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The Cretaceous Songliao Basin: Volcanogenic Succession, Sedimentary Sequence and Tectonic Evolution, NE China

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Abstract: The Songliao basin (SB) is a superposed basin with two different kinds of basin fills. The lower one is characterized by a fault-bounded volcanogenic succession comprising of intercalated volcanic, pyroclastic and epiclastic rocks. The volcanic rocks, dating from 110 Ma to 130 Ma, are of geochemically active continental margin type. Fast northward migration of the SB block occurred during the major episodes of the volcanism inferred from their paleomagnetic information. The upper one of the basin fill is dominated by non-marine sag-style sedimentary sequence of siliciclastics and minor carbonates. The basin center shifted westwards from the early to late Cretaceous revealed by the GGT seismic velocity structure suggesting dynamic change in the basin evolution. Thus, a superposed basin model is proposed. Evolution of the SB involves three periods including (1) Alptian and pre-Aptian: a retroarc basin and range system of Andes type related to Mongolia-Okhotsk collisional belt (MOCB); (2) Albian to Companian: a sag-like strike-slip basin under transtension related to oblique subduction of the Pacific plate along the eastern margin of the Eurasian plate; (3) since Maastrichtian: a tectonic inverse basin under compression related to normal subduction of the Pacific plate under the Eurasian plate, characterized by overthrust, westward migration of the depocenter and eastward uplifting of the basin margin.

Key words: Cretaceous superposed Songliao basin, volcanic rocks, sedimentary sequence, tectonic evolution, Mongolia-Okhotsk collisional belt, Pacific and Eurasian plates, retroarc strike-slip tectonic-inverse basins

1 Introduction

The Songliao basin (SB) is the largest and most important petroliferous basin amongst the 66 Mesozoic/Cenozoic basins in northeast China, with an area of 260,000 km^2, and the basin axis trends northeast (Fig. 1). Petroleum exploration in the SB began in the 1950s (Wang et al., 1993). However, the main strata of interest had been confined in the upper Cretaceous with a buried depth less than 3000 m before the late 1990s. After high productive commercial gases have been drilled hosted in the early Cretaceous volcanic rocks in recent years, people realize that beneath the oil-bearing upper Cretaceous sedimentary sequence there is still another gas-bearing early Cretaceous volcanogenic succession. The two different kinds of fills and petroleum systems make up of the whole story of the basin evolution.

The SB's tectonic interpretation is controversial. According to previously available interpretations (e,g, Chen and Dickinson, 1986; Liu, 1986; Liu, et al, 1993; Zhang, et al., 2006), the SB is a rift basin. Ma et al. (1989) and many others considered the SB as an intracratonic basin. However, the SB exhibits some features difficult to reconcile with these interpretations. For example, the region involved is an active continental margin setting rather than a craton in the Mesozoic. As for the rift model, Einsele (2000) indicated that the phase prior to rifting is characterized by widely extended flood basalts and later the rift valley could be filled by lava flows and tephra of

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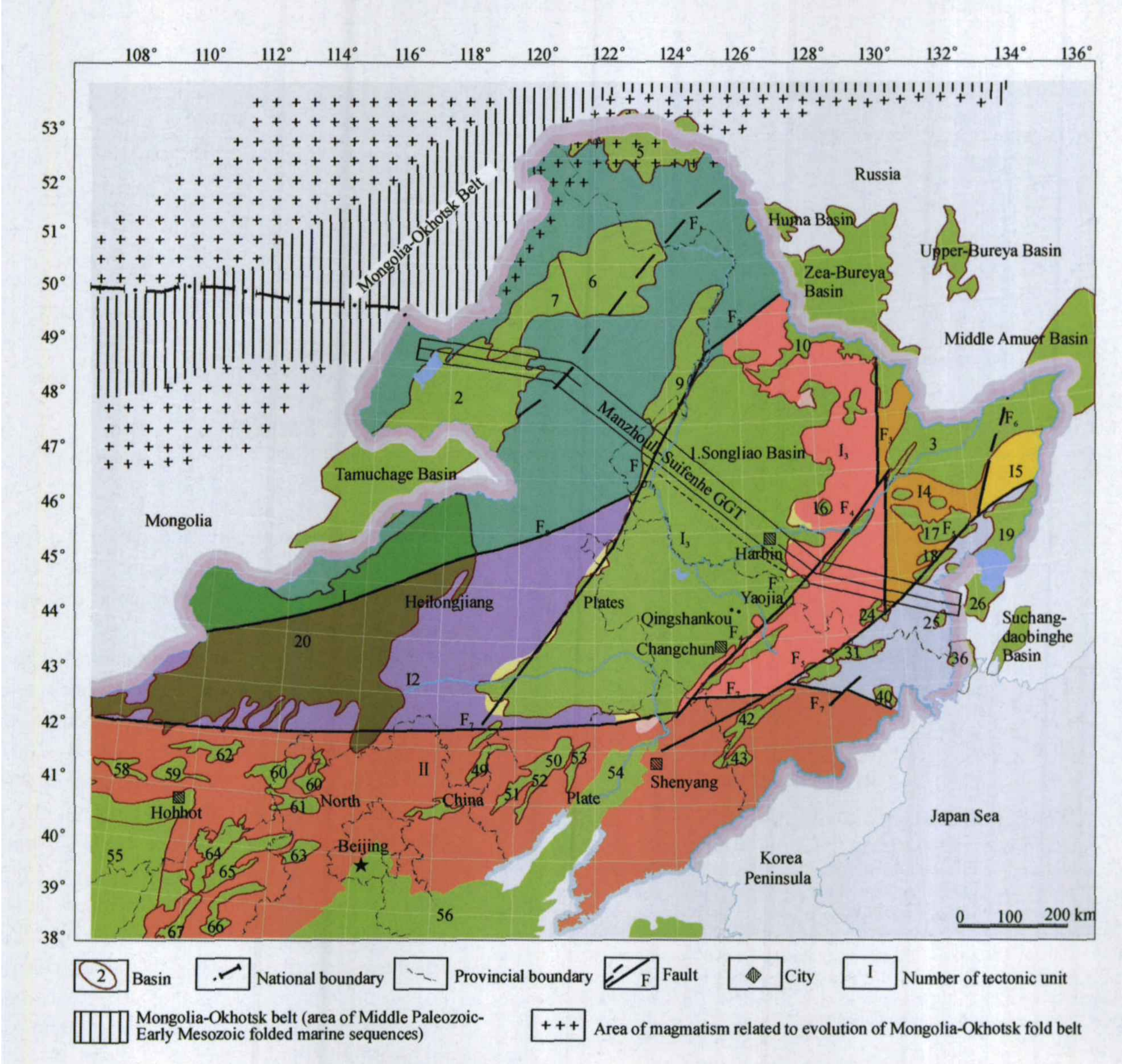

Fig. 1. Map of the Songliao basin, showing tectonic elements, fault system and distribution of sedimentary basins (based on Zhang et al., 1999; Zorin, 1999; Wang et al., 2005; Sun et al., 2007).

Notes: I – Heilongjiang plates; I_1 – Erguna-Hinggan micro-plate; I_2 – Wenduermiao-Hegenshan continental-marginal accretion belt; I_3 – Songliao-Zhangguangcailing micro-plate; I_4 – Jiamusi micro-plate; I_5 – Nadanhada continental-marginal accretion belt. II – North China plate. F_1 – Tayuan-Xiguituqi fault zone; F_2 – Nenjiang fault zone; F_3 – Mudanjiang fault zone; F_4 – Dunhua-Mishan fault zone; F_5 – Jiamusi-Yitong fault zone; F_6 – Xiaheilongjiang fault zone; F_7 – the north margin of the North China plate fault zone; F_8 – Hegenshan fault zone.

variable compositions. In contrast, the SB is rhyolite dominant and there are no such large-scale flood basalts of typical rifting type having been found in the basin filling up to now (Wang et al., 2002a, 2002b).

Based on the facts that the SB has two different kinds of basin fills, up to 5000 m of normal sediments overlaying upon a thick volcanogenic unit, and that its volcanic series is not rift-like but arc-like and shows mixed signatures of both the MORB and the crust (Wang et al., 2006), we outline in this paper the volcanic-sedimentary-tectonic basin evolution and put forward a superposed basin model to better fit these key features.

2 Geological Background

The most important elements are Mongolia-Okhotsk collisional belt (MOCB) to its north and the Pacific plate to its east concerning plate tectonics of the SB. By means of paleotectonic reconstruction, Sengör and Natal'in (1996) showed that the collision at Mongolia-Okhotsk suture lasted from the beginning of the Jurassic to the Jurassic-Cretaceous transition and ended before the Albian. The

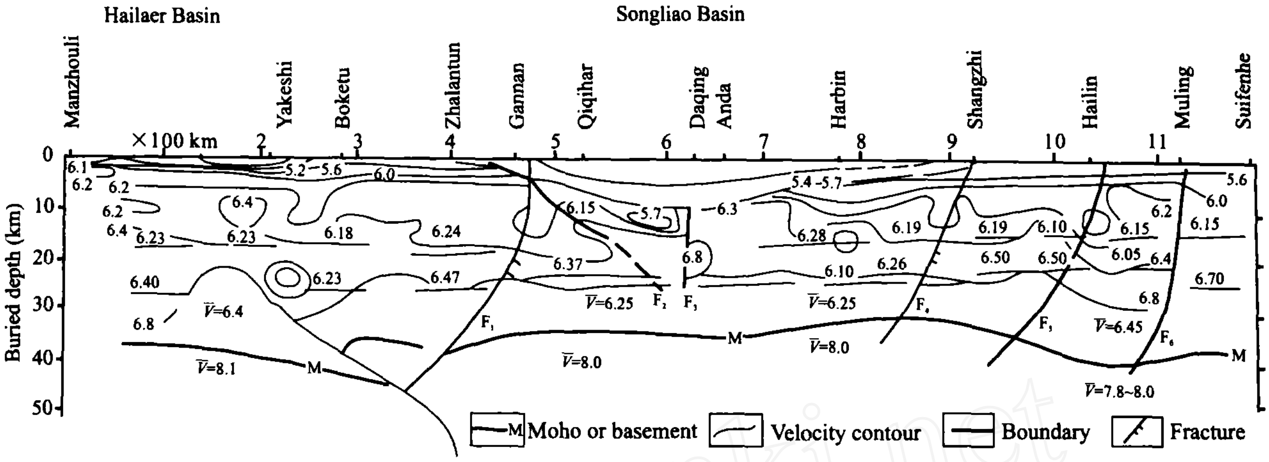

Fig. 2. Seismic velocity structure and geophysical boundaries of the Manzhouli-Suifenhe GGT (after Yang et al., 1996).

Notes: 1. Moho or basement; 2. velocity contour; 3. boundary; 4. fault. F1 – Heihe-Hegenshan suture zone; F2 – Nenjiang fault; F3 – Sunwu fault; F4 – Jiayi fault; F5 – Mudanjiang suture zone; F6 – Dunmi fault.

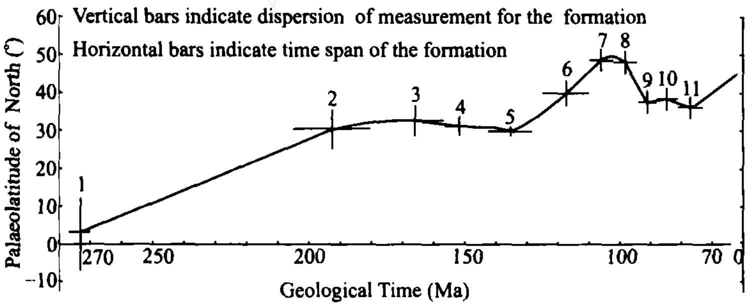

Fig. 3. The paleolatitude migration curve of the Songliao block since the Permian with emphasis on the Jurassic and Cretaceous.

Note: the fast northward movement occurred during the volcanic active stage of point 6. P_1*wj* – Lower Permian Wujiatun Formation; J_1*hq* – Lower Jurasic Hongqi Formation; J_2*wb* – Middle Jurasic Wanbao Formation; J_3*hs*/J_3*hr* – Upper Jurassic Huoshiling/Hurige Formations; 5. K_1*sh*/K_1*fj* – Lower Cretaceous Shahezi/ Fujiawazi Formations; K_1*yc*/K_1*lj*/K_1*bs* – Lower Cretaceous Yingcheng/Longjiang/Baoshi Formations; K_1*dl* – Lower Cretaceous Delouku Formation; K_1*qt* – Lower Cretaceous Quantou Formation; K_2*qs* – Upper Cretaceous Qingshankou Formation; K_2*yj* – Upper Cretaceous Yaojia Formation; K_2*nj* – Upper Cretaceous Nenjiang Formation.

suturing event happened simultaneously with the development of volcanogenic succession in the lower fill of the SB. The Pacific plate, also called Izanagi/Kula plate in the Cretaceous, has been subducting under the Eurasian plate since the early Cretaceous (Maruyama, 1986). Combination of the velocity and the direction of subduction may be the controlling factors on the evolution of the SB. High-speed and perpendicular subduction of the Pacific plate to the eastern edge of the Eurasian plate ought to cause most significant impact on the SB, and vice versa. According to Maruyama (1986), in the early Cretaceous the motion speed of the Pacific plate was high (20–30 cm/yr) but the angle between the Eurasian plate margin and the subducting vector of the Pacific plate was very small (between 20° and 5°), so this simply means that less than 1/3 component of the subducting-derived forces could impress on the continent margin. Since the late Cretaceous, however, combination of the subducting speed and direction was favorable and could reasonably provide strong dynamic impact on the SB region.

The basement of the SB was formed by a series of accretions among 6 micro-plates called the Heilongjiang plate Group before the Triassic (Zhang et al., 1999; Sun et al., 2007). The SB is a fault trilaterally bounded in its west, east and south. The plate margin fault (F7 in Fig. 1) traversing from east to west separates the SB block in the north from the north China plate in the south. Other two boundary faults, the Nenjiang fault in the west and the Jiayi fault in the east, strike northeast identical with the basin orientation, parallel to the basin axis, cutting through the crust deep to the Moho (see F2 and F4 in Figs. 1, 2).

A global geoscience transect (GGT) called the Manzhouli-Suifenhe GGT (Zhang et al., 1999) traversing the central SB shows double Moho uplifts and basin centers beneath the areas, one from Daqing to Anda and the other from Harbin to Shangzhi (Fig. 2). Correlation between the well-log and the seismic reflection indicates that the bottom of the SB can be represented by seismic velocity of ca. 6.3 or 6.28. Accordingly, a regular and another irregular sub-basin bottoms can be recognized in the west (near Daqing) and east (near Harbin) respectively. Considering the volcanogenic successions are well developed and exposed in the eastern part of the SB (Wang et al., 2002b), the east buried sub-basin should be indicative of the features of the early Cretaceous basin fill, suggesting that a previously developed basin was altered by the subsequent basin-forming process.

With reconstruction of paleolatitude of the SB block

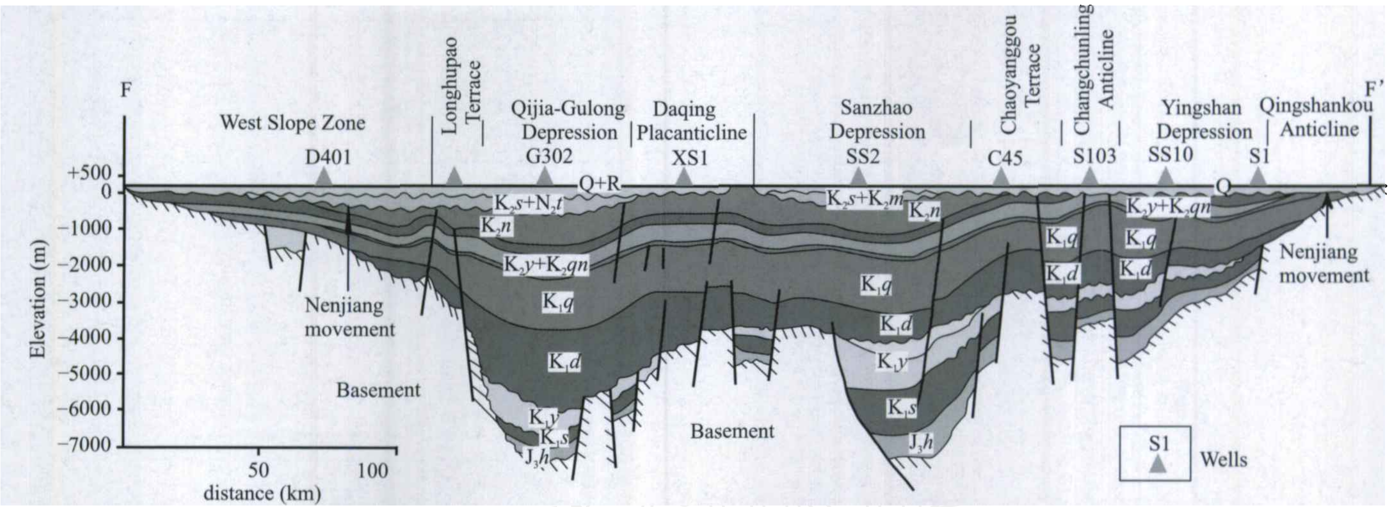

Fig. 4. Cross section of the Songliao basin, showing three cycles of the basin filling. Position of F-F' as shown in Fig. 1.

sampled both from outcrop and core-section (Chi et al., 2000), it is interesting to note that the SB block drifted in Jurassic and Cretaceous periods, and the most significant northward movement of the block occurred in the major episode of the volcanisms in the Cretaceous (point 6 in Fig. 3) corresponding to the lower Cretaceous Yingcheng formation dating from 110 Ma to 130 Ma (Wang et al., 2002b). The relationship between volcanic activity and plate movement suggests that the volcanism is correlate to the tectonically active stage in the region.

3 Volcanogenic Succession

Basin filling of the SB is in a typical ox-head shape and can be obviously subdivided into the upper and lower layers by regional unconformity on top of the Yingcheng Formation (K_1y in Figs. 4, 6). There is significant difference under and above the unconformity both in rock assemblage and strata shape (Fig. 4). The lower layer is characterized by a fault-bounded volcanogenic succession comprising of intercalated volcanic, pyroclastic and epiclastic rocks. The upper part is composed of a normal sedimentary sequence which will be discussed in detail in the following context. A great deal of work on isotopic dating for the volcanic rocks has been done in recent years. They range in general from 110 Ma to 130 Ma, indicating early Cretaceous ages (e.g. Wang et al., 2002a; Zhang et al., 2007).

Although rhyolite dominant the volcanic rocks in the SB cover a wide compositional spectrum from high-silica rhyolite, dacite, trachyte, andesite, trachyandesite, basaltic andesite, basaltic trachyandesite to trachybasalt. The volcanics are either metaluminous or peraluminous, medium-K or high-K, sub-alkaline and calc-alkaline series dominant (Fig. 5). The typical texture of the volcanic rocks is a low phenocryst porphyritic texture with complexity of phenocryst assemblage commonly including quartz, feldspars (sanidine, anorthoclase and plagioclase), biotite, hornblende, magnetite, ilmenite and pyroxene. The phenocrysts are generally less than 30% in volume percent of the volcanic rocks. Because vesicle, amygdaloid and fracture are rich within the volcanic rocks and their porosity can be up to 20%, they are the main type of reservoirs and ca. 90% of the natural gases found are contained in the volcanic rocks in the north Songliao basin (Wang et al., 2003).

Rare earth and trace elements and isotopes of the Cretaceous volcanic rocks of the SB show arc-like signatures evolved on the active continental margin (Wang et al., 2006). They are enriched in large-ion lithophile elements (LILE) and light rare earth elements (LREE) coupled with depletion in high field strength elements (HFSE) and heavy rare earth elements (HREE). They commonly display negative anomalies of Nb, Ti and P. The initial ^{87}Sr/^{86}Sr ratios and εNd-values of these volcanic rocks range from 0.70338 to 0.71055 and from −3.4 to 5.3, respectively, and their δ^{18}O values vary from 3.24‰ to 14.77‰. Initial ^{206}Pb/^{204}Pb and ^{207}Pb/^{204}Pb ratios have ranges of 17.65 to 18.22 and 15.52 to 15.57, respectively. The characteristics in Nd and Sr isotopic composition fit a hyperbolic mixing curve of two components: E-MORB-like material and the subducted sediments/crust. There are some Cretaceous rhyolites, which show abnormally high $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_i$ ratios and low $\varepsilon\mathrm{Nd}_{(i)}$ indicating crustal assimilation. Primary magmas for the volcanic rocks are believed to be derived from metasomatized E-MORB-like sources.

4 Sedimentary Sequence

Above the volcanogenic succession is a thick normal sedimentary sequence with the mean thickness of ca. 3000

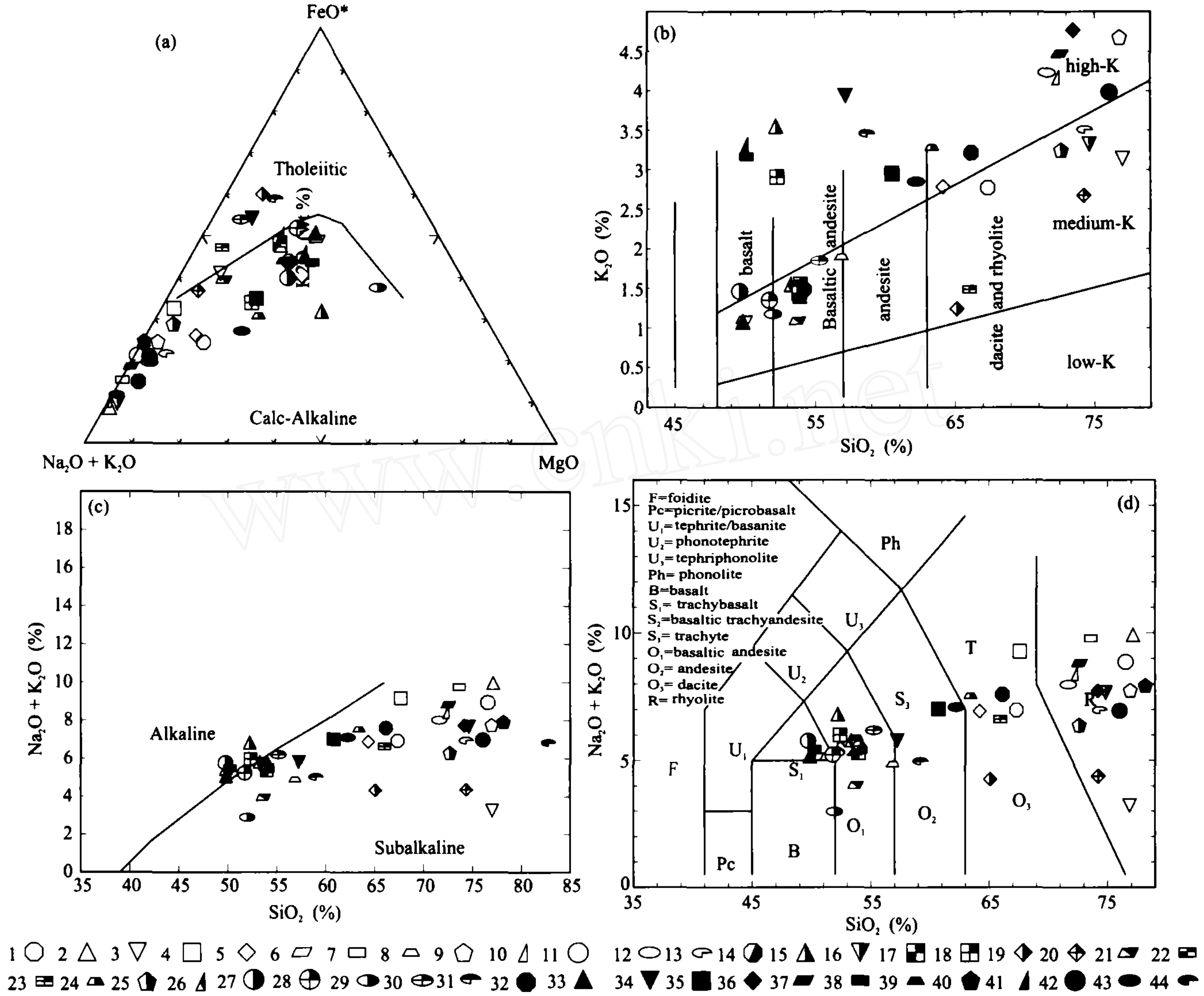

Fig. 5. Geochemical diagrams of the volcanic rocks.

(a) AFM plot (A=Na_2O+K_2O; F=FeO+0.8998Fe_2O_3; M=MgO after Baragar, 1971); (b) Sodium versus silica; (c)Alkali series; (d)Total alkali versus silica (TAS).1 – CaS5-1; 2 – ST17-BS17; 3 – ZhS9-2; 4 – CaS5-2; 5 – SBL2-BS17; 6 – ZhS9-4; 7 – CaS5-18; 8 – Pu1-10; 9 – Zhs10-2890.53; 10 – ST1-BS2; 11 – ZhS6-8; 12 – ZhS9-1; 13 – FS701-1; 14 – LT51-S46; 15 – SuiS1-2; 16 – FS701-2; 17 – LT53-S48; 18 – ShS201-4; 19 – LT67-S62; 20 – SanS2-20; 21 – SoS2-20; 22 – LT54-S49; 23 – SoS1-2; 24 – ShS101-3; 25 – FS9-2; 26 – LT82-B51; 27 – SoS2-28; 28 – LT60-S55; 29 – ShS101-7; 30 – SoS2-7; 31 – CaS5-6; 32 – SBL9; 33 – ZhS9-6; 34 – CaS5-7; 35 – Pu1-7; 36 – Xs1-3451.73; 37 – CaS5-24; 38 – Pu1-14; 39 – LT5-B2; 40 – CaS5-22; 41 – Pu1-12; 42 – CaS5-27; 43 – SuiS1-1; 44 – LT25-S20.

m. The regional unconformity on top of the Nenjiang Formation (Figs. 4, 6) separates the sequence at its thickness about upper one-third. The lower layer of the sequence is mid-Cretaceous fluvial and lacustrine, fine-grained dominant sediments of ca. 2000 m thick. The upper layer is from upper most Cretaceous to Neogene, fluvial deposits with a thickness of ca. 1000 m, and is characterized by coarse grains and syn-sedimentary deformations (Fig. 7).

The lower layer, equivalent to the formations from Denglouku (K_1d) to Nenjiang (K_2n), is composed of a series of onlap sub-sequences, representing transgression and blooming of the basin and comprising principal part of the basin fills. The thick oil shales, developed in Qingshankou (K_2qn) and Nenjiang formations as shown in Fig. 4, are the most important source rocks in the SB and correspond to the period of basin flooding and probable marine ingression (Wang et al., 2000). The depositional region of the SB at that time used to have overstepped the area of the present basin, because at lest 1000 m of mid-Cretaceous sediments have been eroded away at eastern edge of the present SB. The black shale-bearing, deep lacustrine sediments of the two formations are frequently outcropped in the east of the SB (as shown in Fig.7a-c), especially along river banks there. Vitrinite reflectance of the outcropped oil shales is about 0.7% and geothermal gradient of the SB is about 3°C/100 m (Wang et al., 1993), so that the buried depth for having gainned the organic

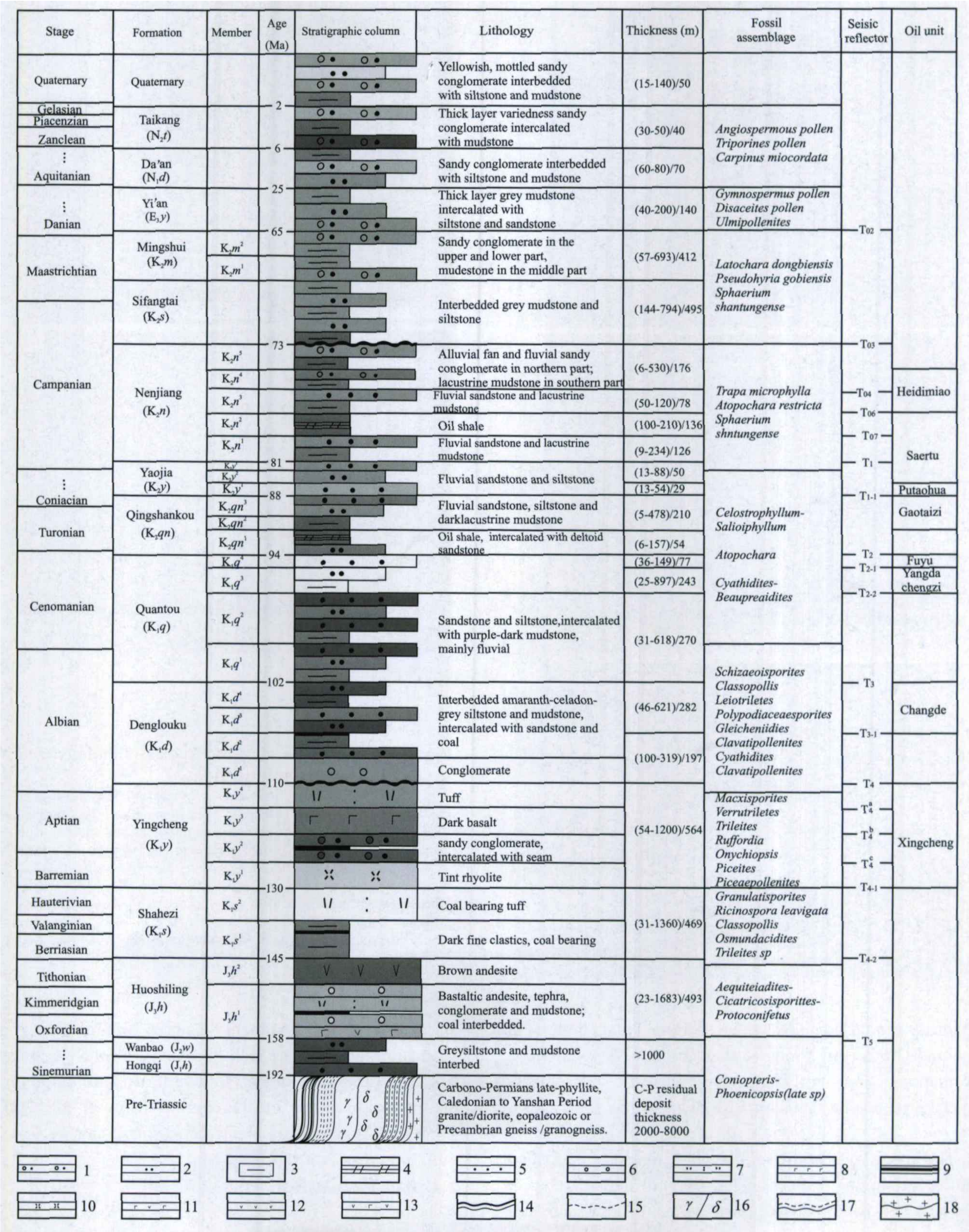

Fig. 6. Stratigraphic column of the Mesozoic successions of Songliao Basin, NE China.

1. sandy conglomerate; 2. siltstone; 3. mudstone; 4.oil shale; 5.sandstone; 6.conglomerate; 7. tuff; 8. basalt; 9. coal seam; 10. rhyolite; 11. basaltic andesite; 12. andesite; 13. andesitic basalt; 14. slate; 15. phyllite; 16. granite/diorite; 17. gneiss; 18. granite gneiss.

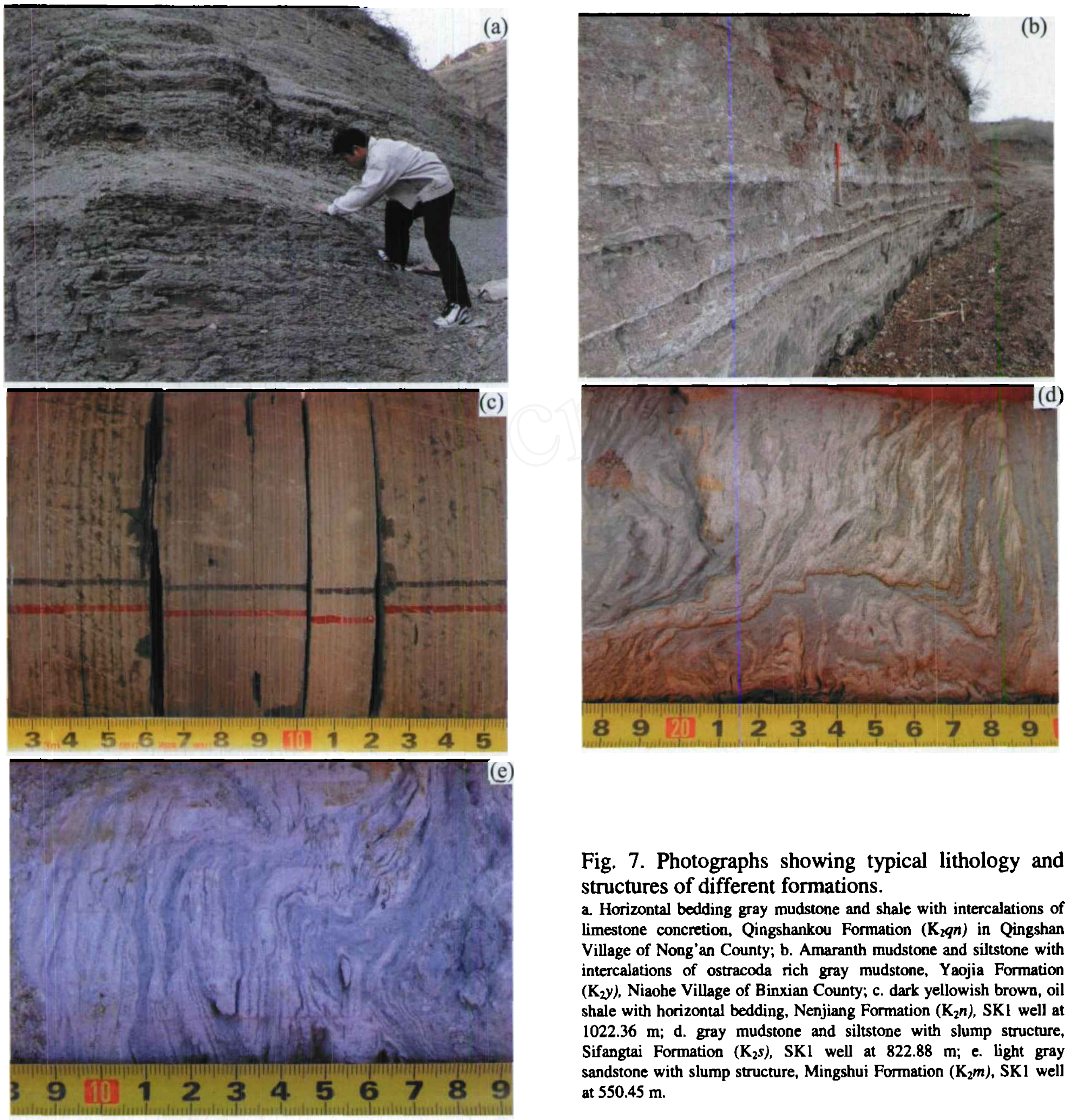

Fig. 7. Photographs showing typical lithology and structures of different formations.

a. Horizontal bedding gray mudstone and shale with intercalations of limestone concretion, Qingshankou Formation (K_2qn) in Qingshan Village of Nong'an County; b. Amaranth mudstone and siltstone with intercalations of ostracoda rich gray mudstone, Yaojia Formation (K_2y), Niaohe Village of Binxian County; c. dark yellowish brown, oil shale with horizontal bedding, Nenjiang Formation (K_2n), SK1 well at 1022.36 m; d. gray mudstone and siltstone with slump structure, Sifangtai Formation (K_2s), SK1 well at 822.88 m; e. light gray sandstone with slump structure, Mingshui Formation (K_2m), SK1 well at 550.45 m.

maturity should be no less than 1000 m. Truncations of all the mid-Cretaceous strata from Quantou (K_1q) to Nenjiang formations can be frequently observed in seismic interpreted profile crossing eastern marginal areas like in Fig. 4.

The upper layer of the sedimentary sequence, equivalent to the formations from Sifangtai (K_2s) to Taikang (N_2t) in Figs. 4, 6, is composed of a series of downlap sub-sequences, representing regression and shrinking of the basin and comprising the last period of the basin fills. Westward migration of basin center can be easily seen both from basin wide cross sections (e.g. in Fig. 4) and from the reconstructed maps of facies and paleogeography (Wang et al., 1994). The prominent features of the layer are coarsening-upward and rich in syn-sedimentary deformed structures as shown in Fig. 6. Overthrusts are common in the structural maps of this period (Zhu et al., 2003), suggesting regional compression tress in dynamics.

5 Basin Evolution

Tectonic explanations for the SB evolution should meet the following relevant facts.

(a) Basin filling of the SB is composed of three superposed cycles including, from bottom to top, the volcanogenic succession, the onlap sedimentary sequence of basin wide and oil shale bearing, and the downlap coarsening-upward sequence with westward migration of depocenter. They correspond to the early Cretaceous, mid-Cretaceous and from top Companian to Neogene, respectively. In between the three cycles there are two regional unconformities on top of the Yingcheng (K_1y) and Nenjiang (K_2n) formations respectively. Under and above the unconformities, there are significant changes in framework of basin filling, structural stile, stratigraphic distribution and orientation, and rock association. All of these differences suggest that the three cycles may be formed at different tectonic regimes.

(b) The whole region of interest has been an active continental margin setting since the Triassic. North to the SB is the Mongolia-Okhotsk collisional belt (MOCB). The suturing event began in the Jurassic and ended at chron M0 (the middle Cretaceous, 118.7 Ma) (Scotese et al., 1988; Sengör and Natal'in, 1996; Zorin, 1999), which happened to some extent simultaneously with development of the volcanogenic succession in the SB. East to the SB is the Pacific plate. Subduction of it under the eastern edge of the Eurasian plate occurred intermittently since 145 Ma (Maruyama, 1986; Sager et al., 1988). According to time and space association, Cretaceous evolution of the SB must have been influenced by the two tectonic elements of both the MOCB and the Pacific plate. Although the SB is a consequence of the composite interactions amongst the dynamic elements involved in the region, it is reasonable to think that the SB may predominantly be controlled by one of the factors for a specific time span. The strongest, which had optimized association of time, space, motion velocity and stress direction, should cause main impact on the SB.

(c) The volcanic series in the SB are not rift-like but arc-like (e.g. Hess, 1989), and show mixed signatures both the MORB and the crust as shown by isotope ratios and trace and rare earth elements. In addition, there are some systematic changes in geochemistry and isotopes from the Jurassic to Cretaceous volcanic rocks, which show an increasing trend of involvement of the MORB, suggesting a decreasing influence of subduction component on source of the magmas (Wang et al., 2006). This should be explained by Jurassic syn-collisional and Cretaceous post-collisional types of volcanic rocks when taking into account the suturing process of the MOCB.

To meet the key factors above, we outline the volcanic-sedimentary-tectonic evolution of the SB as follows.

The evolution of the SB can be subdivided into three periods. The first episode, corresponding to the Alptian and pre-Aptian time, is characterized by the volcanogenic succession. The SB in this period belongs to a basin and range system of Andes type at a retroarc setting related to suturing of the MOCB. Arguments for this interpretation include: (a) About four hundred kilometers north to the SB is the MOCB (Fig. 1), which was formed also in this period, providing a good spatio-temporal coupling between them. (b) The volcanogenic succession is significantly different from the overlying sedimentary sequence suggesting different tectonic origins. Although the sedimentary sequence overlying the volcanic succession, which were formed in different tectonic settings, is commonly accepted to be controlled by the subduction of the Pacific plate (e.g., Wang et al., 1993; Gao, 1995). This tectonic event can hardly explain the formation of the volcanogenic succession under the heretofore observations. In this case, we favor a retroarc (post-collisional) setting for the enormous Cretaceous volcanic activity as the collision along the Mongolia-Okhotsk suture ended about 10 Ma earlier than the volcanism in the Songliao basin.

For the second episode of basin evolution, corresponding to the Albian to Companian time, the SB is a sag-like strike-slip basin. From Fig. 4 we can see that the framework of the basin filling is sag-like because it is large, gently-sloped, continuously subsiding and long-lived, which is similar to an intracontinental sag basin (Einsele, 2000). However, subsidence of a sag basin should be predominantly in response to moderate crustal thinning or to a slightly higher density of the underlying crust in comparison to the neighboring areas. These features do not meet the case of the SB as we see in Fig. 4. In addition, a sag basin needs a tectonic style of divergence, whose mechanism could hardly be provided for the SB by the tectonic setting at that time as discussed in the section of the geological background. Therefore, we preferably consider that the SB seems like a sag basin, but it is not a real sag basin in the sense of tectonics. On the other hand, transform faults are very well developed and preserved both on the margin of and within the SB (Zhu et al., 2003; Sun et al., 2007). And more so, a large-scale crustal separation oblique to the transform faults was recently found (Yang et al., 2005), indicating a strike-slip stage prior to the initiating accretion of new oceanic crust (Einsele, 2000). Accordingly we favor a strike-slip basin for the mid-Cretaceous SB and the post-volcanism flexural thermal subsidence may accelerate its sinking process, giving rise to a large-scale interior basin finally.

Since the late Campanian, the last episode of basin evolution, the SB is a tectonic inverse basin. The structural style of the SB changed significantly after the Nenjiang movement (ca. 73 Ma). Fault-reactivated and cover-folded inversions (Song, 1997) and syn-sedimentary deformed structures (Fig. 7) are commonly recognized in the formations from Sifangtai (K_2s) to Taikang (N_2t). Westward migration of the depocenter and eastward regional uplifting and eroding in this period (Fig. 4) coupled with the inversions are all indications of strong compressional stress coming form the east to the SB. Unlike the underlying volcanogenic succession, which is not confined within the present basin area, the coarsening upward sequence from K_2s to N_2t is deposited just above and confined within the mid-Cretaceous strata and shows subordinate features to the latter. And they together make one entire normal sedimentary sequence in the basin filling as shown in Fig. 4. We therefore consider them as a complete sequence formed at the same tectonic regime. Subduction of the Pacific plate coupled with Miocene spreading of the Japan Sea should be the best reasonable explanation for the dynamics because the region of the SB belongs to the circum-Pacific tectonic regime in these periods and the major geological assemblages there fit well with the Pacific tectonic settings (Maruyama, 1986; Liu et al., 1992; Northrup, 1995; Ren et al., 2002).

6 Conclusions

(1) Up to 8000 m of the SB basin fillings is composed of three superposed cycles including, from bottom to top, the volcanogenic succession, the onlap sedimentary sequence, and the downlap coarsening-upward sequence. The first cycle of Alptian and pre-Aptian belongs to a retroarc basin and range system of Andes type due to the collision of the Mongolia-Okhotsk belt. The second cycle from Albian to Companian was formed in a sag-like strike-slip basin related to oblique subduction of the Pacific plate along the eastern margin of the Eurasian plate. The last cycle of Maastrichtian to Neogene was deposited in a tectonic inverse basin under compression related to the normal subduction of the Pacific plate to the Eurasian plate.

(2) There is no great mantle uplift or large-scale crustal thinning shown by the seismic velocity structure beneath the SB. On the other hand, two medium-sized uplifts of the Moho are observed corresponding approximately to the basin centers of the early Cretaceous volcanogenic succession and the late Cretaceous sedimentary sequence, respectively (Fig. 4). Westward migration of the depocenter continued during the late Cretaceous as revealed by its westward thickening and younging sediments. Regional uplift and erosion in the eastern SB are indicative of compressional stress from east due to the subduction of the Pacific plate coupled with Miocene spreading of the Japan Sea.

(3) The volcanic series in the SB are not rift-like but arc-like, and show mixed signatures of the MORB and the crust. The Cretaceous volcanic rocks were formed under the Mesozoic collisional setting of the Mongolia-Okhotsk belt. The most significant northward movement of the SB block occurred in the major episode of the Cretaceous volcanisms, suggesting that the volcanism correlates to the tectonic active stage in the region.

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