from the lower K2n1 of SKI(s) were collected for study of the calcareous nannofossils. The entire procedure included the following six steps. (1) Trim all outer surfaces of the sample and crush it. (2) Place the powdered sediment into a beaker and add distilled water, to which is added NH₃·H₂O to maintain the pH = 8.5. (3) Stir the suspension and place it into the ultrasonic waves for 8–10 s. (4) Decant the supernatant into a second beaker and allow it to settle for 1–2 days before pouring off the upper supernatant liquid. (5) Drop the sample on the slide, smear the suspension thinly across the surface with a toothpick, and dry rapidly on a hotplate before adding a drop of mounting agent and covering with a coverslip. (6) Keep the slide at room temperature for 6–10 days and then observe the slide at 1000× magnification with highly condensed transmitted light under a polarising microscope.

Samples from SKI(n) were analysed as part of the algae investigation. Samples for algae extraction were taken at about 5–10-m intervals along the entire core. Standard preparation techniques using dilute hydrochloric acid (HCl; 30%) for the removal of carbonates and hydrofluoric acid (HF; 40%) for the digestion of silicates were employed. The recovered organic residues were sieved through a screen of 10-μm mesh, after which they were boiled in potassium hydroxide solution (KOH; 10%) for 10 min to remove soluble humic substances. The sieved residues were strewn mounted on glass slides using epoxy. Algae identification and photographing was carried out using a Leica DM4500P microscope.

All of the fossils are preserved in the Microfossil Laboratory of the China University of Geosciences in Beijing.

4. Results

4.1. Foraminifera

Relatively abundant foraminiferal tests were identified from Member 1 (K2n1) and lower Member 2 (K2n2) of the Nenjiang Fm. About nine species of eight genera were identified from K2n1 and lower K2n2 of SKI(s), including benthic calcareous foraminifera: Gavelinella sp., Anomalinoides sp., Hoplophragmoides sp., and Pullenia sp., benthic agglutinated foraminifera: Karrerulina hokkaidoana, Clavulinoides sp., and planktonic foraminifera: Archaeoglobigerina blowi, Archaeoglobigerina cretacea, and Hedbergella flandirini (Fig. 2). This preliminary result has been reported by Xi et al. (2011a), whereas this study considered the distribution of the foraminifera in detail. The foraminifera fossils occur separately in the lowest, middle, and mid-upper K2n1 and the lowest and lower–middle K2n2 (Fig. 3A). About seven species of seven genera were identified from the K2qn1 of SKI(n), i.e., benthic foraminifera: Gavelinella sp., Conboroides sp., and Anomalinoides sp., and planktonic foraminifera: Archaeoglobigerina cretacea, Gelemblittiria sp., Hedbergella sp., and Globotruncanella sp. (Fig. 2). The foraminifera fossils of SKI(n) occur separately in the lower, middle, and upper parts of K2qn2 (Fig. 3B).

Because of the strong diagenesis of the lower K2qn, fossils in Member 1 (K2qn1) and lower Members 2 and 3 (K2qn2+3) of the Qingshankou Fm. are poorly preserved, and no foraminifera were discovered in the lower K2qn. However, a few poorly preserved foraminifera have been identified from the lower K2qn1 of the C73–85 core from the Songliao Basin.

The main characteristics of the foraminifera are described in the following. (1) Most of the foraminifera are calcareous, with only a small number of agglutinated tests. Furthermore, there are many planktonic foraminiferal specimens. (2) Most of the foraminiferal
The lower K2n1 contains seven species of four genera, which tests are poorly preserved, with some pressed flat. In addition to the agglutinated tests and the few calcareous tests, the other foraminifera are a brownish colour. (3) The abundances of foraminifera are relatively high, with >100 tests per 100 g in several samples. The foraminiferal diversity is moderate and it includes benthic calcareous foraminifera, agglutinated foraminifera, and planktonic foraminifera.

4.2. Nannofossils

Relatively abundant calcareous nannofossils were discovered in the lower K2n1 of SKI(s), and 55 fossil specimens were identified. The lower K2n1 contains seven species of four genera, which included Calculites obscurus, Calculites ovalis, Micula sp., Quadrum sp. (Fig. 4). The layers containing nannofossils are consistent with those containing the foraminiferal fossils discovered previously.

The main characteristics of the calcareous nannofossils are described as follows. (1) Most of the fossils are well preserved, but a large number of broken fragments were detected under a polarising microscope. Some fossils suffered structural solution during the preservation process, which led to the disappearance of cross bars, incomplete shields, and indistinct outlines. (2) The diversity and abundances are relatively high. (3) The calcareous nannofossils occur separately in the middle K2n1. Furthermore, Ye and Wei (1996) discovered a few calcareous nannofossils in the lower K2qn and lower K2n.

4.3. Brackish-water algae

The preservation of Late Cretaceous algae in SK1 was found to be poor to moderate (Zhao et al., 2014). The lower K2qn and K2n yielded relatively abundant, slightly brackish to brackish-water dinoflagellates. Klokansium declinatum, K. regulatum, Cymatiosphaera sp., Sentusidinium minor, Granodiscus granulates, Leiosphaeridia hyaline, and Dinogymniopsis granulate were identified from the K2qn1 and lower K2qn2 of SKI(s). Leiosphaeridia hyaline, Granodiscus granulates, and Batiacaspheara sp. were discovered in the K2n1 of SKI(s), and Leiosphaeridia hyaline, Granodiscus granulates, Filisphaeridium sp., Canningia circularis, Sentusidinium bifidum, S. minor, Cleistosphaeridium nenjiangense, Dinogymniopsis minor, D. spinulosa, and D. tuberculata were found in the K2n (Wang et al., 2001). However, the K2y, K2s, and K2m were dominated by fresh algae such as Pediastrum.

4.4. Other brackish-water and marine fossils of the Qingshankou and Nenjiang formations

In addition to the foraminifera, calcareous nannofossils, and brackish algae, other marine and brackish-water fossils found in the cores include fish, bivalves, and molecular fossils (Gu, 1976; Zhang et al., 1977; Gu and Yu, 1999; Hou et al., 2000; Hu et al., 2015). In the following, we summarise the natures of the fossils that have been discovered. The lower K2n yielded a number of brackish-water to marine fish, e.g., Hama macrostoma, Sungarichthys, and shark teeth. The lower K2qn only yielded a few poorly preserved brackish-water fish (Zhang et al., 1977). The lower K2n yielded brackish-water bivalves, including Mytilus and Musculus. The uppermost K2qn yielded examples of the fresh- to brackish-water bivalve Brachidontes elongatus. The ostracoda fauna of the Songliao Basin comprises mainly fresh- to slightly brackish-water types (Ye et al., 2002). The lower ostracoda fauna of the K2qn and K2n is dominated by Cypridea, Canada, and Mongolocyclus, which might live in a fresh to slightly brackish-water environment (Xi et al., 2012; Qu et al., 2014).

4.5. Geochemical and sedimentary evidence for seawater incursion events in the Songliao Basin

A biomarker is usually used as an index to differentiate marine and non-marine environments. Hou et al. discovered dinoflagellate steranes in the K2qn and lower K2n. Recently, Hu et al. (2015) discovered biomarker 24-n-propyl and 24-isopropyl cholestanes in the lower K2qn and lower K2n1 of SKI(s), and they indicated that sedimentary 24-n-propyl cholestane was derived from marine algae. Furthermore, the abundances of 24-n-propyl and 24-isopropyl cholestanes in the lower K2n1 were much higher than in the lower K2qn. A group of methyltrimethyltridecyl chromans (MTTCS) was found in K2qn1 and K2n2 of SKI, implying enhanced salinity and an anoxic bottom-water layer (Wang et al., 2011b). Wang et al. (2001) used multiple indices such as sulphur isotopes, strontium, and elemental geochemistry as indications that
seawater encroached into the Songliao Basin during the sedimentation of the K2qn1, upper K2qn2+3, and K2n. Sulphur isotopes and the ratio of organic carbon to pyrite sulphur of the K2q4 to K2qn1 of Sk1 suggest seawater incursion events occurred during the K2qn1 (Huang et al., 2013). Based on the analysis of dolomite from SK1 Wang et al. (2008)suggested that the formation of the dolomite from SK1 is related to seawater incursion events.

5. Discussion

5.1. Distribution and ages of the brackish-water fossils in the Songliao Basin

Brackish-water and sea-related fossils have been discovered in the K2qn1 and lower K2qn2, uppermost K2qn2+3, and K2n1+2 (Fig. 5). Most of the brackish-water fossils were found in the K2qn1+2; a few brackish-water fossils were found in the K2qn1 and lowermost K2qn2, and just a few possibly brackish-water fossils were discovered in the uppermost K2qn2+3, e.g., bivalves, ostracods, and the biomarker 24-isopropyl cholestane (1320 m of SK1). The distribution of 24-isopropyl cholestane has good correlation with the foraminifera and other marine and brackish-water fossils. The K2qn1 was deposited in a very deep lake and the fossils in this unit might have suffered strong diagenesis, which could mean that most of the fossils have been destroyed.

According to zircon U–Pb ages and magnetic strata, the K2qn1 and K2qn2+3 are late Turonian, K2n1 is late Santonian, and K2qn2 is early Campanian (He et al., 2012; Deng et al., 2013; Wu et al., 2013). Based on the stratigraphy of foraminifera, calcareous nannofossils, and other sea-related fossils, we provide new evidence concerning the age of the lower K2n1+2.

Planktonic foraminifera A. blowi, A. cretacea, and H. flandrini were discovered, which constrain the age of the lower K2qn1. The range of A. blowi extends from the late Coniacian to the Maastrichtian. A. cretacea ranges from the Coniacian to the Maastrichtian, and H. flandrini ranges from the late Turonian to the early Santonian (Caron, 1989). Benthic foraminifera found in the Songliao Basin were widely distributed regionally in the Upper Cretaceous.
Fig. 5. Distribution of marine and brackish-water fossils in the Songliao Basin. Distribution of foraminifera is based on this study, nannofossils and brackish-water algae are based on this study, Gao et al. (1992), and Ye and Wei (1996); marine and brackish-water bivalves and fish are from Gu and Yu (1999) and Zhang et al. (1977), brackish-water ostracods are from Xi et al. (2012), Qu et al. (2014); biomarker 24-isopropycholestanes/mg g C1 from Hu et al. (2015).
strata (Kaiho et al., 1993). The range of C. obscursus extends from the middle Turonian to the late Maastrichtian; that of C. ovalis extends from the late Coniacian to the early Campanian, Micula sp. extends from the late Coniacian to the late Maastrichtian, Quadrupum sp. extends from the early Turonian to the early Campanian (Perch-Nielsen et al., 1985). These calcareous nannofossils were mainly identified in the lower K5N1. According to the global distribution of the abovementioned planktonic foraminifera and calcareous nannofossils, the lower K5N1 appears to be of late Coniacian to early Santonian age.

5.2. Palaeoecology of the brackish-water fossils and salinity change

5.2.1. Palaeoecology

The palaeo Songliao Lake was at its greatest extent in the Late Cretaceous with continuous sediment deposition. This period witnessed a notable evolution of terrestrial biota, which is known as the Songhua biota (Gao et al., 1994; Wan et al., 2013). However, the discovery of foraminifera, calcareous nannofossils, marine and brackish-water fish, bivalves, algae, and other fossils indicate that a mixture of marine and non-marine fauna, or at least brackish-water fauna, existed during the late Turonian (lower K5qn) and late Santonian–early Campanian (K5n1−2).

Foraminifera are a type of marine organism, although a few benthic foraminifera have been reported from brackish water or saline lakes (Cann and De Decker, 1981; Sun et al., 1992; Li et al., 1997; Wennrich et al., 2007). These are normally limited to certain groups such as Nonion, and they are characterised by lower diversity, abnormality of tests, and the absence of planktonic foraminifera (Wu, 1993). Planktonic foraminifera are indicators of normal marine facies. The foraminifera in the Songliao Basin represent various types, but especially planktonic foraminifera. These are distributed worldwide in the marine Cretaceous sediments and almost all planktonic and benthic foraminifera are known in the Northwest Pacific (Caron, 1989; Kaiho et al., 1993; Nishia et al., 2003). Taking into account that the Songliao Basin was a nearshore continental basin, the foraminiferal fauna is relatively abundant and diverse, but it is not continuous in its vertical distribution. This indicates that these foraminifera were introduced into the basin via marine water intrusion.

Calcareous nannofossils commonly occur in the strata of marine environments, with only a few species discovered in sediments accumulated from fresh- to brackish-water transitional environments (Perch-Nielsen et al., 1985; Tang, 1985). Therefore, calcareous nannofossils are generally indicative of marine environments. Sun et al. (2002) suggested that calcareous nannofossils from saline lakes are characterised by very low abundance and diversity. Although deformation has meant that some of our specimens from the Songliao Basin in this study could not be identified at the species level, most of the genera are typical of marine origin, and are usually reported from shallow or coastal marine environments (Perch-Nielsen et al., 1985). The abundance and diversity of the calcareous nannofossils in the Songliao Basin are lower than from a typical marine environment, but much higher than from a typical inland lake. Therefore, we propose that there might have been a marine transgression from the west Pacific into the Songliao Basin, which resulted in a mixture of sea- and freshwater. In such a circumstance, calcareous nannofossils would have been introduced into the palaeo Songliao Lake, and the fossil specimens of some species subjected to deformation because of the salinity decline.

The dinoflagellates in the lower K5qn and K5n1−2 are typical examples of brackish-water species, while those in the K5y, K5s, and K5m are freshwater species. The Palaeoecology of the dinoflagellates suggests that the K5y, K5s, and K5m were deposited in a freshwater environment, whereas the lower K5qn and K5n1−2 were deposited in lightly brackish to brackish-water environments (Gao et al., 1992; Zhao et al., 2014).

The fish Halec, Gaudryella, and Humbertia, which are similar to H. macrostoma, Sungarichthys, and filinichthys, have been discovered in the lower Upper Cretaceous marine stratigraphy in southeast England and the Mediterranean (Zhang et al., 1977). In addition, most shark teeth have been discovered in marine environments. However, the fish Pleisolycoptera daqingensis, found in the K5y, is similar to Lycoptera, which is a typical freshwater fish. Although the fish in the K5qn are relatively poorly preserved, these fossils are similar to those of fish in the K5n1−2. The fish of the K5n1−2 and lower K5qn are possibly related to marine water. However, compared with typical marine fish fauna, the diversity is much lower. We suggest that a few marine fish were brought into the palaeo Songliao Lake when the seawater intruded into the Songliao Basin.

About 64 species of 23 genera of bivalves have been discovered in the Songliao Basin (Gu and Yu, 1999). Most bivalves are freshwater species, but Hendersonna and Lepthes in the lower K5n were discovered in a Cretaceous marine environment (Gu, 1976; Gu and Yu, 1999). Although most species of Brachidontes live in freshwater environments, a few species can survive in a marine environment (Gu and Yu, 1999). Hence, it is suggested that B. elongatus in the uppermost part of the Qingshanou Fm. could have been brought into the Songliao Basin via seawater incursion events.

The dominant species in the Songliao Basin is Cypridea, which is considered to live in a freshwater to oligohaline environment (Hou et al., 2002). Thus, this indicates that the salinity of the palaeo Songliao Lake must have been freshwater to oligohaline during the period of Cypridea dominance. The appearance of abundant ostracoda fauna with noded carapaces in the lowermost K5qn and K5n1−2 possibly indicates a decline in salinity and a freshwater environment (Carbonel and Colin, 1988). In the mid-upper K5qn, Triangulicypris became the dominant genera, which could be attributed to an increase in salinity (Xi et al., 2012).

5.2.2. Salinity change

Based on the analysis of the foraminifera, calcareous nannofossils, algae, bivalves, fish, and ostracods, and other evidence in the K5qn and K5n, it is suggested that at the time of the deposition of these sediments, brackish-water and sea-related fauna existed. Although these brackish-water fossils could have been physically carried into the Songliao Basin (Huang et al., 1999), it is unreasonable to expect that the great number of different sea-related fossils could have been introduced into the lake by birds or by the wind. Furthermore, the discovery of shark teeth indicates that there was at least a river or other similar channel between the palaeo Songliao Lake and the western Pacific. Therefore, we suggest that the brackish-water fauna found in the K5qn and K5n might be related to marine water.

Deposits of gypsum or salt were not discovered in the K5qn and K5n, which indicates that evaporation was not strong during this period (Gao et al., 2008, 2009a, 2009b). The presence of spores and pollen also indicates that during the time of the lower K5qn and lower K5n, the climate was relatively warm and humid (Gao et al., 1999; Zhao et al., 2014). Therefore, the change in salinity could have been the result of seawater incursions rather than a climate-induced effect.

5.3. Seawater incursion events in the Songliao Basin

The Cretaceous Songliao Lake was formed within a large continental rift basin, where deposition was largely controlled by tectonic subsidence and climate change. The seawater incursion events were interrelated with tectonic activity, sea level change, and lake transgressions (Xi et al., 2011b; Hu et al., 2015). A deep and large lake
formed during the late Turonian K2qn1 and late Santonian—early Campanian K2n1+2 (Yang et al., 1985; Feng et al., 2010; Xi et al., 2011; Wang, 2013; Wang et al., 2013). The deep lacustrine facies during the depositional phase of the lower K2qn covered an area of more than 1 × 10⁶ km², K2n1 covered an area of about 1 × 10⁶ km² (Fig. 6B), and the lower K2n1 covered an area of more than 2 × 10⁶ km² (Gao et al., 1994). The area of the palaeo Songliao Lake expanded beyond the existing basin boundary (Gao et al., 1992). The Songliao Basin was a large nearshore tectonic continental basin (Fig. 6A). Large lake transgressions occurred during the deposition of the K2qn1 and K2n1+2 and consequently, the level of the lake rose and the lake area enlarged. It is suggested that during the largest lake transgression, the lake boundary expanded and the lake area became larger than it is today (Gao et al., 1992; Huang et al., 1998).

During the late Turonian to early Campanian, the sea level was approximately 200-m higher than it is today (Haq et al., 1987; Miller et al., 2005; Haq, 2014). The sea level was high during the late Turonian K2qn1, earliest Coniacian upper K2qn2-3, and late Santonian—earliest Campanian K2n1+2. As the ocean was not far from the eastern margin of the Songliao Basin (Gao et al., 1992; Hu et al., 2015), the seawater ingress into the palaeo Songliao Lake likely occurred when the levels of both the lake and the sea were high. A large, shallow embayment opening eastwards to the palaeo Pacific existed in eastern Heilongjiang and northeastern China during the Early Cretaceous (Sha et al., 2003; Sha, 2007). The Late Cretaceous basins of Northeast China are characterised by non-marine deposits with intercalations of volcanic rocks and marine or brackish-water deposits (Chen and Chang, 1994; Sha 2007; Wan et al., 2007). There is no direct channel or bay that allowed seawater to pass into the Songliao Basin. Because detailed palaeogeographic evidence is lacking, the exact position and nature of the channel between the Songliao Basin and the palaeo Pacific remain unknown.

The palaeo Songliao Lake was located in East Asia and the movement of the Izanagi/Kula Plate strongly influenced its morphology (Hu et al., 2015; Song et al., 2015). The palaeo Pacific Ocean Plate, IKP, suddenly changed direction at the ages of 90, 84, and 71 Ma (Norton, 2007; Yang, 2013; Song et al., 2014; 2015; Hu et al., 2015). The timing and stress field of this uplift event coincided with the global plate reorganisation between the Eurasian and palaeo Pacific plates, beginning at around 90–89 Ma and culminating around 88–87 Ma (Song et al., 2014). The turning times at 90, 88–87, and 84 Ma, coincide well with those of the SWIEs in SLB. Therefore, it is suggested that large tectonic activities created sinistral slip fault systems, allowing seawater to enter the palaeo Songliao Lake.

As has been discussed above, the seawater incursion events into the Songliao Basin were controlled by regional tectonic activity, lake evolution, and global sea level change. The seawater likely entered the palaeo Songliao Lake when the sea level was high, there was strong tectonic activity, and the lake area expanded. Discovery of the foraminifera, calcareous nannofossils, brackish-water bivalves, fish, and algae in the Songliao Basin indicate seawater incursions during the sedimentation of the K2qn1, lowermost K2n1, and K2n1+2. Because of the periodic seawater incursions, marine biota were transported into the Songliao Basin. The seawater is believed to have entered the Songliao Basin through rivers, fault systems, or other such channels. However, the locations of the channels of the marine incursions into the basin remain unknown. Therefore, further studies investigating the details of the Late Cretaceous palaeogeography of East Asia and the identification of the exact seawater channels need to be undertaken. The seawater incursion events into the Songliao Basin might have enhanced the productivity in the lake and helped in the preservation of the source rocks (Feng et al., 2011; Xi et al., 2011a; Hu et al., 2015).

Fig. 6. Location and tectonic map of the Songliao Basin (A, modified from Song et al. (2015)) and palaeogeography of the K2n1 (B, modified from Feng et al., 2010); SLB: Songliao Basin, SAB: Sanjiang Basin.
6. Conclusion

Discovery of relatively abundant benthic and planktonic foraminifera, nano fossils, brackish-water algae, fish, and bivalves in the K2qn1, lowermost K2qn2, uppermost K2qn3, and K2n1–2 provide evidence supporting the hypothesis of periodic seawater incursions into the Songliao Basin. These seawater incursion events into the Songliao Basin were controlled by regional tectonic activity, evolution of the palaeo Songliao Lake, and global sea level change. Furthermore, because of these periodic seawater incursions, marine biota were carried into the Songliao Basin.

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