A new understanding of the sedimentary environment of the Laiyang Group in the Lower Cretaceous of Lingshan Island, Shandong Province, East China

ZHANG Xiangyu1,2, LI Shoujun1,*, ZHAO Xiuli1, GENG Geng1 and YAN Mingming1

1 College of Earth Science & Engineering, Shandong University of Science and Technology, Qingdao, Shandong, 266590, China
2 Key Laboratory of Stratigraphy and Palaeontology, Ministry of Natural Resources, Beijing, 100037, China

Abstract: The sedimentary background and sedimentary environment of the Lower Cretaceous of Lingshan Island, Shandong, remain unclear. There is considerable controversy as to whether the sedimentary environment was marine or continental. In this study, analyses were conducted with respect to indicators of paleosalinity, the chemical composition of clay, paleobiota, the characteristics of strata exhibiting salinization in eastern China during the Early Cretaceous, and the relationship between paleosalinity and paleoclimate. The results indicate that the sedimentary environment of the Lower Cretaceous Laiyang Group of Lingshan Island was that of a salified lake rather than a marine environment. This study not only provides a reference for determining the sedimentary environment of the Lower Cretaceous Laiyang Group of Lingshan Island but also offers a new perspective for the study of Cretaceous strata with salinization characteristics in eastern China.

Keywords: Lingshan Island; Lower Cretaceous; paleobiota; paleosalinity; paleoclimate; a salified lake

E–mail: lishoujun@126.com

1 Introduction

The sedimentary strata formed in the Early Cretaceous of Lingshan Island were generally considered fluvio–lacustrine deposits, and their characteristics are considered consistent with those of Jiaolai Basin (Shandong Provincial Bureau of Geology and Mineral Resources, 1991). In recent years, however, hypotheses on the genesis of the sedimentary strata in Lingshan Island have varied between scholars. Some researchers maintain that it was a marine sedimentary environment (Lü et al., 2011; Zhang et al., 2013; Wang et al., 2014, 2016; Zhou et al., 2015; Yang et al., 2017; Zhang et al., 2017; Zhou et al., 2017), while others believe that it was a continental depositional environment (Zhong, 2012; Shao et al., 2014; Ge and Zhong, 2017; Li, 2017; Meng et al., 2018a; Meng and Li, 2019).

Lü et al. (2011) proposed that the flysch with well–developed soft–sediment deformation structures was formed in a marine sedimentary environment. On this basis, the attributes of the Laiyang Group in Lingshan Island are considered to be different from those of Jiaolai Basin and the soft–sediment deformational layer in the basin was established as a new lithostratigraphic unit—the Lingshandao Formation (Zhang et al., 2013). Many scholars have conducted trace element analysis of mudstone or siltstone in the study area and speculated that the sedimentary environment of the strata was marine (Zhang et al., 2017; Yang et al., 2017; Zhou et al., 2019).

However, Zhong et al. (2012, 2016) and Li et al. (2017) have raised some opposing ideas in which the strata are continental lacustrine deposits. Li et al. (2017) discovered fish and conchostracan fossils in the Lower Cretaceous of Lingshan Island and proposed that both species were widespread in the Jiaozhou–Laiyang Basin of Shandong Provence and that they belonged to typical continental lacustrine fauna of the Early Cretaceous. The continental lacustrine environment during the Early Cretaceous was determined according to the trace element analysis of the clastic rock of the Laiyang Group (Shao et al., 2014; Meng et al., 2018a; Meng and Li, 2019).

Xu et al. (2015) discovered more glauconite in thin sections of Lingshan Island and believed that the sedimentary environment might be the marine sedimentary environment or developed saline water
Yang et al., (2018) emphasized that lithology descriptions and lithofacies analysis are not convincing evidence to determine sedimentary environment since the lithofacies in Lingshan Island may also deposited in lacustrine setting.

Considering the above, it seems that none of the five approaches above (trace-element analysis, identification of fossils, sedimentary structure analysis, analysis of minerals, lithofacies analysis) offers a decisive proof regarding the sedimentary setting. However, a combination of geochemical indicators and paleontological evidences, and particularly the indices of paleoclimate may jointly provide convincing proof. Therefore, based on previous research, the present study analyzes geochemical elements combined with the morphology and distribution of paleobiota in the study area, the relationship between paleoclimate and paleosalinity are analyzed to solve the dispute over the type of sedimentary environment of the Laiyang Group in Lingshan Island.

2 Geological settings

As the first high island in Northern China, Lingshan Island, with an altitude of 513.6 m, is located in the coastal area of the Yellow Sea in the southeast of Huangdao Region, Qingdao City, Shandong Province. Lingshan Island was formed by multiple processes, including tectonism and magmatism (Luan et al., 2010). Lingshan Island has a special geographic location, and the tectonic location is close to the collision suture zone between the North China Plate and the Yangtze Plate. With respect to its geotectonic location, the Lingshan Island lies to the east of the Sulu orogenic belt (Fig. 1 (a)). It separates the Jiaolai Basin to the north, connects with the Jiaonan uplift to the west, and extends to the Haiyang Sag of the Jiaolai Basin to the east. There are three main faults: the Tan–Lu fault to the west, the Wulian–Yantai fault to the north, and the Qianliyan uplift to the southeast (Cai et al., 2005; Zhang et al., 2007; Zhou et al., 2015; Zhang et al., 2015).

Lingshan Island strata can be divided into five different lithologic units, namely, the mafic intrusive body, medium–fine sand–mudstone interbedding, medium–thick rhyolite, gravel–bearing coarse sandstone and volcaniclastic lava (Wang et al. 2014, 2016), from bottom to top, as shown in Fig. 1 (b). Two sets of strata developed in the basin, mainly the Fajieying Formation of the Laiyang Group in the Lower Cretaceous (K1Lf) and Bamudi Formation of the early Cretaceous Qingshan Group (K1Qb); from bottom to top; Fig. 1 (b)). The lower part of the Fajieying Formation consists of thin greyish–yellow sandstones alternating with dark gray to black shales, with a large number of soft sedimentary deformation structures (Fig. 2). These deposits are unconformably overlain by a rhyolite of varying thickness, which in turn is overlain by a succession of more than 150 m of both siliciclastic sediments (conglomerates, sandstones and mudstones) and volcaniclastic and effusive rocks. The

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rhyolite and overlying rocks together constitute the Early Cretaceous Bamudi Formation (Wang et al., 2014, 2016; Meng et al., 2018b).

Fig. 2. Typical deformation structure in the Laiyang Group of the Lower Cretaceous in Lingshan Island. (a) Deformation structures in Chuanchang; (b)–(e) deformation structures in Dayukou Village; (f) deformation structure in Laohuzui.

3 Samples and Methods

3.1 Field survey and sample collection

The west side of Lingshan Island was selected as the study area. The starting point of the sampling route was the Chuanchang, with southerly passes through Dayukou Village and upper portions of the lighthouse; the endpoint of the route was at Laohuzui, as shown in Fig. 1 (c). The stratum exposed in the Chuanchang section is a gray–black siltstone and black mudstone interbedded layer with a visible deformation structure, where three fresh mudstone samples were selected and numbered as LSD–1, LSD–2 and LSD–3. The strata of Dayukou Village are gray–black siltstone and black mudstone interbed, gray–black mud shale, gray–black siltstone, gray–black mudstone and siltstone interbed (including fish and conchostracan fossils). The samples of fresh shale were retrieved from Dayukou Village and its adjacent strata. The samples were numbered from LSD–4, until LSD–10, respectively. The upper part of the lighthouse is exposed with yellow fine sandstone, mudstone and yellow conglomerate, where the fresh mudstone sample, numbered LSD–11, was taken. The grey–white rhyolite can be seen in Laohuzui, as shown in Fig. 3.

3.2 Analytical methods

In this study, eleven fine clastic rock samples were selected from the Laiyang Group of Lower Cretaceous in Lingshan Island, in which eight samples are grey–black shale and three samples are black shale (Fig. 3). All samples were crushed to less than 200–mesh powder in an agate mill for further geochemical study.
### 3.2.1 Analytical method of major elements

Powdered samples were firstly dried at 120°C for 8 hours and stored in a dryer. About 500 mg of each sample powers were weighed and mixed with lithium tetraborate (4000 mg) evenly. Then the mixed samples were poured into platinum and 3 drops of 10% LiBr solution (release agent) were added into the platinum crucible. Platinum crucible with samples was placed in muffle furnace at 700°C for 5 minutes, while the samples can be fully oxidized. Finally the samples were heated to 1000°C by gradient for 7 minutes until totally melted, during which the platinum crucible was in a state of steady shaking. Major element contents were analyzed by ZSX Primus II X-ray fluorescence spectrometer (XRF) with an accuracy of 0.5% in Qingdao Sparta Analysis & Testing Co., Ltd. The analysis data is shown in table 1.

### 3.2.2 Analytical method of trace elements

Powdered samples were digested in a capped Teflon beaker with 1 mL ultrapure HF and 0.5 mL ultrapure HNO₃ at 200°C for 24 hours until totally dissolved. After digestion of the powder, the vial was opened to air and heated to 130°C for 3 hours until the sample was fully dried. The dried sample was finally diluted in 2 mL ultrapure HNO₃ and 5 mL ultrapure water. Trace element contents were determined by atom inductively coupled plasma mass spectrometer (ICP–MS) of the British nu company with an accuracy of 1% in Qingdao Sparta Analysis & Testing Co., Ltd. The analysis results are shown in Table 1.

#### Table 1 Statistics on geochemical elements and element ratios of the Laiyang Group in Lingshan Island

<table>
<thead>
<tr>
<th>strata</th>
<th>lithological column</th>
<th>samples sampling locations</th>
<th>lithological description</th>
<th>field pictures</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSD-11</td>
<td></td>
<td></td>
<td>grey-white rhyolite</td>
<td></td>
</tr>
<tr>
<td>LSD-10</td>
<td></td>
<td></td>
<td>yellow conglomerate, mudstone and siltstone</td>
<td></td>
</tr>
<tr>
<td>LSD-9</td>
<td></td>
<td></td>
<td>yellow mudstone and sandstone</td>
<td></td>
</tr>
<tr>
<td>LSD-8</td>
<td></td>
<td></td>
<td>grey-black mudstone and siltstone interbeds, containing fish and conchostracan fossils</td>
<td></td>
</tr>
<tr>
<td>LSD-7</td>
<td>Dayukou Village</td>
<td></td>
<td>grey-black siltstone and black mudstone interbeds</td>
<td></td>
</tr>
<tr>
<td>LSD-6</td>
<td></td>
<td></td>
<td>grey-black siltstone and black mudstone interbeds</td>
<td></td>
</tr>
<tr>
<td>LSD-5</td>
<td></td>
<td></td>
<td>Grey-black shale</td>
<td></td>
</tr>
<tr>
<td>LSD-4</td>
<td></td>
<td></td>
<td>grey-black siltstone and black mudstone interbeds</td>
<td></td>
</tr>
<tr>
<td>LSD-3</td>
<td></td>
<td></td>
<td>grey-black siltstone and black mudstone interbeds, the deformation structure is visible</td>
<td></td>
</tr>
<tr>
<td>LSD-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSD-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Comprehensive stratigraphic column of the Laiyang Group in the Lower Cretaceous on the west side of Lingshan Island.
Analysis of elemental geochemical characteristics is an important aspect associated with restoring the sedimentary environment of sedimentary rocks (Zhao et al., 2009; Garni et al., 2012; Neidhardt et al., 2013; Kim et al., 2014; Yang et al., 2014; Li and Jiang, 2016; Yu et al., 2017). Many scholars have studied the sedimentary environment by analyzing the elemental geochemical characteristics of sediments and have made significant contributions to the scientific research (Allwood et al., 2010; Kemkin and Kemkina, 2015; Ye et al., 2016).

4 Results

3.3 The quantitative calculation of paleosalinity

X-ray diffraction of clay minerals was performed in Qingdao Sparta Analysis &Testing Co., Ltd. Clay mineralogy was determined for the < 1 μm fraction of the samples by means of a peak–area comparison of oriented–aggregate X–ray diffraction patterns (Table 2). ‘Kaolinite boron’ (B_k) was calculated for each sample according to Couch (1971):

\[ B_k = B/(4X_k + 2X_{ch} + X_i) \]

Where: B_k = ‘kaolinite boron’ concentration (in ppm), B = measured boron concentration in the samples (in ppm) and X_k, X_{ch}, X_i = weight fractions of illite, chlorite and kaolinite, respectively, as determined by X–ray diffraction.

Paleosalinity (Sp) was calculated according to Couch (1971) by the formula:

\[ \log B_k = 1.28 \log Sp + 0.11 \]

4.1 Analysis of the chemical composition characteristics of clay
The chemical composition of clay deposits can provide useful sedimentary information and evidence during the analysis of sedimentary environments (Sun et al., 1997; Alipour and Mosavi, 2018). Based on the data shown in Table 1, the relative contents of \( \text{Al}_2\text{O}_3 \), \( \text{K}_2\text{O} \) and \( \text{MgO} \) in mudstones and siltstones in the Laiyang Group of the Lower Cretaceous in Lingshan Island are plotted on the ternary diagram shown in Fig. 4. It is apparent that the content of \( \text{Al}_2\text{O}_3 \) in the clay (retrieved from the study area) is relatively high, which is analogous with the composition of marine clay.

Fig. 4. Contents of the \( \text{Al}_2\text{O}_3 \), \( \text{K}_2\text{O} \), \( \text{MgO} \) of the mudstone and siltstone in the Lower Cretaceous of Lingshan Island (modified after Sun et al., 1997).

4.2 Analysis of the indicators of paleosalinity

The analysis of trace elemental composition of rock has become an important approach to the study of rock formation environments (Yao et al., 2002; Zhang and Zhang, 2006; Xie et al., 2018; Li et al., 2018). The distribution of trace elements in the stratum is closely related to the environment in which they were formed. At the same time, the occurrence of many trace elements is unaffected by the environmental changes after diagenesis. Therefore, the proportions and ratios of some trace elements are good indicators of the sedimentary environment (Mongenot et al., 1996; Frimmel et al., 2008; Xin et al., 2016). The relative abundances and ratios of B and Ga are more sensitive in distinguishing between freshwater and salt water environments and are often used to distinguish marine facies from continental facies (Degens et al., 1957; Adams et al., 1965; Walker et al., 1968; Goodarzi and Swaine, 1994; Li et al., 2009; Feng et al., 2018).

4.2.1 Quantitative relations of B–Ga–Rb

With differences in the sedimentary environment, the relative proportions of B, Ga and Rb in clay change regularly, and thus, the B–Ga–Rb content relationship can be indicative of the sedimentary environment (Yan et al., 1979). Based on the data shown in Table 2, the ternary diagram of the relative proportions of the B, Ga and Rb in mudstones and siltstones in the Laiyang Group of the Lower Cretaceous in Lingshan Island was constructed (Fig. 5). It is apparent that the values of the seven samples are all distributed in the area of transitional facies, indicating the sedimentary environment of transitional facies.
4.2.2 Characteristic analysis of the B content, and Ga content

Walker and Price (1963) suggested that the B content of freshwater sedimentary rocks is less than 80 ppm, the B content of marine–continental transition facies is between 80 ppm and 100 ppm, and the B content of marine sedimentary rocks is greater than 100–120 ppm.

According to Fig. 6, in samples of the Laiyang Group, only three samples have a B content within the range of those of marine facies, while two samples have a B content within the range of those of transitional facies, and the B contents of other samples fell in the range of those of continental facies.

Compared with B, the transfer ability of Ga is much lower, mainly due to poor geochemical activity. The Ga content is higher within rocks formed in freshwater than in rocks formed under ocean conditions. Therefore, Ga can be used as an indicator of paleosalinity (Sun et al., 1997; Chen et al., 2011).

The minimum Ga content of the study area is 16.28 ppm, the maximum is 24.29 ppm, which is higher than that of the marine facies. As indicated by Fig. 6, the Ga content indicates that the sedimentary environment at that time was continental facies.

4.2.3 The characteristics of the B/Ga ratio

The B/Ga ratio can be used as the basis of the salinity index (Couch 1971; Sun et al., 1992). Previous researchers (Yan et al., 1979; Wu et al., 2001; Li et al., 2009; Yang et al., 2017; Zhang et al., 2017) used the B/Ga ratio to distinguish marine facies from continental facies. The B/Ga ratio of < 3.3 represents freshwater facies; that of 3.3–4.5 represents brackish or paralic facies or continental facies; and that of 4.5–5 represents marine facies.

In this experiment, only two samples have a B/Ga ratio in the range of marine facies (4.5–5), while the B/Ga ratio of four samples fell in the range of transitional facies, and the B/Ga ratio of four samples fell in the continental facies (Fig. 6).

4.2.4 Analysis of paleosalinity

The highest palaeosalinity value of the Lower Cretaceous in Lingshan Island is 15.7‰, and the lowest is 5.3‰ (Fig. 6). Hence, the palaeosalinity values suggest a brackish water sedimentary environment of the Laiyang Group in the Lower Cretaceous of Lingshan Island.

Considering above, it seems that the indicators of paleosalinity offer a different result and can’t offer a decisive proof regarding the sedimentary setting. But it is certain that the paleo–water properties were brackish water.
Fig. 6. Paleosalinity discrimination diagram of the Laiyang Group in the Lower Cretaceous of Lingshan Island. (a) Distribution range of the B content; (b) distribution range of paleosalinity; (c) distribution range of the B/Ga ratio; (d) distribution range of the Ga content.

5. Discussions

In order to prove that such a different result above offered via the indicators of paleosalinity is not occasional, geochemical indexes from the Laiyang Group of Lingshan Island were collected from existing studies and analyzed (Table 3, 4 and 5).

Table 3 Analysis of the B, Ga and Rb contents and the B/Ga ratio of mudstone in Lingshan Island (modified from Yang et al., 2017, 2018)

<table>
<thead>
<tr>
<th>Samples</th>
<th>ZC1</th>
<th>ZC2</th>
<th>ZC3</th>
<th>DT1</th>
<th>DT2</th>
<th>DT3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ga (ppm)</td>
<td>18.148</td>
<td>18.201</td>
<td>22.591</td>
<td>18.949</td>
<td>20.252</td>
<td>19.031</td>
</tr>
<tr>
<td>B (ppm)</td>
<td>119.946</td>
<td>97.313</td>
<td>174.672</td>
<td>103.977</td>
<td>107.395</td>
<td>82.734</td>
</tr>
<tr>
<td>Sp (%)</td>
<td>15.84</td>
<td>13.48</td>
<td>21.10</td>
<td>13.61</td>
<td>15.06</td>
<td>11.98</td>
</tr>
</tbody>
</table>

Table 4 Analysis of the B, Ga and Rb contents and the B/Ga ratio of siltstone in Lingshan Island (modified from Zhang et al., 2017)

<table>
<thead>
<tr>
<th>Samples</th>
<th>Chuanchang section</th>
<th>Qiancengya section</th>
<th>Lighthouse section</th>
<th>Diaoyutai section</th>
</tr>
</thead>
<tbody>
<tr>
<td>B (ppm)</td>
<td>158.00</td>
<td>159.00</td>
<td>199.00</td>
<td>149.00</td>
</tr>
<tr>
<td>B/Ga</td>
<td>8.85</td>
<td>11.08</td>
<td>7.34</td>
<td>5.94</td>
</tr>
<tr>
<td>Rb (ppm)</td>
<td>97.84</td>
<td>94.68</td>
<td>117.24</td>
<td>118.61</td>
</tr>
</tbody>
</table>

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Table 5 Analysis of the major elements of the siltstone in the Laiyang Group of Lingshan Island (wt%)
(modified from Zhang et al., 2017)

<table>
<thead>
<tr>
<th>Samples</th>
<th>Chuanchang section</th>
<th>Qiancengya section</th>
<th>Lighthouse section</th>
<th>Diaoyutai section</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CC–1</td>
<td>CC–2</td>
<td>CC–3</td>
<td>QCY–1</td>
</tr>
<tr>
<td>SiO₂</td>
<td>55.55</td>
<td>55.98</td>
<td>54.72</td>
<td>46.48</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>6.13</td>
<td>6.36</td>
<td>5.56</td>
<td>6.70</td>
</tr>
<tr>
<td>K₂O</td>
<td>2.52</td>
<td>2.52</td>
<td>3.41</td>
<td>2.58</td>
</tr>
<tr>
<td>MgO</td>
<td>2.63</td>
<td>2.69</td>
<td>4.13</td>
<td>3.81</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.83</td>
<td>1.72</td>
<td>1.30</td>
<td>3.02</td>
</tr>
<tr>
<td>MnO</td>
<td>0.08</td>
<td>0.06</td>
<td>0.05</td>
<td>0.09</td>
</tr>
<tr>
<td>Na₂O</td>
<td>3.10</td>
<td>3.29</td>
<td>2.22</td>
<td>2.78</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.24</td>
<td>0.12</td>
<td>0.10</td>
<td>0.20</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.68</td>
<td>0.37</td>
<td>0.39</td>
<td>0.65</td>
</tr>
</tbody>
</table>

5.1 Sedimentary environment revealed by the indicators of paleosalinity

5.1.1 Sedimentary environment indicated by the relationship of the B–Ga–Rb contents

According to the data in Tables 1, 3 and 4, a ternary diagram of B, Ga and Rb in the study area was constructed (Fig. 7). Evidently, the sedimentary environment indicated by the B–Ga–Rb ternary diagram is not a marine environment.

Fig. 7. Contents of the B, Ga, Rb of the mudstone and siltstone in the Lower Cretaceous of Lingshan Island (modified after Yan, 1979; Wu, 2001).

5.1.2 Sedimentary environment indicated by the B and Ga contents, B/Ga ratio and paleosalinity

The paleosalinity indexes deemed to indicate a marine sedimentary environment in previous studies was consistent with those in this study, which also offer a different result of the sedimentary environment. The specific results of the analysis are as follow: Ten samples have a B content within the range of those of marine facies, while nine samples have a B content within the range of those of transitional facies (Fig 8 (a)). It can be seen from Fig. 8 (b) that the B/Ga ratios are significantly higher and exceeded those of normal marine facies (4.5–5). The values of paleosalinity are in the range of brackish water, which suggest a brackishwater facies (Fig. 8 (c)). Figure 8 (d) shows that the values of Ga content are mainly in the range of continental facies, which suggests a continental sedimentary environment.
Fig. 8. Paleosalinity discrimination diagram of the Laiyang Group in the Lower Cretaceous in Lingshan Island. (a) Distribution range of the B content; (b) distribution range of the B/Ga ratio; (c) distribution range of paleosalinity; (d) distribution range of the Ga content.

Obviously, the occurrence of multiple sedimentary environments, as indicated via paleosalinity indicators, is not random. What is certain is that paleosalinity indexes do not offer decisive proof of the sedimentary setting in addition to paleosalinity information. Therefore, fossils should also be taken into account when interpreting the sedimentary setting of sediments.

5.2 Paleoenvironment revealed by palaeontological fossils

Li et al. (2017) discovered the fossils of fish and conchostracans buried in the Lower Cretaceous of Lingshan Island and proposed that the fish were Lecoptera sinensis Woodward and that the conchostracans were Yanjiestheria Chen, both of which were continental lacustrine fauna of the Early Cretaceous.

The study of fossil burial forms is the basis for restoring sedimentary setting and only organisms buried in situ have the significance of indicating sedimentary environment. It can be seen from the para-ecological characteristics of fossils that fish fossils can be deposited as complete specimens without distortion and directed distribution. The right and left valves of conchostracan fossils were hinged together and few moved to a relatively small extent. The convex valve of most fossils faces downward, while the concave valve faces upward, without evidence of much movement (Fig. 9). Thus, the assemblage and characteristics of fossils play an important role in understanding the sedimentary environment of the study area.
Fig. 9. Conchostracan and fish fossils in the study area (modified from Li et al., 2017).

(a)–(m) Two valves together preservation of conchostracan fossils; (n) group preservation of conchostracan; (o)–(q) Lepoptera sinensis Woodward.

Yanjiestheria Chen is the euryhaline species that can live in brackish water. Studies have shown that the fossil assemblages of conchostracans in the study area are well preserved and characterized by high fossil abundance and low species diversity, conforming to the distribution and conservation characteristics of organisms in salified lakes. Due to the salinization of lake water, it is not suitable for the existence of large numbers of organisms, and only the conchostracans, which are euryhaline species, can flourish in large quantities (Sun et al., 1997).

In some developmental stages of brackish lakes, there were some living organisms, such as conchostracans, ostracods, fish, dinoflagellate and charophytes (Chen, 1979; Sun et al., 1997; Amils et al., 2007; Albuquerque et al., 2012). This explains the storage of Lepoptera sinensis Woodward and Yanjiestheria Chen in the same stratum. It was not uncommon to have storage of terrestrial brackish water organisms and freshwater fish in the same stratum (Fig. 9). Terrestrial brackish water ostracoda and freshwater carp survived in salinized water in the Qaidam Basin in the middle Miocene epoch (Song et al., 2017).

In fact, the Laiyang Group of Lingshan Island is not the only Early Cretaceous sedimentary strata with salinization in eastern Shandong (Fig. 10). The Wawukuang and Shuinan Formations of the Lower Cretaceous Laiyang Group of Jiaolai Basin are also characterized by salinization (Feng et al., 2018). It is noteworthy that the Wawukuang and Shuinan Formations are rich in Lepoptera sinensis Woodward and Yanjiestheria Chen fossils (Regional Geological Survey Team of Bureau of Geology and Mineral Resources of Shandong Province, 1990). Besides, various deformation structures developed in the Shuinan Formation of the Lower Cretaceous Laiyang Group in Jiaolai Basin (Zhou et al., 2011), which are similar to those of Lingshan Island. Therefore, it is not difficult to ascertain that the Laiyang Group strata in Jiaolai Basin and Lingshan Island are comparable.
In terms of the whole of Eastern China, the Early Cretaceous strata with salinization characteristics are not only discontinuous in sedimentary time and space but are also rich in continental fossils, such as ostracoda, gastropods, dinoflagellates, conchostracans, fish, etc. (Regional Geological Survey Team of Bureau of Geology and Mineral Resources of Shandong Province, 1990; Li and Zhao, 1992; Zheng et al., 2009; Yan et al., 2014; Feng et al., 2018), as shown in Fig. 11. Only continental salified lakes can have such a biological assemblage.

Remarkably, Yanjiestheria Chen, which is a euryhaline species, has been found in all strata with salinization (Fig. 11). Therefore, it is difficult to imagine that the Fajiaying Formation of the Laiyang Group in Lingshan Island was formed in a residual ocean basin; however, other strata in Eastern China also show signs of salinization. What is more important is that the same terrestrial fossils occur in these strata. Thus, it seems that the sedimentary environment of the Laiyang Group of Lingshan Island may be that of a salified lake, because this would reasonably explain the temporal and spatial discontinuities in the salinized strata of Eastern China, and the continental fossils they contain.
A certain temperature is necessary condition for salinization, so paleoclimatic indexes might provide useful information. Research shows that a Sr/Cu ratio ≤ 10 indicates a warm, humid climate, while a Sr/Cu ratio > 10 indicates a dry, hot climate (Fu et al., 2018). The CaO/MgO Al₂O₃ ratio can sensitively reflect the relative level of endogenous carbonate content as well as temperature changes, with high values indicating warm periods and low values indicating relatively cold periods (Fu et al., 2018). Paleosalinity indexes show good responses to the proxies of paleoclimate in the study area; with a decrease in the temperature of paleoclimate, paleosalinity also decreased (Fig. 12). The climate of the Early Cretaceous in eastern Shandong was hot and dry overall, although there were some short-term drops in temperature (Regional Geological Survey Team, Bureau of Geology and Mineral Resources of Shandong Province, 1990; Cao, 2010; Jin, 2018). Under such climatic conditions, the evaporation from lakes was greater than precipitation, which can be proven via the gypsum–salt interlayers in the Wawukuang Formation of the Laiyang Group (Feng et al., 2018) and the Tianjialou Formation of the Dasheng Group (Fig. 13).
It is intuitive that local salinization is a response of continental lakes to a high-temperature climate. Under hot, arid, tropical–subtropical climatic conditions, the inland waters of southeastern China turned into salt lakes during the Cretaceous (Chen, 1997). The Lishu Depression in Songliao Basin Salinized during the Early Cretaceous (Yan et al., 2014). These facts are in agreement with the conclusions of this paper.

5.3 Chemical components of clay

Based on the data in Tables 1 and 5, a ternary diagram of the relative proportions of $\text{Al}_2\text{O}_3$, $\text{K}_2\text{O}$ and $\text{MgO}$ in mudstone and siltstone in the study area was constructed (Fig. 14). It is apparent that the chemical compositions of the mudstone and siltstone in the study area are characterized by $\text{Al}_2\text{O}_3$ enrichment.
Fig. 14. Contents of the Al$_2$O$_3$, K$_2$O, and MgO of the mudstone and siltstone in the Lower Cretaceous of Lingshan Island (modified after Sun et al., 1997).

Sun et al. (1997) conducted research on the sedimentary environment of Cenozoic salified lakes in China and proposed that the chemical composition of clay in salified lakes is characterized by Al$_2$O$_3$ enrichment. Evidently, the chemical composition of clay in the Lower Cretaceous Laiyang Group of Lingshan Island is consistent with that of continental salified lakes.

As stated above, the sedimentary environment of the Laiyang Group is that of a continental salified lake rather than a marine environment. Not only might this reasonably explain the coupling relationship between the indexes of paleosalinity and the proxies of paleoclimate, it may also explain the Al$_2$O$_3$ enrichment of clay, and the existence of continental fossils and glauconite in the strata.

6 Conclusions

The paleontological community of the Lower Cretaceous Laiyang Group of Lingshan Island is dominated by the euryhaline genus Yanjiestheria Chen. This genus coexisted with freshwater fish and strongly halophilous dinoflagellates, a situation similar to that in salinized strata of Eastern China. Such salinized strata are discontinuous in time and space. The paleosalinity of Lingshan Island has a close relationship with paleotemperature; with decreases in temperature, the paleosalinity also decreases. The fine clastic rocks in the study area are characterized as being rich in Al$_2$O$_3$. Therefore, the authors speculate that under the background of a warm Cretaceous climate, salinization occurred locally in Eastern China and the sedimentary environment of the Laiyang Group of Lingshan Island is that of a continental salified lake rather than a marine facies.

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About the first author
Zhang Xiangyu, male, born in 1988 in Weifang City, Shandong Province; master; graduated from Shandong University of Science and Technology in 2018 and is now a PhD student at the same institution. He is now interested in the study on stratigraphy and palaeontology. Email: xiangyu_159@126.com; phone: 15662553812.

About the corresponding author
Li Shoujun, male, born in 1962 in Linqu City, Shandong Province; Ph.D., graduated from Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences; professor of Shandong University of Science and Technology. He is now interested in the study on stratigraphy and palaeontology. Email: lishoujun@126.com; phone: 13789879228.