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Research paper

# Micropaleontology and palaeoclimate during the early Cretaceous in the Lishu depression, Songliao basin, Northeast China

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A B S T R A C T

Diverse and abundant microfossils, such as palynomorphs, algae and Ostracoda, were collected from lower Cretaceous strata of Lishu depression, located in southeastern Songliao basin, and were identified and classified in order to provide relevant, detailed records for paleoclimate research. The early Cretaceous vegetation and climate of southeastern Songliao basin have been inferred from the analysis of palynomorph genera, algae and Ostracoda of the LS1 and SW110 wells. The lower Cretaceous strata include, in ascending stratigraphic order, the Shahezi, Yingcheng and Denglouku formations. Palynological assemblages for each formation, based on biostratigraphic and statistical analyses, provide an assessment of their longitudinal variations. During deposition of the Shahezi Formation, the climate was mid-subtropical. Vegetation consisted of coniferous forest and herbage. During deposition of the Yingcheng Formation, the climate was south Asian tropical. Vegetation consisted mainly of coniferous forest and herbal shrub. In addition, fresh and saline non-marine water dominated the lacustrine setting during deposition of these formations. Deposition of the Denglouku Formation, however, occurred under a hot and dry tropical climate. The vegetation was mostly coniferous forest and lake waters became saline. Palaeoclimate variation is correlated by the lake level change and the development of sedimentary facies. Palaeoclimate contribute to the formation of hydrocarbon source rocks and reservoir.



## 1. Introduction

The types and distributions of plants physiologically respond to climate, such as temperature and humidity, and thus vegetation is a reflection of the ambient climatic zone (Hubbard and Boulter, 1983; OttoBliesner and Upchurch, 1997). According to the sporopollen spectrum, palaeovegetation and palaeoclimate zones may be inferred from research regarding the ecological environment, temperature, as well as humidity (Hubbard and Boulter, 1983; Van der Zwan et al., 1985; Gao, 1988; Kalkreuth et al., 1993; Gao et al., 1994; White et al., 1997; Liu et al., 2002; Barrón et al., 2006; Larsson et al., 2010; Wan et al., 2013). Furthermore, data from analysis of algae and ostracods may indicate water salinity. These studies provide the basis for a quantitative study of palaeoclimate (Ye and Zhang, 1985; Huang et al., 1998; Yuan et al., 1999).

The studies of palynomorph genera during the Cretaceous period in the Songliao basin have involved two aspects. One is the study of palynological assemblages and their characteristics. This involves the taxonomy, age determination, biostratigraphic correlations, and reconstruction of palaeoclimates and palaeovegetation, as well as other geological inferences (Gao, 1988; Wang, 1989; Gao et al., 1994, 1999; Jia et al., 2008). The other aspect concerns outer-wall color, reflectance, transmittance, and the fluorescence of sporopollen, as well as the relationship between shape and temperature. Geochemistry has been used to study the chemical

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composition of sporopollen and the efficiency of hydrocarbon production (Gao, 1988; Huang et al., 1998; Hou et al., 2003; Huang et al., 2007). This work could contribute towards a more complete understanding of organic maturation and petroleum generation (Tissot and Welte, 1984; Morrow and Issler, 1993).

More research has been conducted on upper Cretaceous strata than on lower Cretaceous strata in the past ten to fifteen years (Huang et al., 1998; Gao et al., 1999; Wan et al., 2013; Wang, 2013; Wang et al., 2013). Songliao basin was an inland lake with a warm and humid climate during middle–late Cretaceous (Wang et al., 2013). There were two large marine incursions during this time period (Wang, 2006; Huang et al., 2007, 2013). The palaeogeographic and palaeoclimatic framework during the middle–late Cretaceous has already been described from the implementation of continental systematic drilling, called SK1n and SK1s under the framework of the International Continental Scientific Drilling Program (Li et al., 2011; Xi et al., 2011, 2012; Scott et al., 2012; Chamberlain et al., 2013; Huang et al., 2013; Song et al., 2013; Wan et al., 2013; Wang, 2013; Wang et al., 2013; Qu et al., 2014). However, only preliminary work has been done for lower Cretaceous strata, especially concerning the micropaleontology and palaeoenvironment for these strata in southern Songliao basin (Zhang, 1987; Shang and Wang, 1991).

The Songliao basin is the most productive lacustrine petroliferous basin in the world. The Lishu depression is a northeast-facing half-graben located in the southeast uplift area of the Songliao basin (Fig. 1). The Sangshutai Fault controls the western boundary of the depression. The Lishu depression is a composite basin that underwent several stages of subsidence (Shou et al., 1996; Jun et al., 2006; Yan et al., 2012; Wang et al., 2015; Zhu et al., 2015). The lower part includes strata deposited during fault development and are referred to herein as "fault depression strata" (strata controlled by boundary fault of depression, Fig. 1). Upper Cretaceous basinal strata, which overlie the fault-related strata, were deposited across the entire Songliao basin.

The fault depression itself is divided into four secondary tectonic units: the northern slope, the Central Structural belt, the East slope and the Sangshutai sub-sag (Fig 1). The lower Cretaceous fault depression strata have been divided, in ascending order to: the Shahezi Formation ($K_1sh$), the Yingcheng Formation ($K_1yc$), and the Denglouku Formation ($K_1d$) (Fig. 2). This succession mainly consists of sand conglomerate, sandstone and mudstone (Fig. 2). A few carbonaceous layers occur within the Shahezi and Yingcheng formations. The Denglouku Formation contains of some visible brown mudstone. Thirty-six lower Cretaceous core samples from SW110 and LS1 wells (Fig. 1, Table 1) were examined. Many microfossils, such as fern spore, angiosperms and gymnosperms pollen, as well as algae and Ostracoda were collected from these cores.

The objective of this study is to document, for the first time, the micropaleontology of Lishu depression in southern Songliao basin during early Cretaceous. In order to accomplish this objective, the percentage changes in flora and fauna (Fig. 2, Table 2), and changes in the palynological assemblages, and in the types and abundances of algae and Ostracoda are determined from the systematic collection of data basinwide (Fig. 5). The establishment of microfossil assemblages is of great significance for stratigraphic classification and correlation in the Lishu depression, and for comparison with strata of other regions. This database is used to draw inferences concerning paleoclimatic changes within the depositional environment (Fig. 9), and to discuss the significance of palaeoclimate on the quality of hydrocarbon source rocks and on potential reservoir facies.

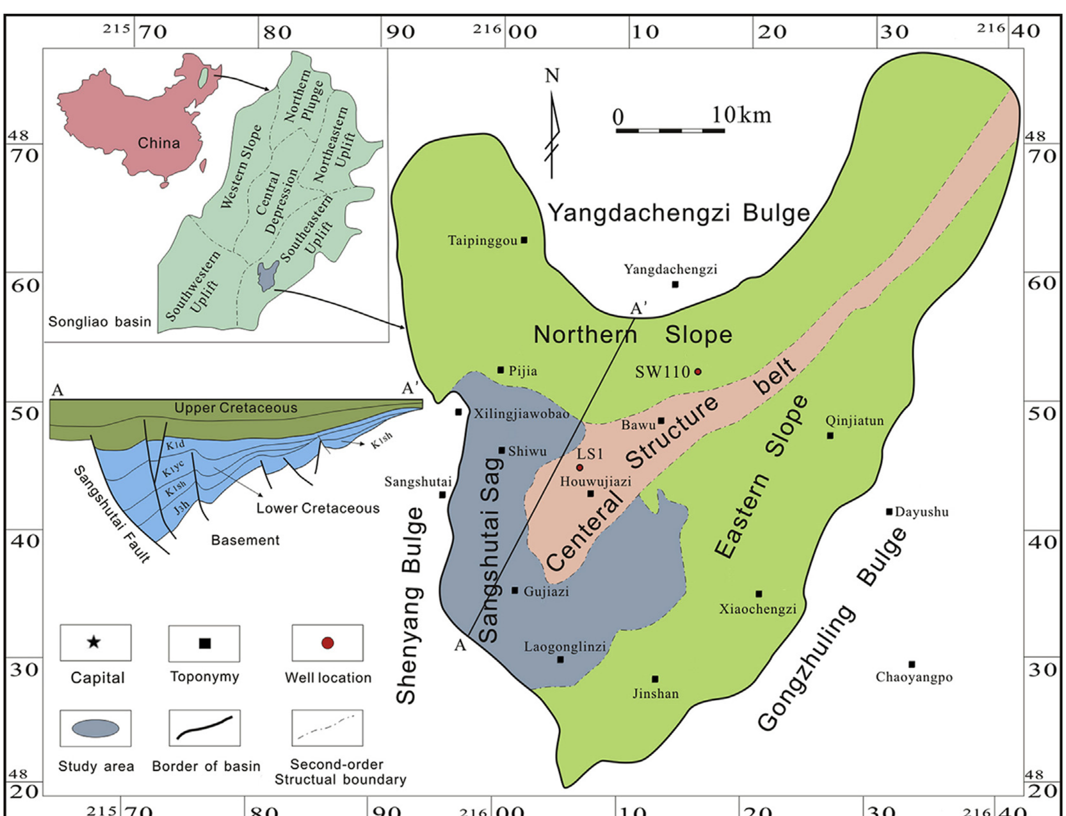


**Figure 1.** The location of Lishu depression and division of tectonic units. A–A′: geological section in NNE direction. Lower Cretaceous showed in A–A′: Shahezi Formation ($K_1sh$); Yingcheng Formation ($K_1yc$); Denglouku Formation ($K_1d$). Blue strata in A–A′ is "fault depression stata", which controlled by the Sangshutai Fault.

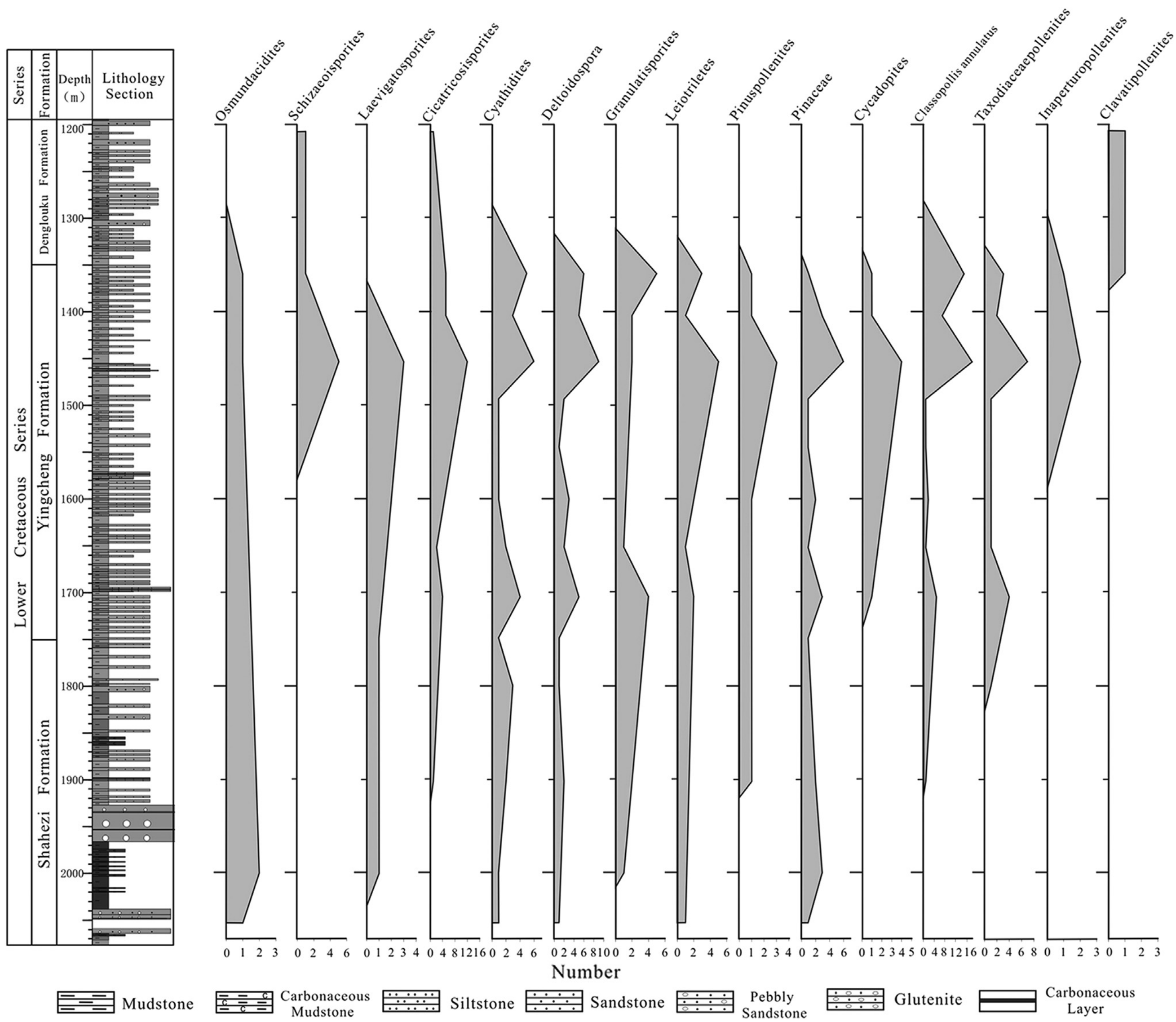


**Figure 2.** Typical sporopollen distribution's curve graph of SW110 well. The location of SW110 was shown in Fig. 1.

**Table 1**
Sample collection from the cores of SW110 with average interval of 50 m and LS1 with average interval of 100 m. All of samples are dark mudstone.

| Sample No. | Well | Depth (m) | Formation | Sample No. | Well | Depth (m) | Formation |
|---|---|---|---|---|---|---|---|
| 1 | SW110 | 1208.2 | Denglouku | 19 | LS1 | 1608.1 | Denglouku |
| 2 | SW110 | 1258.5 | Denglouku | 20 | LS1 | 1708.3 | Denglouku |
| 3 | SW110 | 1306.1 | Denglouku | 21 | LS1 | 1813.1 | Denglouku |
| 4 | SW110 | 1350.0 | Denglouku | 22 | LS1 | 1900.2 | Denglouku |
| 5 | SW110 | 1405.1 | Yingcheng | 23 | LS1 | 1996.0 | Denglouku |
| 6 | SW110 | 1454.3 | Yingcheng | 24 | LS1 | 2061.2 | Denglouku |
| 7 | SW110 | 1494.4 | Yingcheng | 25 | LS1 | 2112.3 | Denglouku |
| 8 | SW110 | 1545.2 | Yingcheng | 26 | LS1 | 2198.4 | Denglouku |
| 9 | SW110 | 1601.2 | Yingcheng | 27 | LS1 | 2309.1 | Denglouku |
| 10 | SW110 | 1652.4 | Yingcheng | 28 | LS1 | 2400.2 | Denglouku |
| 11 | SW110 | 1705.3 | Yingcheng | 29 | LS1 | 2510.1 | Denglouku |
| 12 | SW110 | 1749.1 | Yingcheng | 30 | LS1 | 2700.3 | Yingcheng |
| 13 | SW110 | 1800.2 | Shahezi | 31 | LS1 | 2809.3 | Yingcheng |
| 14 | SW110 | 1850.1 | Shahezi | 32 | LS1 | 2901.2 | Yingcheng |
| 15 | SW110 | 1902.0 | Shahezi | 33 | LS1 | 3018.2 | Yingcheng |
| 16 | SW110 | 1952.4 | Shahezi | 34 | LS1 | 3116.1 | Yingcheng |
| 17 | SW110 | 2000.2 | Shahezi | 35 | LS1 | 3214.0 | Yingcheng |
| 18 | SW110 | 2053.1 | Shahezi | 36 | LS1 | 3301.1 | Yingcheng |

## 2. Material and methods

These processes utilize China's oil and gas industry standards for sporopollen (following GB SY/T 5915-2000) identification and microfossil (ostracods, gastropods, round algae, following GB SY/T 5522-1992) analysis methods (see Wang et al., 2014). Pollution-free samples were collected from the cores of SW110 Well and LS1 Well. 200 g samples were taken sequentially. Samples were machine crushed and then washed. Oil was removed with carbon tetrachloride, then, depending on the presence of carbon, samples were washed in hydrochloric or nitric. Because the color of most samples is black, with elevated carbon content, these samples were typically washed with nitric acid. In addition, oil-free samples were treated with hydrofluoric acid. After the samples were washed, they were submerged in heavy liquid for separation by flotation. This was followed by dilution in acetic acid, and water-washing. Finally, slides were prepared for the observation of microfossils. Micropaleontologic determinations were performed under a low-power Zeiss Axioskop binocular microscope. All samples were prepared at Experimental Centre of Exploration and Development Research Institute, China Petroleum Company.

**Table 2**
Showing the percentages of sporopollen of Lishu Depression layer in Songliao Basin.

| Spores and pollen number | Denglouku Formation | | Yingcheng Formation | | Shahezi Formation |
|---|---|---|---|---|---|
| | LS1 | SW110 | LS1 | SW110 | SW110 |
| Fern Spores: | | | | | |
| *Osmundacidites* sp. | | 1 (1.9%) | | 1 (0.5%) | 3 (8.6%) |
| *Baculatisporites* sp. | 1 (3.6%) | | 1 (14.3%) | | |
| *Schizaeoisporites* sp. | | 2 (3.7%) | | 7 (3.8%) | |
| *Laevigatosporites* sp. | 1 (3.6%) | | | 3 (1.6%) | 3 (8.6%) |
| *Cicatricosisporites* sp. | | 6 (11.1%) | | 23 (12.6%) | 1 (2.9%) |
| *Toroisporis* sp. | | | | 1 (0.5%) | |
| *Klukisporites* sp. | | | 1 (14.3%) | | |
| *Pilosisporites* sp. | | | | 4 (2.2%) | |
| *Punctatisporites sp.* | 2 (7.1%) | | | | |
| *Concavissimisporites* sp. | | | | 1 (0.5%) | |
| *Aequitriradites verrucosus* | | | | 3 (1.6%) | 2 (5.7%) |
| *Brevilaesuraspora* sp. | | | | | 1 (2.9%) |
| *Plicifera* sp. | | 1 (1.9%) | | | |
| *Cyathidites* sp. | 2 (7.1%) | 5 (9.3%) | | 19 (10.4%) | 7 (20%) |
| *Deltoidospora* sp. | | 6 (11.1%) | 2 (28.6%) | 28 (15.4%) | 5 (14.3%) |
| *Granulatisporites* sp. | 4 (14.3%) | 5 (9.3%) | | 9 (4.9%) | 1 (2.9%) |
| *Biretisporites* sp. | | | | 2 (1.1%) | |
| *Leiotriletes* sp. | | 3 (5.6%) | | 9 (4.9%) | 1 (2.9%) |
| Gymnosperm Pollen: | | | | | |
| *Podocarpidites* sp. | 2 (7.1%) | 1 (1.9%) | | | |
| *Piceaepollenites* sp. | 1 (3.6%) | | | 1 (0.5%) | |
| *Pinuspollenites* sp. | 1 (3.6%) | 1 (1.9%) | | 5 (2.7%) | 1 (2.9%) |
| *Pinaceae* sp. | 3 (10.7%) | 1 (1.9%) | 1 (14.3%) | 17 (9.3%) | 6 (17.1%) |
| *Protoconiferus* sp. | | | | 1 (0.5%) | 1 (2.9%) |
| *Psophosphaera* sp. | | | | | 1 (2.9%) |
| *Cycadopites* sp. | 1 (3.6%) | 1 (1.9%) | | 6 (3.3%) | |
| *Cedripites* sp. | 1 (3.6%) | | | | |
| *Classopollis annulatus* | 1 (3.6%) | 15 (27.8%) | | 24 (13.2%) | 1 (2.9%) |
| *Perinopollenites* sp. | | | | 1 (0.5%) | |
| *Taxodiaceaepollenites* sp. | 1 (3.6%) | 3 (5.6%) | 1 (14.3%) | 15 (8.2%) | 1 (2.9%) |
| *Ephedripites* sp. | 1 (3.6%) | | 1 (14.3%) | | |
| *Inaperturopollenites* | 2 (7.1%) | 1 (1.9%) | | 2 (1.1%) | |
| Angiosperm Pollen: | | | | | |
| *Clavatipollenites* sp. | 2 (7.1%) | 2 (3.8%) | | | |
| *Triporopollenites* sp. | 2 (7.1%) | | | | |
| Total | 28 | 54 | 7 | 18 | 35 |

## 3. Data

The palynological analysis of SW110 shows that pteridophyte spores accounts for 67.65% of all microflora in the Shahezi Formation, while gymnosperm pollen takes up 32.35%. In the Yingcheng Formation, the content of pteridophytic spores is 57.1%, while the gymnosperm pollen accounts for 42.9% of microflora. In the Denglouku Formation, pteridophytic spores account for 53.7%, while gymnosperm pollen takes up 42.6%, and the content of angiosperm pollen is 3.7% of all microflora (Table 2). It is evident that, from the Shahezi Formation to the Denglouku Formation, the percentage of pteridophytic spore decreased, whereas gymnosperm pollen increased (Fig. 4). Angiosperm pollen did not appear up until deposition of the Denglouku Formation. In addition, some other scattered microfossils, such as Ostracoda and algae, also occurred in the samples.

The pteridophyte spore type predominates (67.65%) in the sporopollen assemblage of the Shahezi Formation in SW110 well (Table 1). *Cyathidites* (20%) is the most abundant pteridophyte spore, followed by *Deltoidospora* (14.3%), *Osmundacidites* (8.6%), *Laevigatosporites* (8.6%), *Cicatricosisporites* (2.9%), *Granulatisporites* (2.9%) and *Leiotriletes* (2.9%) (Table 2). For gymnosperm pollen, the greatest amount is *Pinaceae* (17.1%), with a small proportion (2.9%) of *Pinuspollenites*, *Classopollis annulatus* and *Taxodiaceaepollenites* (Table 2).

Microfossils are relatively abundant in the Yingcheng Formation (Fig. 3). Species diversity and abundance of microfossils increases significantly (Figs. 2 and 4, Table 2). The pteridophyte spore content of the Yingcheng Formation is lower than that of the Shahezi Formation, but the gymnosperm pollen content is greater. The contents of *Deltoidosporea* (15.1%), *Cicatricosisporites* (12.6%) and *Cyathidites* (10.4%) are among the most abundant in the pteridophytic spore of SW110 well, followed by *Leiotriletes* (4.9%), *Granulatisporites* (4.9%), *Schizaeoisporites* (3.8%), *Pilosisporites* (2.2%), *Laevigatosporites* (1.6%), and *Osmundacidites* (0.5%) (Table 2). In LS1, pteridophyte spores are mainly *Deltoidospora* (28.6%), *Baculatisporites* (14.3%) and *Klukisporites* (14.3%). As for the gymnosperm pollen, *Classopollis annulatus* (13.2%), *Pinaceae* (9.3%), and *Taxodiaceaepollenites* (8.2%) are among the most abundant in SW110, followed by *Cycadopites* (3.3%), *Pinuspollenites* (2.7%), and *Inaperturopollenites* (1.1%). In the LS1, pteridophyte spores are mostly *Pinaceae* (14.3%), *Taxodiaceaepollenites* (14.3%) and *Ephedripites* (14.3%) (Table 2). Angiosperm pollen is not present in the Yingcheng Formation (Fig. 2, Table 2).

The result of the palynological analysis of SW110 shows that *Cicatricosisporite* (11.1%) and *Deltoidospora* (11.1%) are the most abundant pteridophyte spores in the Denglouku Formation, followed by *Cyathidites* (9.3%), *Granulatisporites* (9.3%), *Leiotriletes* (5.6%), Schizaeoisporites (3.7%), and *Osmundacidites* (1.9%) (Table 2). Pteridophytic spores of LS1 are mainly *Granulatisporites* (14.3%), followed by *Cyathidites* (7.1%), *Punctatisporites* (7.1%), *Laevigatosporites* (3.6%), and *Baculatisporites* (3.6%). The gymnosperm pollen in the Denglouku Formation of SW110 are *Classopollis annulatus* (27.8%), *Taxodiaceaepollenites* (5.6%), and a small number of *Cycadopites*, *Inaperturopollenites*, *Pinuspollenites* and *Pinaceae*, contributing 1.9% to the microfloral content (Table 2). In LS1, however, the most abundant gymnosperm pollen is *Pinaceae* (10.7%), followed by *Podocarpidites* (7.1%), *Inaperturopollenites* (7.1%), *Pinuspollenites* (3.6%), *Cycadopites* (3.6%) and *Classopollis annulatus* (3.6%) (Table 2). Aangiosperm pollen appears in the Denglouku Formation. The angiosperm pollen is *Clavatipollenites* (taking up 3.8% in SW110 and 7.1% in LS1) and *Triporopollenites* (taking up 7.1% in LS1). Therefore, the emergence of angiospermous pollen (*Clavatipollenites*) is one of the key features in classifying the Denglouku Formation (Figs. 2 and 4, Table 2).

## 4. Data interpretation

### 4.1. Palynological assemblages

A wide variety of microfossil genera are found in the lower Cretaceous strata of Lishu depression, including sporopollen, Ostracoda, and algae. Palynological assemblages are significant in stratigraphic classification, biostratigraphic correlations for marine-terrestrial or international continental strata, as well as being palaeoenvironment indicators (OttoBliesner and Upchurch, 1997; Jia et al., 2008).

Sporopollen is the abbreviation for spore and pollen (Wu et al., 2004). The spore of pteridophyte and the pollen of angiosperm and gymbeinosperm are parts of reproductive organs in plants. The cytoderm of sporopollen is composed of two walls: the inner wall is mainly cellulose and composed of two layers, which is soft and is easily degraded. The outer wall, which composed of one layer, is compact and firm, and is more likely to be preserved. Fossil spore/pollen from lake deposits provides a record of local and regional vegetation and, indirectly, climate. Sporopollen is widely used for stratigraphic chronology indication and stratigraphic correlation, as well as reconstructing palaeobotany and palaeoclimates (Wang, 1989; Shang and Wang, 1991; Jia et al., 2008). Shahezi Formation, then, is characterized

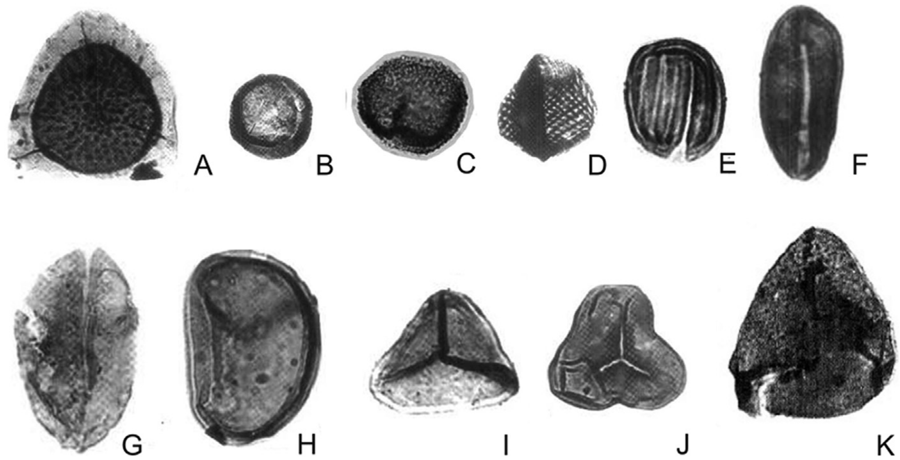


**Figure 3.** Selected spore and pollen taxa form samples of SW110 well. A: Aequitriradites verrucosus Cookson et Dettmann 1961, sample No. SW110-06. B: Classopollis annulatus (Verbitzkaja) Li 1974, sample No. SW110-04. C: Osmundacidites sp., sample No. SW110-17. D: Cicatricosisporites sp., sample No. SW110-11. E: Schizaeoisporites sp., sample No. SW110-05. F: Cycadopites sp., sample No. SW110-06. G: Taxodiaceaepollenites sp., sample No. SW110-06. H: Laevigatosporites sp., sample No. SW110-17. I: Deltoidospora sp., sample No. SW110-09. J: Cyathidites sp., sample No. SW110-10. K: Granulatisporites sp., sample No. SW110-01.

by an *Osmundacidites*–*Cyathidites*–*Aequitriradites*–*Pinaceae* assemblage, whereas the Yingcheng Formation is characterized by a *Cicatricosisporites*–*Pilosisporites*–*Classopollis*–*Cyathidites*–*Deltoidospora* assemblage (Fig. 3). A *Cicatricosisporites*–*Classopollis*–*Schizaeoisporites*–*Clavatipollenites*–*Leiotriletes* palynological assemblage characterizes the Denglouku Formation (Fig. 5).

### 4.2. Algae and Ostracoda

A variety of algae and Ostracoda populate strata of the Lishu depression. The dinoflagellate *Sentusidinium*, and the acritarchs *Granodiscus*, and *Filisphaeridium* are present in the Shahezi Formation (Fig. 6). Ostracoda are also very abundant, such as *Cypridea ihsienensis, Limnocypridea posticontracta, L. qinghemenensis*; and *Yixianella elliptica, Mongolocypris globa, Darwinuia contracta, Mantelliana, Candoniella Schneider* are also present (Fig. 6). Volcanic activity was weaker during deposition of the Shahezi Formation than during deposition of the Huoshiling Formation, and lacustrine ecosystems became extensive. The Green algae *Pediastrume* and the acritarch *Filisphaeridium* occur in the Yingcheng Formation. During deposition of the Yingcheng Formation, however, Ostracoda became far less abundant and Ostracoda fragments are sparse in the Yingcheng Formation. This decrease may be due to active tectonic movement and frequent volcanic activity during deposition of the Yingcheng Formation (Shou et al., 1996; Yan et al., 2012). During this time, the environmental stress rose and the number of species in the lake basin diminished. Algae found in the Denglouku Formation are mainly acritarchs, but some ostracods also are present, such as *Cypridea sp., Mantelliana sp., Candona regulania, Darwinuia contracta, Darwinula sp*. Volcanic activity declined during deposition of the Denglouku Formation, whereas biomass increased in comparison to during the Yingcheng Formation deposition (Yan et al., 2012).

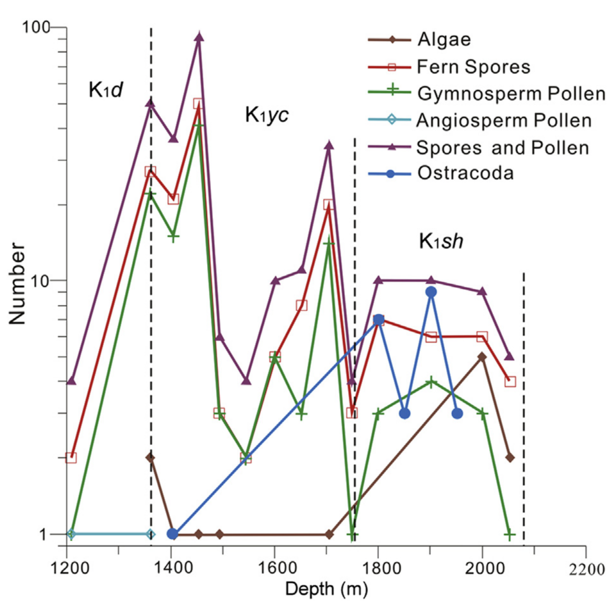


**Figure 4.** The paleontological overall change curve of microfossil of SW110 Well. K$_1$*sh*: Shahezi Formation; K$_1$*yc*: Yingcheng Formation; K$_1$*d*: Denglouku Formation.

### 4.3. Palaeoclimate and paleovegetation analysis

The global climate during the Cretaceous period is described as a pantropical climate, with an annual average temperature higher than that of the present (Gao et al., 1999; Skelton, 2003; Bice et al., 2006), and tropical and subtropical climatic zones were wider. Currently, the Songliao basin belongs to a temperate climate zone. The basin's present vegetation consists of forest and steppe zone (Gao et al., 1994, 1999; Huang et al., 1998). The climate in the Cretaceous period of the Lishu depression was very variable compared to the current climate. Cretaceous flora was divided into four categories: herbs, shrubs, broad-leaved, and coniferous plants. Broad-leaved was divided between evergreen and deciduous plants. Climatic zones fall into five categories: tropical zone, tropical-subtropical zone, subtropical zone, tropical-temperate zone, temperate zone (Zhao et al., 1992; Gao et al., 1994). According to palynofloral characteristics and their proportions, the vegetation types and the temperate zone in the Lishu depression during early Cretaceous have been classified (Table 2 and Fig. 6).

Climatic humidity is divided into three categories: xerophytic, mesophytic and humidogene (Gao et al., 1994). The humidity of each period is inferred from an appraisal of the humidity types that characterize of the growth of specific palynoflora (Gao et al., 1994, 1999). Algae and Ostracoda are more sensitive to lacustrine

| Series | Fm. | Stage | Songliao Basin: QIU Songyu, 1991 | Songliao Basin: GAO Ruiqi, 1994 | The North of Songliao Basin | Lishu Depression |
|---|---|---|---|---|---|---|
| Lower Cretaceous Series | Denglouku Formation | Albian | *Classopollis-Cycadopites-Tricolpopollenites* | 4th Member: *Leiotriletes-Classopollis-Schizaeoisporites*<br>3rd Member: *Cicatricosisporites-Leiotriletes-Polyporites*<br>1st Member and 2nd Member: *Cyathidites-Leiotriletes-Clavatipollenites* | Anda Area (QIU songyu,1992): *Cicatricosisporites-Appendicisporites-Clavatipollenites* | *Classopollis-Schizaeoisporites-Cicatricosisporites-Clavatipollenites-Leiotriletes* |
| | Yingcheng Formation | Aptian<br>Barremian | *Cicatricosisporites-Appendicisporites-Clavatipollenites* | *Paleoconiferus-Lygodiumsporites-Cyathidites* | Beian Area (WAN Chuanbiao,2002): *Cicatricosisporites-Cyathidites-Leiotriletes* | *Cicatricosisporites-Taxodiaceaepollenites-Classopollis-Deltoidospora-Cyathidites* |
| | Shahezi Formation | Hauterivian<br>Valanginian<br>Berriasian | *Cicatricosisporites-Aequitriradites-Palaeoconiferus* | Upper Member: *Granulatisporites-Lophotriletes-Cicatricosisporites*<br>Lower Member: *Classopollis-Piceites-Osmundacidites* | Cangwu Area (REN Yanguang,2003): Upper Member: *Lophotriletes-Cicatricosisporites*<br>Lower Member: *Classopollis-Piceites* | *Osmundacidites-Cyathidites-Aequitriradites-Pinaceae* |

**Figure 5.** The contrast table of palynological assemblages in the Songliao Basin (Qiu, 1991, 1992; Gao et al., 1994; Wan et al., 2002; Ren et al., 2003).

environmental parameters, so algae and Ostracoda could be a representative indicator of salinity (Yuan et al., 1999).

### 4.3.1. Shahezi Formation

Strata of the Shahezi Formation have a content of herbaceous plants of 43%. The highest concentration is *Deltoidospora* (14.3%), followed by *Osmundacidites* (8.6%) and *Laevigatosporites* (8.6%). The coniferous plants account for 31.6%, among which the most abundant is *Pinaceae* (17.1%) (Table 2). Consequently, the vegetation of the Shahezi Formation is characteristically coniferous forest and herbage. During deposition, 48.3% of plants were tropical and tropical-subtropical. Tropical plants account for 22.5% of plant

| Strata: Series | Strata: Fm. | Palynological Assemblages | Algae | Ostracoda | Vegetation | Climate | Humidity | Salinity |
|---|---|---|---|---|---|---|---|---|
| Lower Cretaceous Series | Denglouku Fm. | *Cicatricosisporites*<br>*Classopollis*<br>*Schizaeoisporites*<br>*Clavatipollenites*<br>*Leiotriletes* | *Filisphaeridium*<br>*Granodiscus*<br>*Leiosphaeridia* | *Cypridea sp.*<br>*Mantelliana sp.*<br>*Candona regulania*<br>*Darwinuia contracta* | Coniferous Forest | Tropical | Semiarid | Saline non-marine Water |
| | Yingcheng Fm. | *Cicatricosisporites*<br>*Pilosisporites*<br>*Classopollis*<br>*Deltoidospora*<br>*Cyathidites* | *Pediastrum*<br>*Filisphaeridium* | few and fragmentary | Coniferous Forest, Herbal shrub | South Subtropical | Humid | Fresh Water or Saline non-marine Water |
| | Shahezi Fm. | *Osmundacidites*<br>*Cyathidites*<br>*Aequitriradites*<br>*Pinaceae* | *Sentusidinium*<br>*Granodiscus*<br>*Filisphaeridium* | *Cypridea ihsienensis*<br>*Limnocypridea sp.*<br>*Mongolocypris globa*<br>*Mantelliana sp.*<br>*Darwinuia contracta* | Coniferous Forest, Herbage | Middle Subtropical | Humid | Fresh Water or Saline non-marine Water |

**Figure 6.** Microfossils, palaeoclimates and paleovegetation of each formation in Lishu depression. Palynomorph genera, algae and Ostracoda occurred in the samples of LS1 Well and SW110 Well.

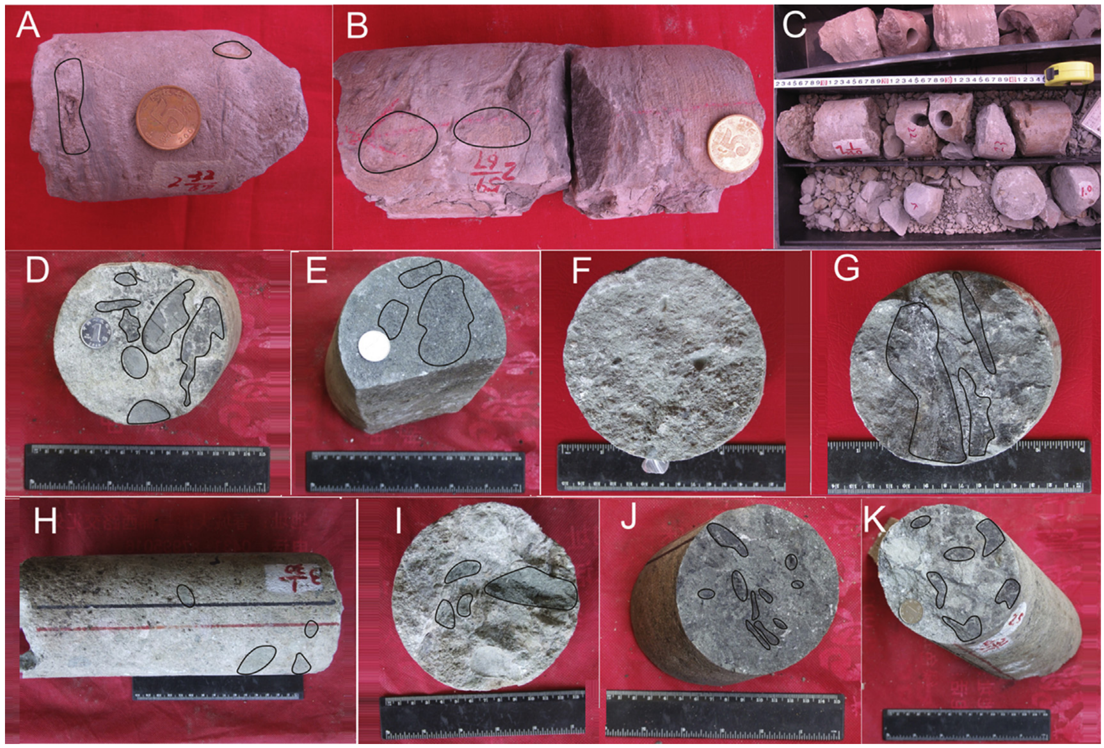


**Figure 7.** The core characteristic of Denglouku Formation, Yingcheng Formation and Shahezi Formation. A: SN117 Well, 617.16–617.25 m, Denglouku Formation, gray thin red sandstone containing argillaceous stripes; B: SN117 Well, 620.33–621.03 m, Denglouku Formation, Gray thin red sandstone; C: SN118 Well, 837.27–837.67 m, Denglouku Formation, Gray and gray thin red sandstone; D: SW110 Well, 1463.29 m, Yingcheng Formation, gray fine-grained sandstone, mud layer, containing mud layers and oil stains; E: SW110 Well, 1463.56 m, Yingcheng Formation, Dark gray fine sandstone; containing laminae of carbonaceous debris; F: SW110 Well, 1575.3 m, Yingcheng Formation, dark gray conglomeratic-mud thin sandstone (gravel diameter: 2–5 mm), good separation; G: SW110 well, 1577 m, Yingcheng Formation, Dark gray fine-grained sandstone, containing carbonaceous debris of roots; H: SW110 Well, 1694.1 m, Yingcheng Formation, noise glutenite, containing dark gray and celadon boulder, maximum particle size is more than 4 cm; containing clay grains; I: SW110 Well, 1698.5 m, Yingcheng Formation, light gray glutenite, containing large dark gray clumps and green silty mud pebble; J: SW110 Well, 1898.1 m, Shahezi Formation, dark gray fine-grained sandstone, seeing the carbon plant debris; K: SW110 Well, 1899.4 m, Shahezi Formation, gray conglomeratic sandstone containing celadon boulder, separation and roundness is general, the average particle size is about 1.5 cm, seeing the carbon plant debris.

material, including abundant *Cyathidites*, whereas tropical-temperate, temperate plants account for 51.7%, of which 23% are temperate plants (Table 2). Therefore, the palaeoclimate may be characterized as having been subtropical.

Analysis of palynoflora indicates that hygrophytes, accounting for 91.3% of palynoflora, are dominant during the period. The content of *Cyathidites* (20%) is highest, followed by *Pinaceae* (17.1%) and *Deltoidospora* (14.3%), with lesser contents of mesophyte (5.8%), and xerophytes (2.9%). These data indicate that the climate of Shahezi Formation was humid (Table 2). *Granodiscu*, *Sentusidinium* and *Filisphaeridium* found in the Shahezi Formation indicate a fresh water and saline non-marine water environment (Fig. 6) (Qiao et al., 2002; Zhang and Bao, 2009; Zhao et al., 2014). The Shahezi Formation contains abundant Ostracods, with a variety of species indicative of freshwater environment, such as *Limnocypridea* (Gao et al., 1999; Chen, 2003; Wan et al., 2007),.These paleontological determinations indicate that fresh or saline non-marine water settings prevailed during deposition of the Shahezi Formation.

#### 4.3.2. Yingcheng Formation

In strata of the Yingcheng Formation, the content of shrubs (20.2%) is relatively high than the Shahezi Formation, and *Cicatricosisporites* accounts for 12.6% of all shrub vegetation. The content of herbaceous plants in the Yingcheng is 29.4%, the greatest proportion of which is the *Deltoidospora* (15.4%), followed by *Leiotriletes* (4.9%) and *Schizaeoisporites* (3.8%) (Table 2). Coniferous plants account for 36%, the most of which is *Classpllisannulatus* (13.2%), followed in abundance by *Pinaceae* (9.3%) and *Taxodiaceapollenites* (8.2%), both of which generally, grow in temperate zones (Table 2). Consequently, this indicates vegetation was dominated by coniferous forest and herbal shrub. The proportion of tropical plants and tropical-subtropical plants is greater. Tropical-subtropical plants account for 41.6% of preserved plant material, among which *Deltoidospora* (15.4%) and *Classopollis* (13.2%) account for a large proportion. Vegetation found in the tropical-temperate zone accounts for 10.8% of plant material, of which *Granulatisporites* (4.9%) forms the greatest amount. The content of temperate plants is relatively low, at only 20.1%, and are mainly represented by *Pinaceae* (9.3%) and *Taxodiaceaepollenites* (8.2%) (Table 2). Therefore, a south Asian tropical climate prevailed during deposition of the Yingcheng Formation.

Compared with that of the Shahezi Formation, the xerophyte content, especially of *Classopollis* (13.2%) (Table 2), is greater than that of the Yingcheng Formation. The mesophyte content is 7.6%, including Cycadopites (3.3%), and the hygrophilous plant content is 76.4%, which is less than the content of hygrophilous plant (91.3%) in the Shahezi Formation. This indicates climate of the Yingcheng Formation was humid (Fig. 6, Table 2). The abundance of algae and Ostracoda is significantly less in the Yingcheng. The algal content includes *Pediastrum and Filisphaeridium*, but for Ostracoda, only sporadic fragments appear.

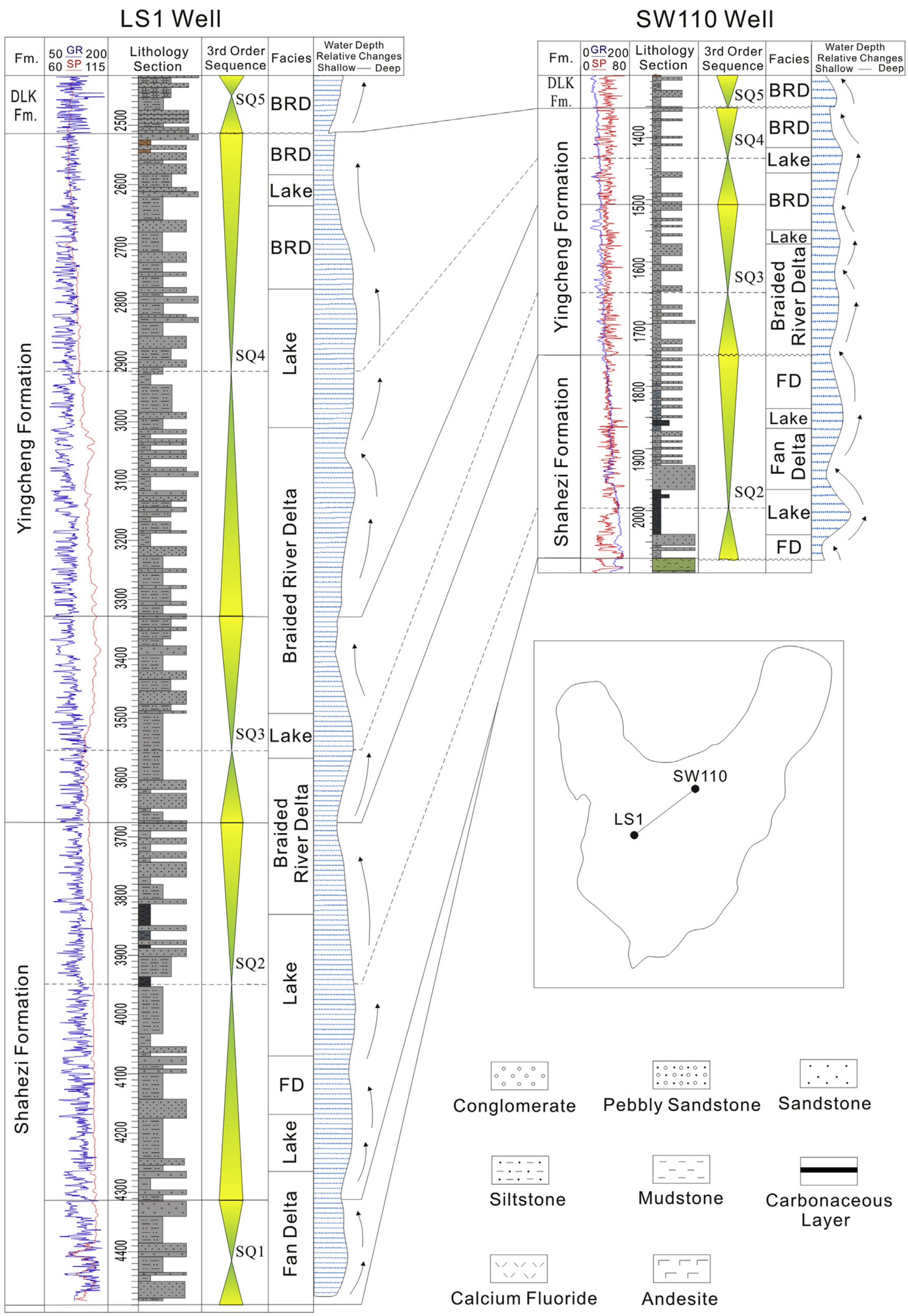


**Figure 8.** The cross-section from LS1 well to SW110 well and the relative water depth changes. Fm: Formation; DLK Fm: Denglouku Formation; BRD: Braided River Lake; FD: Fan Delta. 3 rd. Sequences of each formation were divided with sequence division methods (Vail et al., 1977; Van Wagoner et al., 1990; Vail, 1991; Catuneanu et al., 2009). Well log and lithology for SQ1–SQ5 of LS1 and SQ2–SQ5 of SW110 showed the relative changes of water depth. Well location is also marked in Fig. 1.

*Pediastrum* is a broadly distributed phytoplankton in freshwater lake environments and lives in shallow lakes or depressions where there is poor circulation and overturn of the water column. *Pediastrum* is typically well preserved after burial. Consequently, *Pediastrum* is a very reliable indicator for shallow water environments with poor circulation (Evitt, 1963; Gao et al., 1999; Komarek and Jankovská, 2001; Turner et al., 2014). *Pediastrum* found in the Yingcheng Formation is also an indicator of a shallow-water lacustrine environment. The presence of a small proportion of Filisphaeridium, which is indicative of saline non-marine water settings (Gao et al., 1999; Hou et al., 2000; Qiao et al., 2002; Zhang and Bao, 2009; Zhao et al., 2014), implies that the Yingcheng Formation was deposited in an environment of fresh to saline water.

#### 4.3.3. Denglouku Formation

In the Denglouku Formation, the content of coniferous flora at 41% is relatively great, especially *Classopollis* (27.8%) which lived in the tropical-subtropical zone (Gao et al., 2013) (Table 2). The content of shrub and herbage vegetation is correspondingly relatively low and include *Deltoidospo*ra (11.1%) and *Cicatricosisporites* (11.1%), both of which are tropical-subtropical plants (Gao et al., 1994) (Table 2). Unlike in underlying formations, angiosperms, such as evergreen broad-leaved plant *Clavatipollenites,* whose content is 3.8% (Table 2), are present in the Denglouku. During deposition of this unit, the content of tropical plants and tropical-subtropical plants increased. The content of tropical plants in the Denglouku is 28%, including *Cicatricosisporites* (11.1%). the content of tropical-subtropical plants is 50.1%, dominated by *Classopollis* (27.8%) (Table 2). Therefore, the palaeoclimate was tropical and the vegetation was coniferous during the period of the Denglouku Formation (Fig. 6).

Also, the content of xerophytes in the Denglouku is relatively great, up to 31.5%. Most were *Classopollis* (27.8%), indicative of a semi-arid climate (Gao et al., 1994). The algal and Ostracoda contents of the Denglouku are somewhat greater than those in underlying units, which may indicate a more saline non-marine water depositional setting. Some fresh-saline water types of algae and Ostracoda are also present, such as *Granodiscus*, *Leiosphaeridia*, *Cypridea* and *Darwinula*. The water could become more saline during deposition of the Denglouku Formation because the climate was relatively hot and dry at this time (Fig. 6).

## 5. Discussion

### 5.1. Microfossils preservation

The composition and morphology of microfossils would change in a burial environment (Gao et al., 1999). The Songliao basin is characterized by a high geothermal gradient of 3.9–6.5 °C/100 m; and the average geothermal gradient in the south of Songliao basin is about 4.2 °C/100 m (Ren, 1999; Zhang et al., 2015). When buried depth was more than 2500 m and temperature would over 100 °C, some vulnerable microfossils were hard to preserve because of the high temperature and thermal metamorphism. The sample depths are between 1200 and 2055 m in SW110, and 1600–3300 m in LS1 (Table 1). The depths would exceed 2500 in some periods if plus the denudation thickness (Yan et al., 2012). With the increase of depth, the numbers of microfossils would get less.

### 5.2. The comparison with other areas

Some paleontologists commonly identify the Jurassic and Cretaceous periods by the presence or absence of *Cicatricosisporites* (Qiu, 1991, 1992; Gao et al., 1994). During deposition of the Shahezi Formation, *Cicatricosisporites* spread across the Songliao basin, including the north of the basin, and it increased in abundance significantly in the upper Shahezi Formation (or 3rd, 4th units of the Shahezi Formation) (Fig. 5; Qiu, 1991; Gao et al., 1994). This species also appeared in the Lishu depression (2.9%, Table 2), indicating that the Shahezi Formation of the Lishu depression was deposited in the early Cretaceous. During deposition of the Yingcheng, *Cicatricosisporites* became more abundant across the entire Songliao basin, including the Lishu depression (Fig. 2, Table 2). Some plants of the early Cretaceous were evolved from the plants of late Jurassic period in the entire Songliao basin and also the north of Songliao basin (Qiu, 1992; Wan et al., 2002; Ren et al., 2003). Therefore, the drought-resistant deciduous species *Classopollis* existed during the early stages of Shahezi deposition, the content of which is 17.6% in the entire Songliao basin. During the later stages of Shahezi deposition, however, its content decreased dramatically to 1.7% (Gao et al., 1994).

In the Lishu depression, conversely, the content of *Classopollis* was quite small, and instead the content of *Pinaceae*, indicative of a more humid climate, is abundant, taking up 17.1% (Table 2, Fig. 2). This indicates that the Lishu depression, southern Songliao basin, was more humid than in the northern parts of the basin during Shahezi deposition. The hygrophyte *Aequitriradites* (5.7%) was also found in Shahezi of Lishu depression (Table 2). The taxon *Aequitriradites* has been recorded in strata of the lower upper Cretaceous of northwestern Wyoming and northwestern Utah, lower Cretaceous in the Patagonia (Argentina), Rajmahal Formation of Rajmahal basin (India), Siberian palaeobasin, Ejina basin of West Inner Mongolia, and Jurassic–Cretaceous of northwestern desert of Egypt (Upshaw, 1963; Archangelsky and Gamerro, 1967; Nichols and Warner, 1978; E.l. Beialy, 1994; Wang et al., 1998; Mahmoud and Moawad, 2000; Tripathi, 2001; Pestchevitskaya, 2008; Tripathi, 2008).

During deposition of the Yingcheng Formation, the shrub plant *Cicatricosisporites* and the broad-leaved forest plant *Cyathidites* populated the entire Songliao basin (Fig. 5). There were a large number of *Taxodiaceapollenites* in the Lishu depression, accounting for 8.2% of microflora in the Yingcheng (Table 2). During this time, the number and diversity of plant species reached a peak, especially the ferns, gymnosperms, and angiosperms, such as *Clavatipollenites*. However, in strata of the Lishu depression, no angiosperm pollen was recorded. *Clavatipollenites* was first discovered and described in the Wealden Formation of the United Kingdom (Hughes, 1958), then in the plains of Europe (Muller, 1970), North America's Atlantic coast (Doyle and Robbins, 1977), as well as in the Strata of Albian in western Canada (Jarzen and Norris, 1975) and the strata of Barremian in Africa (Wolfe et al., 1975). Additionally, *Clavatipollenites* also appeared in the lower Albian in Russia (Chlonova, 1977) and Australia (Stover and Partridge, 1982). During deposition of the Denglouku Formation, angiosperms were widely distributed throughout the Lishu depression, such as *Clavatipollenites* (3.8%) found in SW110 Well. At the same time, the xerophilous plant *Clossopollis* and *Schizaeoisporites* also increased in abundance (Table 2 and Fig. 2).

### 5.3. Sedimentary environment and vegetation evolution

#### 5.3.1. Core features

The colors of rocks characterized by gray and gray red in the Denglouku Formation reflect the arid and oxidized environment. Rocks are gray-red because of the presence of variably oxidized iron compounds that might be hematite and/or limonite (Miller Jr and Folk, 1955). The presence of oxidized iron compounds indicates that rainfall was sporadic and the climates was hot and dry (Fig. 7A, B, C). The cores from various horizons within the Yingcheng and Shahezi Formations are typically light gray and dark gray fine sandstone with some dark-gray boulders (Fig. 7D, H, I) and plant debris (Fig. 7E, G, J, K). The color of these is darker than that of the Denglouku Formation well cores, indicating that more reducing environmental conditions prevailed during Yingcheng and Shahezi deposition. The argillaceous and organic matter content and plant content was greater in the Shahezi Formation, indicating a warmer and more humid climate prevailed during Shahezi deposition.

### 5.3.2. Geochemical indicators

The pristine to phytane ratio (Pr/Ph) is considered to be a geochemical indicator, that reflects changes in the sedimentary environments. A Pr/Ph $< 2$ indicates a reducing environment, but a Pr/Ph of between 2 and 4, indicates oxidizing environmental settings (Didyk, 1978; Sinninghe Damsté et al., 1987). Geochemical analyses of rock samples from the LS1 well of strata of the Shahezi Formation yielded Pr/Ph values of between 0.5 and 1.2. This indicates that a reducing environment prevailed during deposition of the Shahezi Formation. The corresponding value for Pr/Ph in the Yingcheng Formation samples range between 0.8 and 1.2. This range indicates weakly reducing environment prevailed during Yingcheng deposition (Li, 2009).

### 5.3.3. Evolutionary process

In the early Cretaceous, the southwest region of the Lishu depression was a deep depression, whereas the northern, eastern, and southeastern parts of Lishu depression were slopes that bordered the southwest lacustrine depression. During deposition of the lower part of the Huoshiling Formation and the overlying Shahezi Formation, the fault depression's morphology had several breaks, or inflections, in the slopes around the depression, which evolved to form one single slope break during deposition of the Yingcheng and Denglouku formations (Fig. 1A–A′). The LS1 Well is close to the deep depression area, but the SW110 Well is located within the northern slope setting, so Shahezi and Yingcheng strata in the LS1 Well is significantly thicker than that in the SW110 Well (Fig. 1).

During deposition of the Shahezi and Yingcheng formations, changes in the water depths exhibited a variety of different patterns (Fig. 8). During Shahezi deposition, water depths were relatively deep and the amplitudes of base level changes were greater than corresponding changes during Yingcheng deposition. During deposition of the lower part of the Shaheizi Formation, a fan delta system occupied most of Lishu depression. Then, at the end of this period, a braided river delta system developed along the northern and eastern gentle slopes, while the fan delta system continued to occupy the steep slope of Lishu depression (Figs. 8 and 9). A humid climate and large sediment source caused development of the braided river delta system. Vegetation transitioned to hygrophyte types from xerophytes, and coniferous forest and herbaceous plants thrived (Fig. 9). A certain number of broad-leaved forests (Cyathidites, taking up 20%, Table 2) also grew during this time. Algae and Ostracoda indicated that the water during this time was fresh to saline.

When depths decrease, the water became more saline, in an inverse correlation with water depth. The sedimentary framework at the end of Shahezi deposition continued during Yingcheng deposition, and braided river deltas developed across the northern and eastern gentle slope zones (Figs. 8 and 9). Plant life was

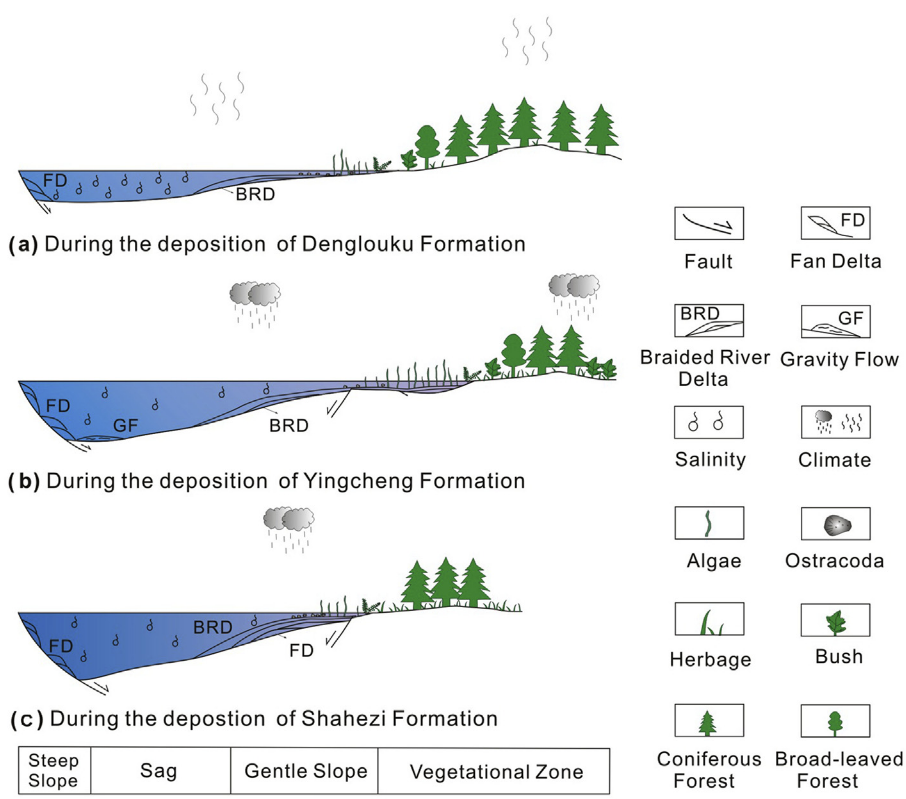


**Figure 9.** The basin development and vegetation evolution pattern in different period of early Cretaceous, (a) the sedimentary period of Denglouku Formation, (b) the sedimentary period of Yingcheng Formation, (c) the sedimentary period of Shahezi Formation; FD: Fan delta; BRD: Braided river delta; GF: Gravity Flow.

extremely abundant during Yingcheng deposition. The main plant types were coniferous forest, herbage, bushes, and a number of broad-leaved forest and algae (Fig. 9). The lake waters were fresh to during this time, but because of the effects of volcanic activity, Ostracoda diminished in abundance.

The gammacerane index of LS1 well indicates a freshwater environment during Shahezi and Yingcheng deposition. Gammacerane is a triterpene compound and its abundance provides an index that correlates with environmental salinity (Peters, 1986; McCaffrey et al., 1994). The content of gammacerane in the Shahezi Formation and the Yingcheng Formation is less than 0.2 (Li, 2009), indicating the prevalence of a relatively freshwater setting.

During deposition of the Denglouku Formation, parts of basin were uplifted and denuded because of tectonism (Chen et al., 1999). The climate at this time became hot and arid. A xerophytic coniferous forest subsequently developed, but there were a few broad-leaved forests, shrubs, and herbage (Fig. 9). Enhanced evaporation led to shallower lacustrine water depths, and more salinelake waters.

### 5.4. Petroleum significance

Palaeoclimatic changes significantly affected the production of organic matter and the formation of hydrocarbon source rocks in the petroleum basin. At the same time, the climate controlled the supply of sediment source, controlling the development of a delta system and the distribution of fluvial sand bodies. Additionally, the climate governed the amount of rainfall that controls the rates of dissolution of exposed strata, and, in turn affecting the quality of porosity in potential reservoir facies.

#### 5.4.1. Hydrocarbon source rocks

The lacustrine mudstone in the Shangshutai sub-sag area is relatively rich in organic material and is relatively thick (Figs. 8 and 10). Consequently, it is an ideal hydrocarbon source rock (Figs. 9 and 10). Geochemical analysis of the rock samples from LS1 well indicate that the organic carbon content of the Shahezi Formation is 0.38–2.24%, with a content of chloroform bitumen "A" of 158–1140 ppm, and a total hydrocarbon content of between 156.14 and 189.75 ppm. The organic carbon content of the Yingcheng

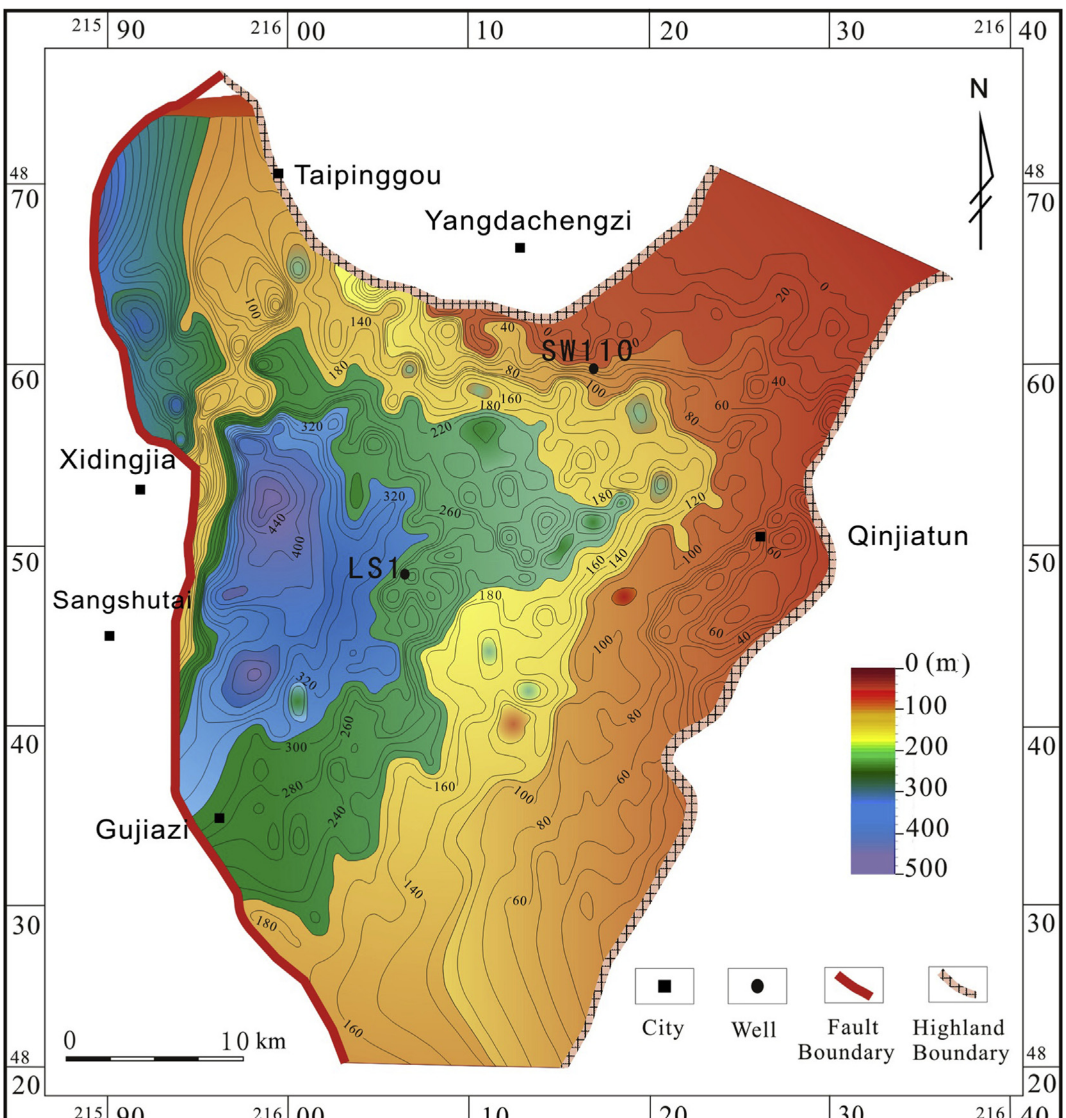


**Figure 10.** The strata thickness figure of the Yingcheng Formation.

Formation is 0.5–1.6%, with a content of chloroform bitumen "A" more than 1000 ppm, and total hydrocarbon content of between 494.10 and 4432.43 ppm. The organic carbon content of the Denglouku Formation, however, is between 0.12 and 0.47%, with a content of chloroform bitumen "A" of between 21 and 143 ppm, indicating a low hydrocarbon potential for the Denglouku Formation (Li, 2009). The organic matter types of the Shahezi Formation and Yingcheng Formation are mainly sapropelic-humic type (II2) and humic type 1 (III1), the deep sub-sag area contains humic-sapropel type (II1) and sapropel type (I) (see classification of Smyth et al., 1984). This is due to the warm and humid climate that prevailed during Shahezi and Yingcheng deposition when the lake maintained a relatively constant and significant water depth and flourishing biota in a relatively freshwater lacustrine setting. This climate created conditions that led to development of hydrocarbon source rocks. The mudstone of the Shahezi Formation in Shangshutai sub-sag area is thicker, with high-quality hydrocarbon source rocks. During Yingcheng deposition, the lake area expanded and hydrocarbon source rock developed across a wider area than during Shahezi deposition.

In contrast, most of the organic matter in the Denglouku Formation is humic type (III). During deposition of the Denglouku, the climate was hot and arid so that lacustrine water depths became shallow and more oxidizing. This led to oxidation of organic material during deposition and poor hydrocarbon source rock potential.

#### 5.4.2. Reservoir types and distribution

Climate changes affect sediment source supply and volumes of seasonal water (or flush flood) which facilitate increases in the number and directions of sediment sources. Fan deltas and submarine fans developed near sediment sources along the western steep slope, and braided river deltas developed along the northern gentle slope zone (Fig. 9).

Potential reservoir facies of the Shahezi and Yingcheng Formations are coarse sandstone and fine sandstone characterized by inter-granular porosity. North and southeast of the depression, sedimentary facies reflect deposition from braided river deltas. This braided river delta system formed vertically stacked sand bodies across a broad area, forming thick and continuous potential facies belts of petroleum reservoir (Figs. 9 and 10). During Denglouku deposition, the lake located in southwest Songliao basin became shallow because of climatic aridity and a large area of strata was exposed to subaerial erosion and weathering (Yan et al., 2012). Secondary porosity developed as groundwater of meteoric origin invaded the Denglouku Formation, forming intergranular, intragranular, and moldic dissolutional porosity, and including an occurrence of a pore that appears to have originated by dissolution of cement, as well as a large number of fractures (Chen et al., 1999; Yan et al., 2012). After multiple episodes of corrosion and weathering, the exposed strata of the Denglouku Formation probably contain good reservoir facies along the eastern slope and central uplift zones of the Lishu depression.

#### 5.4.3. Migration channel and the analysis of reservoir and cap

The climate was more humid and rainfall was steady during Shahezi deposition, causing efficient sediment transport into the center of the basin. Sandstone commonly was interbedded with mudstone providing an effective conduit for the lateral migration of oil and gas. Oil and gas generated from deeply buried hydrocarbon source rocks could migrate through the main basin-bounding fault to potential petroleum reservoirs in the Denglouku Formation. The development of these reservoirs was enhanced by weathering and shallow subsurface dissolution. Late tectonization (Chen et al., 1999) may also caused oil and gas from deep reservoirs to migrate vertically and be trapped in the Denglouku Formation in secondary reservoirs. Oscillatory changes in water depth caused development of multiple transgressive-regressive depositional sequences (Fig. 8). The superimposed style of sand bodies and the common interbedding of thick sand bodies and thinner mudstone also reflect the cycle changes of depth and climate. The Shahezi and Yingcheng formations contain multiple sets of hydrocarbon source rocks and a diversity of reservoirs facies types. Dense dark mudstone formed hydrocarbon source rocks near the upper reservoir facies of the lower Cretaceous. Oil and gas can migrate laterally through sand bodies and/or vertically through faults, so that the vertical superimposed traps and lateral continuous traps of oil and gas could form in the petroleum system of the Lishu depression.

## 6. Conclusions

The identification and statistical analysis of palynomorph genera, algae and Ostracoda from lower Cretaceous rocks of Lishu depression strata have implications for better understanding of its palaeoclimate. The palaeovegetation and palaeoclimate changed significantly from the time of Shahezi Formation deposition to the Denglouku Formation deposition. Palaeovegetation was dominated by coniferous forest and herbage during Shahezi deposition, whereas coniferous forest, and herbal shrub vegetation dominated during Yingcheng deposition, and coniferous forest vegetation was established during deposition of the Denglouku Formation.

The temperature zones were mid-subtropical during Shahezi deposition and south subtropical-tropical during deposition of the Yingcheng Formation. Taken together, the climate for these two periods was warm and humid and the lake was fresh to somewhat saline. During deposition of the Denglouku Formation, however, the climate became a relatively hot and dry tropical climate and lacustrine environments gradually became more saline. The climate became dryer with the increase in the average annual temperature.

Climatic change during deposition of this entire succession was not a uniform process and many small reversals occurred, but major trends are clear. One such major climatically induced trend led to the emergence of angiosperms specifically during deposition of the Denglouku Formation. Another climatically induced trend was the enhanced growth of algae and reduction in Ostracoda abundance during Yingcheng deposition. Good potential petroleum was produced and preserved in Lishu depression because of climate changes.

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