

PS Evaluation of High Quality Source Rocks in Saline Environment of Continental Rift Basin: A Case Study in Laizhouwan Depression, Offshore Bohai Bay Basin, China*

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Abstract

Bohai Bay Basin is a petroliferous basin located on the east coast of China. Generally, three organic-rich layers (Es3, Es1 and Ed members) have been proved to be the main sources of oil accumulation. The fourth member of the Shahejie Formation (E2s4) was previously paid little attention as it is featured with deep burial depths of more than 3500 m (11,483 ft) and few source rocks were discovered. However, in our recent investigation, regionally extensive evaporites were discovered in E2s4 Formation of Laizhouwan depression during the Early Eocene when the Bohai Bay Basin was developing as a rift basin. The E2s4 strata is featured with gypsum, halite, mudstone and carbonates deposits. Influence by the Tan-Lu Fault, a salt arch structure was formed. Based on Rock-Eval pyrolysis, total organic carbon, gas chromatography (GC), gas chromatography-mass spectrometry (GC-MS), isotope data of the saturate and aromatic fractions of source rock, and rock trace element data of 150 samples, geochemical characterization of source rocks in saline environment of Offshore Bohai Bay Basin were analyzed for the first time. TOC contents between 0.28 and 5.09% and S1+S2 values range from 0.17 to 36.24 mg HC/g rock, source rock display strong heterogeneity. Hydrogen indices for E2s4 samples range from 25.02 to 768.77 mg/g TOC, revealing different types. Rock-Eval Tmax values range from 424 to 443°C, indicating that samples mixed with immature and mature for hydrocarbon generation. Low vitrinite reflectance, obvious C35 homohopane preference, low pristane/phytane ratios and high gammacerane indices (0.21-0.78), indicate evaporate or high-salinity environments. Crude oil from Laizhouwan depression has high sulfur contents (higher than 1%, maximum of 2.92%), while other depressions have low sulfur contents. The thermal maturity of crude oil evaluated by analysis of the biomarkers, crude oil from E2s4 displays C29 $\beta\beta$ ($\beta\beta+\alpha\alpha$) sterane ratios between 0.36 and 0.47 which has not reached the endpoint values. The source rock evaluation in saline environment of continental rift basin can be applied for resource assessment and petroleum exploration. We finally analyzed the origin of source rocks in saline environment. Theory of transgression, deep brine and closed evaporation were proposed, of which closed evaporation theory is the most probable origin, we find evaporation is greater than the injection in the enclosed environment and deposits overlying evaporites are often of high quality.

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Abstract: Bohai Bay Basin is a petroliferous basin located on the east coast of China. Generally, three organic rich layers (E_{s3} , E_{s1} and E_d members) have been proved to be the main sources of oil accumulation. The fourth member of the Shahejie Formation (E_{2s4}) was previously paid little attention as it is featured with deep burial depths of more than 3500m (11483ft) and few source rocks were discovered. However, in our recent investigation, regionally extensive evaporites were discovered in E_{2s4} Formation of Laizhouwan depression during the Early Eocene when the Bohai Bay Basin was developing as a rift basin. The E_{2s4} strata is featured with gypsum, halite, mudstone and carbonates deposits. Influence by Tan-Lu fault activities, a salt arch structure was formed. Based on Rock-Eval pyrolysis, total organic carbon, gas chromatography (GC), gas chromatography-mass spectrometry (GC-MS), isotope data of the saturate and aromatic fractions of source rock, and rock trace element data of 150 samples, geochemical characterization of source rocks in saline environment of Offshore Bohai bay basin were analyzed for the first time. TOC contents between 0.28 and 5.09% and S_1+S_2 values range from 0.17 to 36.24 mg HC/g rock, source rock display strong heterogeneity. Hydrogen indices for E_{2s4} samples range from 25.02 to 768.77 mg/g TOC, revealing different types. Rock-Eval Tmax values range from 424 to 443°C, indicating that samples mixed with immature and mature for hydrocarbon generation. Low vitrinite reflectance, obvious C_{35} homohopane preference, low pristane/phytane ratios and high gammacerane indices (0.21-0.78), indicate evaporate or high-salinity environments. Crude oil from Laizhouwan depression has high sulfur contents (higher than 1%, maximum of 2.92%) , while other depressions have low sulfur contents. The thermal maturity of crude oil evaluated by analysis of the biomarkers, crude oil from E_{2s4} displays $C_{29}\beta\beta(\beta\beta+\alpha\alpha)$ sterane ratios between 0.36 and 0.47 which has not reached the endpoint values. The source rock evaluation in saline environment of continental rift basin can be applied for resource assessment and petroleum exploration. We finally analyzed the origin of source rocks in saline environment. Theory of transgression, deep brine and closed evaporation were proposed, of which closed evaporation theory is the most probable origin, we find evaporation is greater than the injection in the enclosed environment and deposits overlying evaporites are often of high quality.

1. Geological Setting

- The Offshore Bohai Bay Basin is a Tertiary lacustrine basin locating in northeastern China and filled with up to 12 km of sediments. (Figure 1)
- Laizhouwan depression is a pull-apart sub-basin that is related to the strike-slipping of Tan-lu fault zone, and it is divided into major depression in the north and southern sub-depression in the south. (Figure 2)
- Figure 3 shows the generalized Cenozoic stratigraphy of the Offshore Bohai Bay Basin. The basin has undergone two tectonic evolution stages, Paleogene synrift stage and Neogene postrift stage. Three organic rich layers (E_{s3} , E_{s1} and E_d members) have been proved to be the main sources, while E_{s4} formation was previously paid little attention.

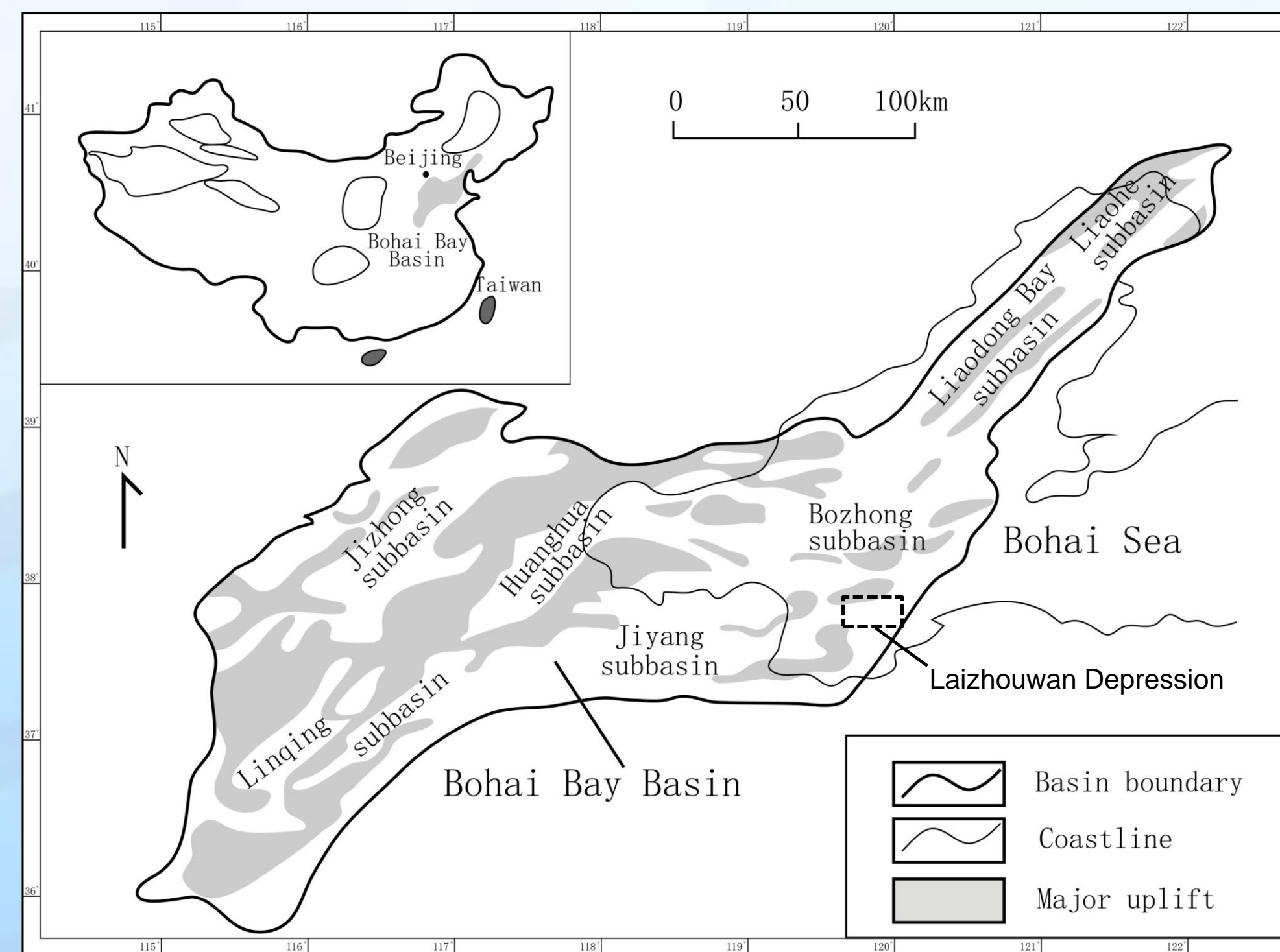


Figure 1. Subbasins of the Bohai Bay Basin
 (modified from Hao et al.,2007)

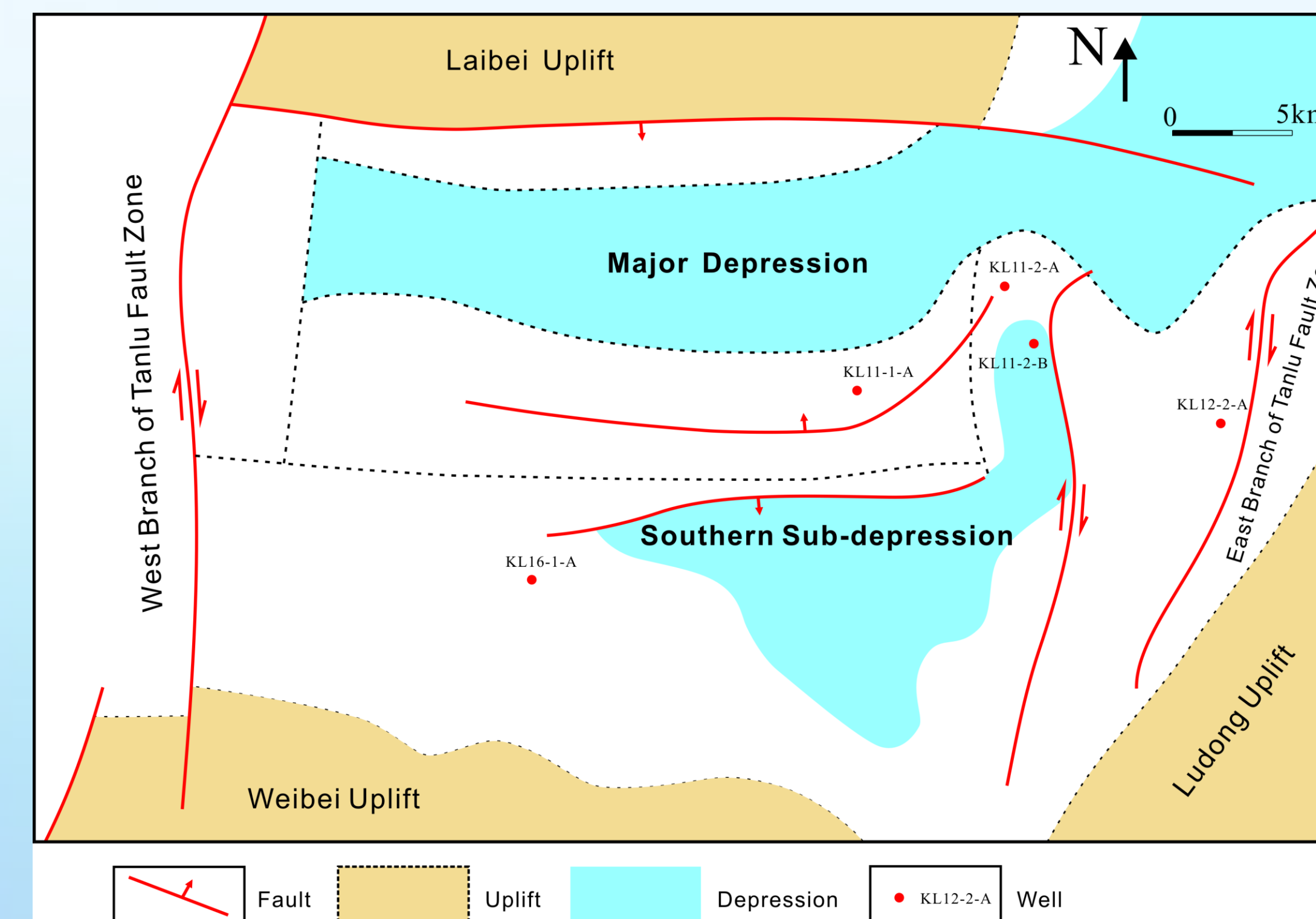


Figure 2.
 Regional Geological conditions of Laizhouwan depression

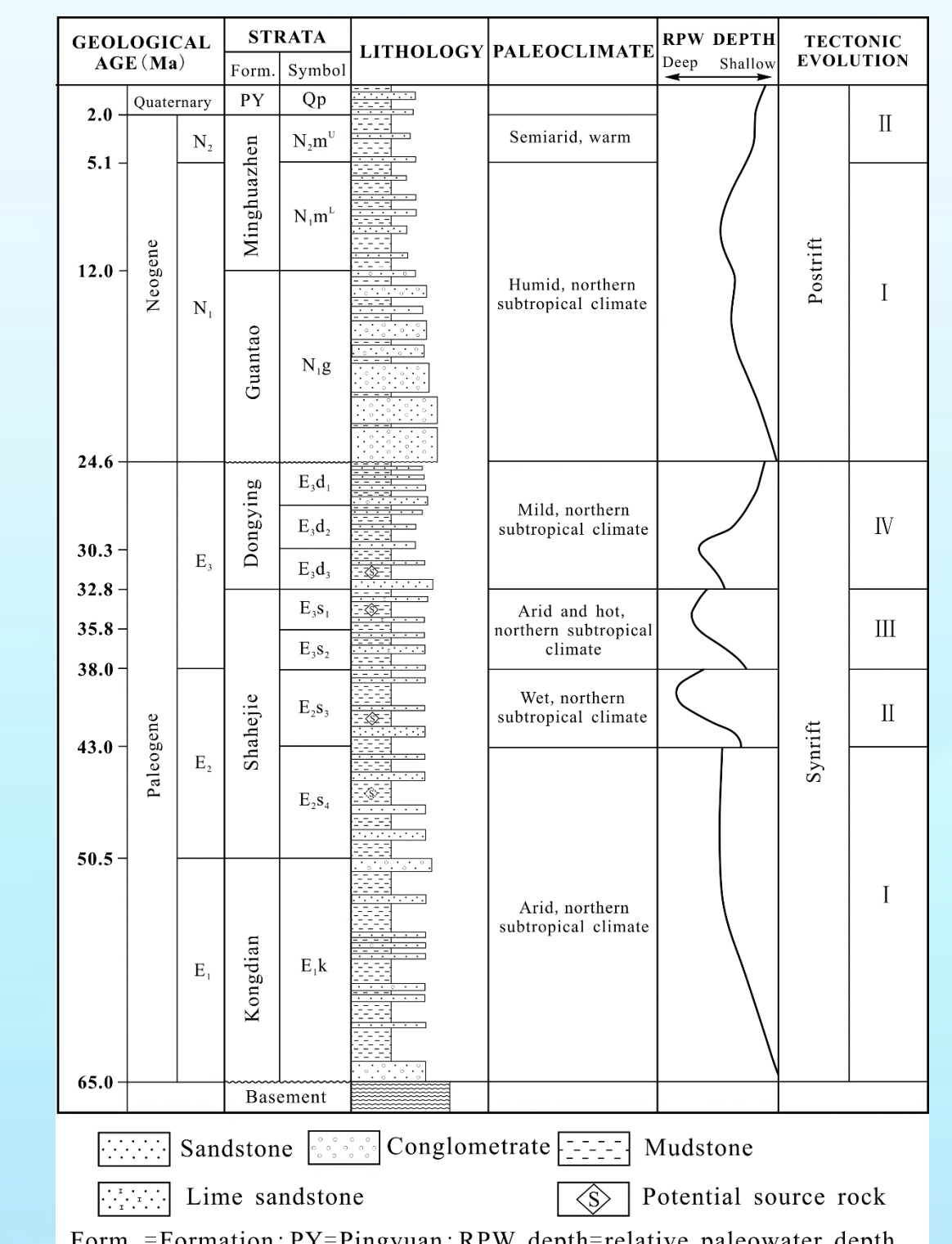


Figure 3. Generalized Cenozoic stratigraphy of the Bohai Bay Basin



2. Characteristic Analysis of Source Rock

2.1 Hydrocarbon generating potential

The possible source rock intervals in the Laizhouwan depression display wide variations in TOC contents, S_1+S_2 peaks, and hydrogen indices (Figures 4,5,6), suggesting considerable spatial and temporal heterogeneity. Dongying Formation and the first member of the Shahejie Formation are of minor significance as source rocks because their kerogens type and low organic matter richness. Es_3 and Es_4 are the most important source rocks in the Laizhouwan depression, and Es_4 may play a more important role in the region.

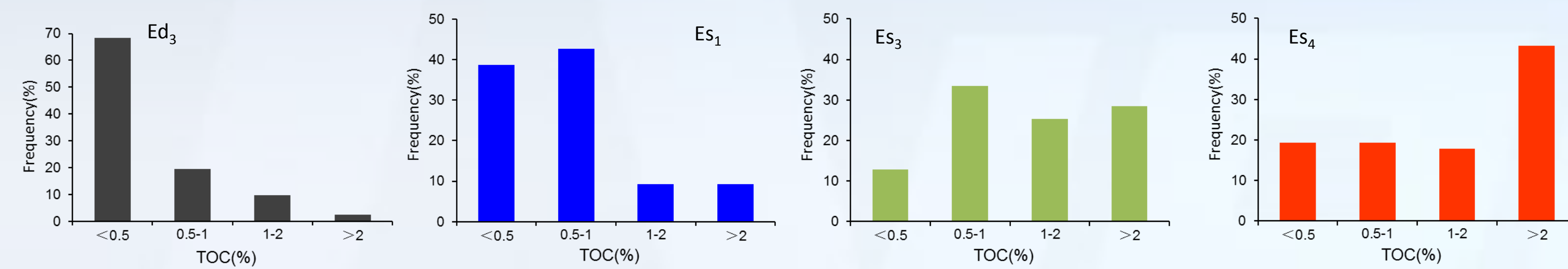


Figure 4. Total organic carbon (TOC) contents for samples from Laizhouwan depression

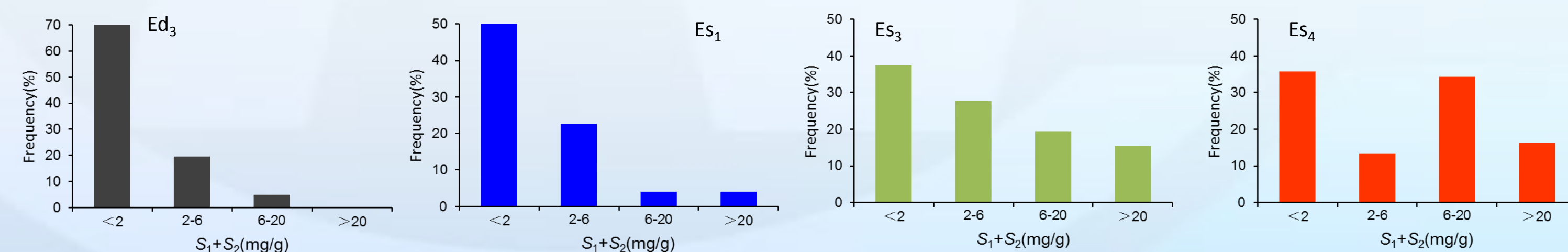


Figure 5. Rock-Eval S_1+S_2 peaks for samples from Laizhouwan depression

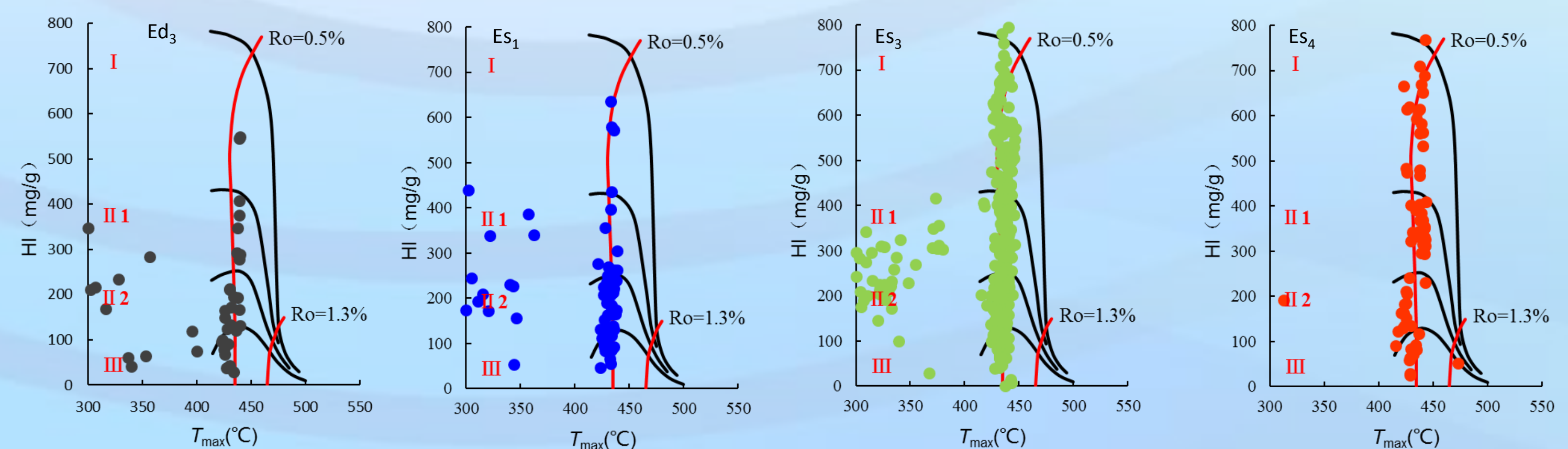


Figure 6. Variation of Rock-Eval hydrogen index with T_{max} for samples from different possible source rock intervals in Laizhouwan depression

2.2 Basin modeling

Basin modeling by Trinity shows that source rocks from the third and fourth members of the Shahejie Formation are buried deep and Es_4 has a relative better conditions particularly. Es_4 has a Vitrinite reflectance value higher than 1.0 and TOC contents larger than 2.6% in southern sub-depression where saline sediments develop, these all indicate good potential of the formation in the region (Figures 7, 8, 9).

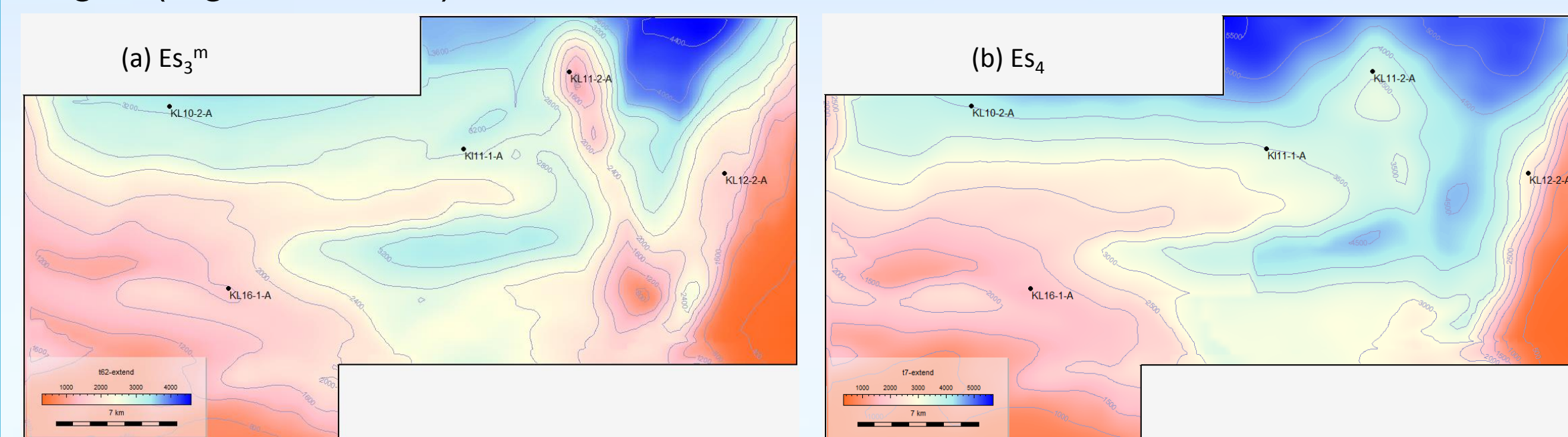


Figure 7. Base depth of Laizhouwan depression

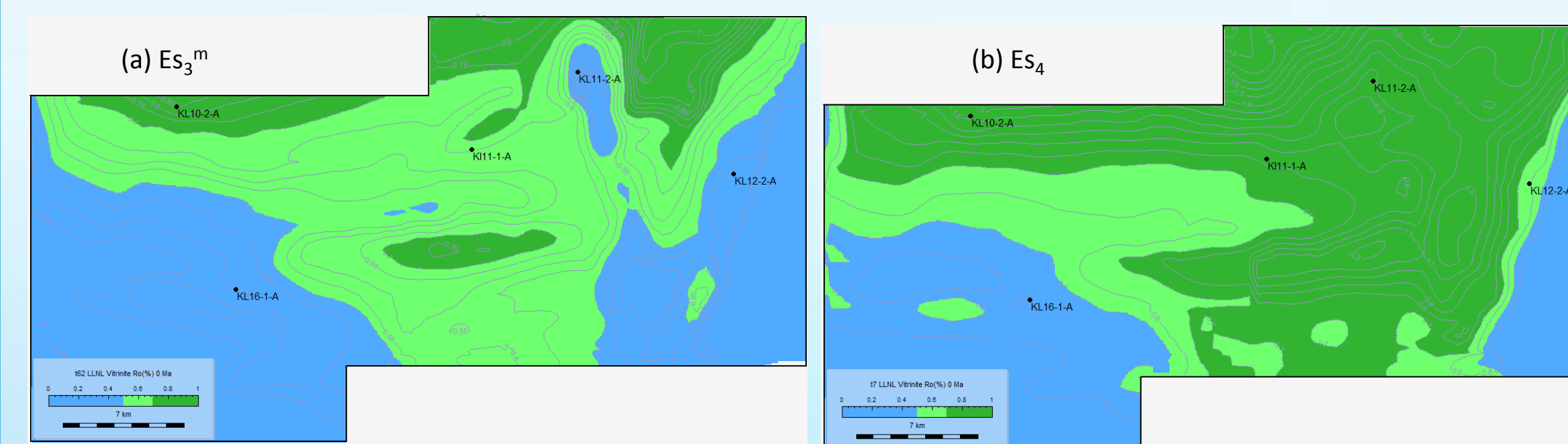


Figure 8. Vitrinite reflectance of Laizhouwan depression

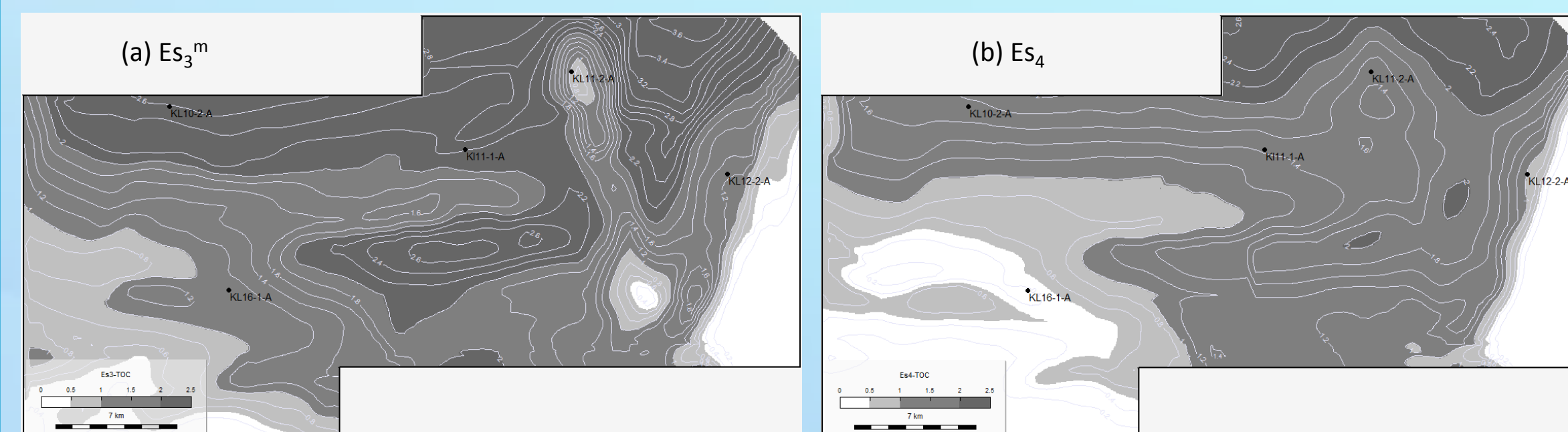


Figure 9. Total organic carbon of Laizhouwan depression

2.3 Hydrocarbon expelling

Influence by the Tan-Lu fault activities, Laizhouwan depression has a relative lower depth of expulsion threshold contrast to Bozhong depression (Figure 10). And saline lacustrine source rock has a lower Vitrinite reflectance and earlier expulsion time contrast to normal lacustrine (Figure 11).

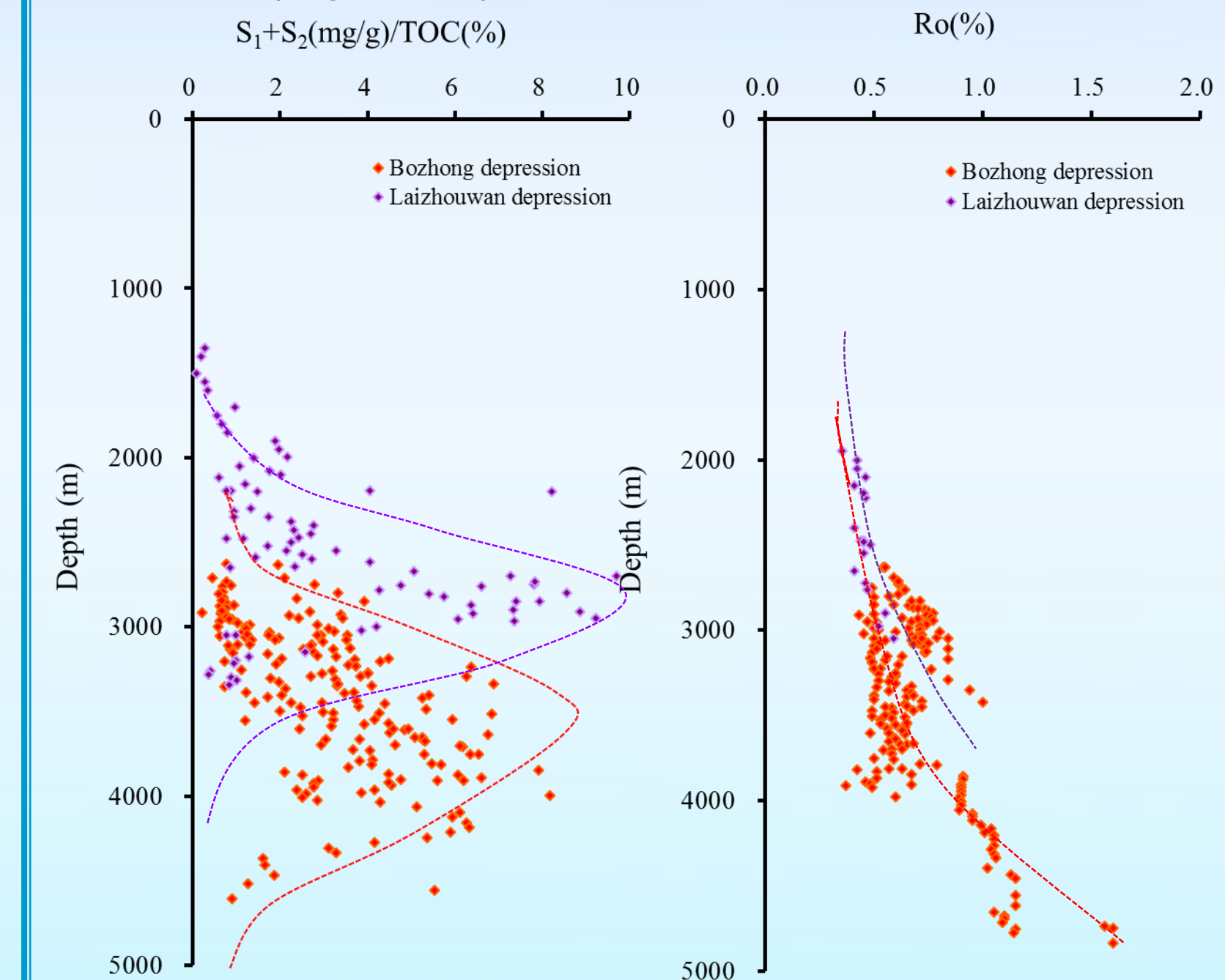


Figure 10. Expulsion threshold of different depressions

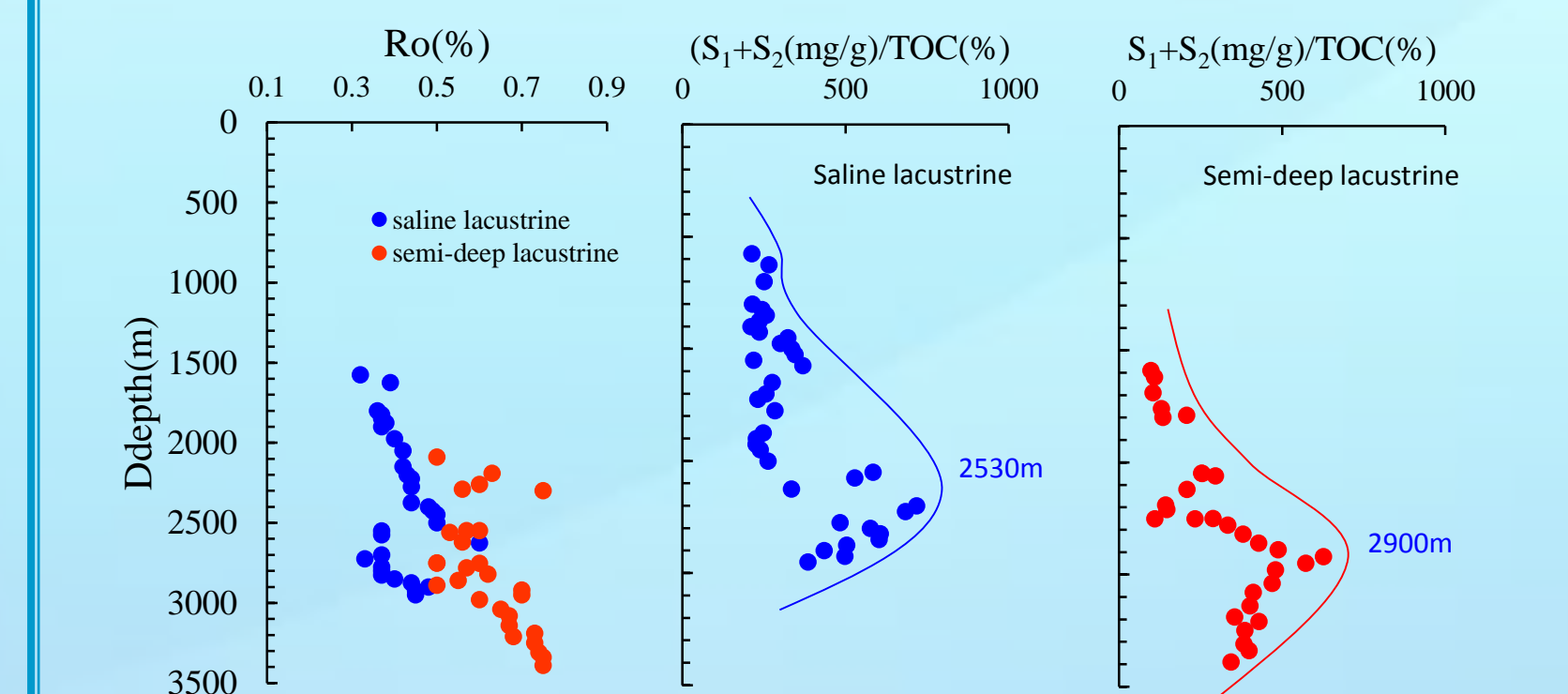


Figure 11. Expulsion threshold of different environments

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3. Evaluation of Source Rock

3.1 Environment of source rock

Different environments produce different sediments, and develop different facies in Laizhouwan depression, accordingly produce different types of Es₄ source rock, including semi-deep lacustrine, shallow lacustrine and saline lacustrine. Well-A, located next to the major depression, developing gray mudstone mainly, is semi-deep lacustrine facies; Well-B, located in the central uplift zone, developing yellowish-brown calcareous mudstone and mudstone mainly, is saline lacustrine facies; Well-C, located in the southern uplift, which has a shallow buried depth is strongly affected by the lateral tectonic movements, developing various lithologies, is fan delta facies mainly; Well-D, located in the southern sub-depression, sedimenting thick gypsum and salt, is brine lacustrine facies. (Figures 12,13)

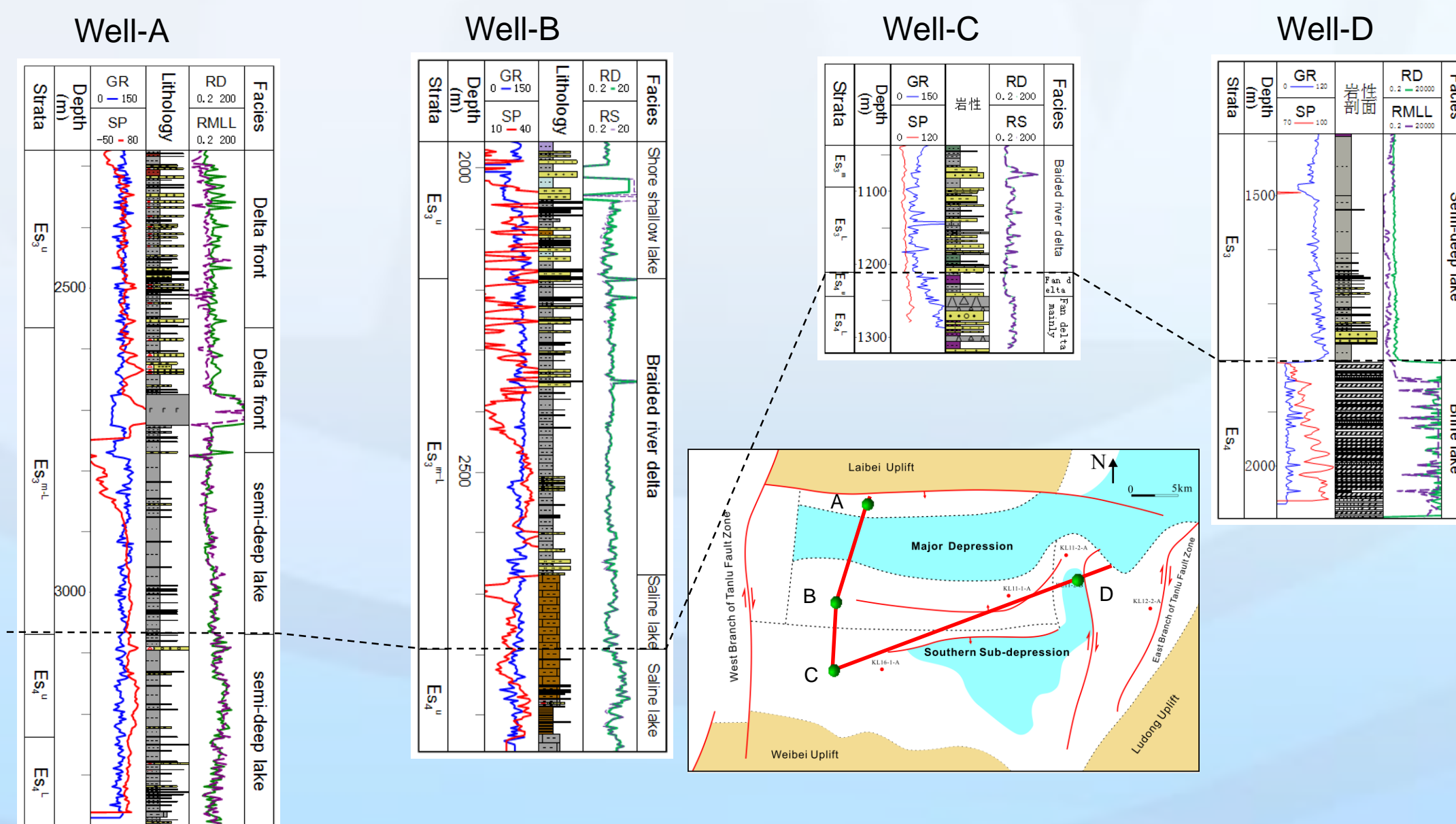


Figure 12. Comprehensive cross-hole of Laizhouwan depression



Figure 13. Sediment environment profile of Laizhouwan depression

3.2 Special characteristics of oil

Oils derived from Bohai sea are characterized by low sulfur contents, mainly below 1%, but oils found in Laizhouwan depression have relatively high sulfur contents, rang from 0.93% to 2.92% (Figure 14), which indirectly reflect the saline environment characteristics. We use FT-ICR MS methods to analysis the origin of the sulfur, showing that KL16-1-A has high sulfur content concentrating in carotane and sterane, indicating that the sulfur is generated in early diagenesis section, not TSR section or other sections. (Figures 15,16,17,18)

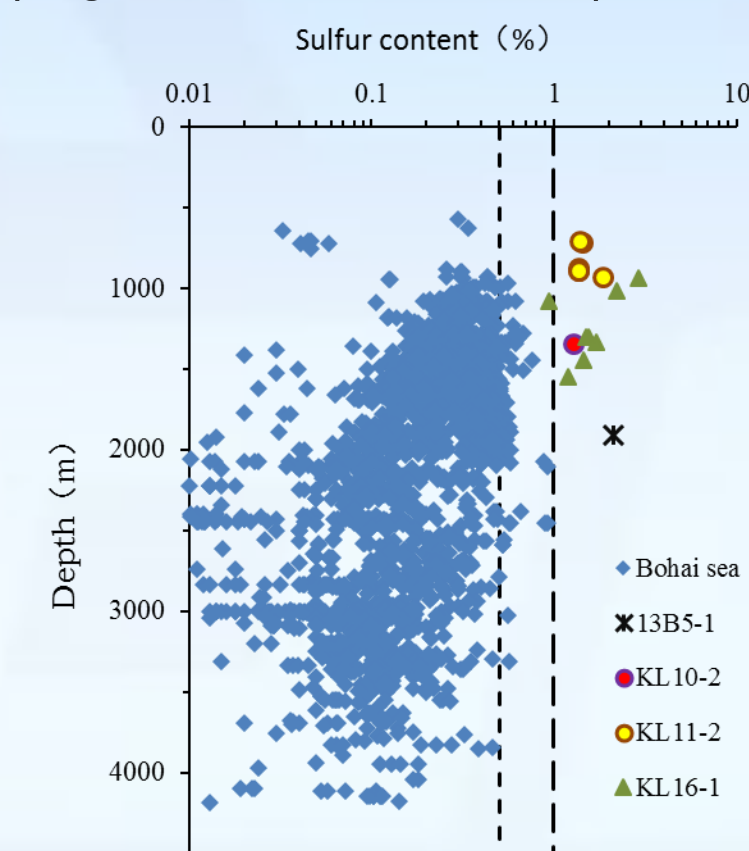


Figure 14. Sulfur contents of Bohai sea

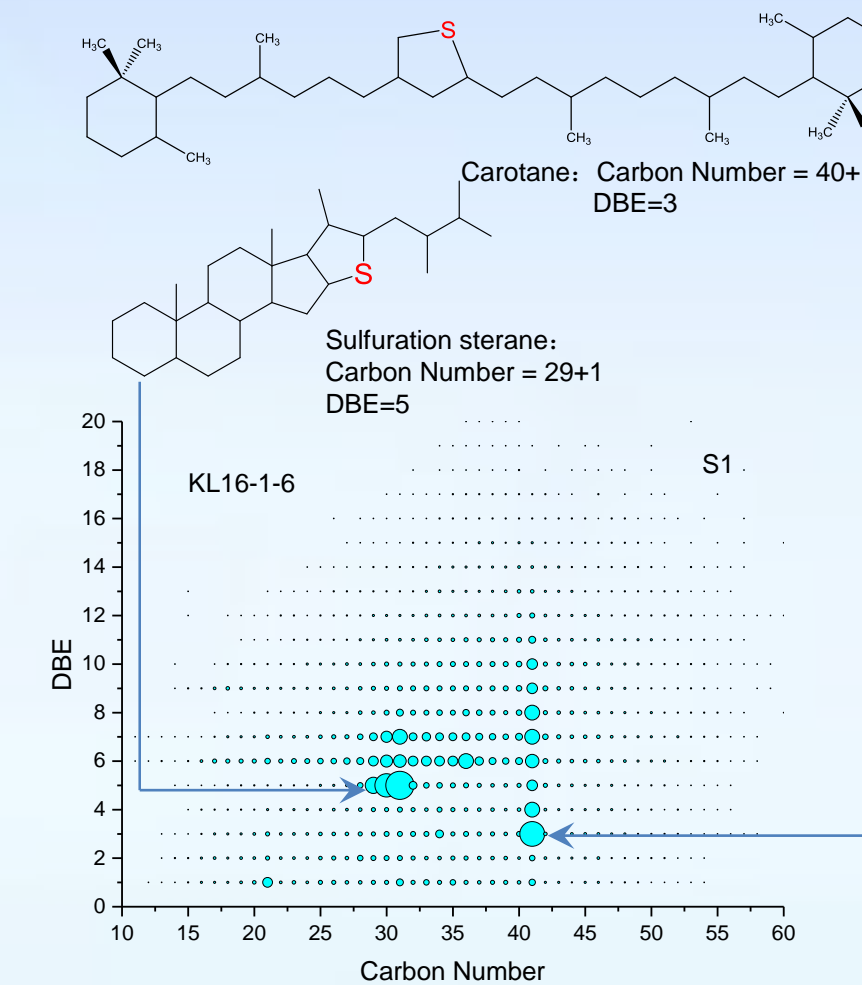


Figure 15. Oil from KL16-1

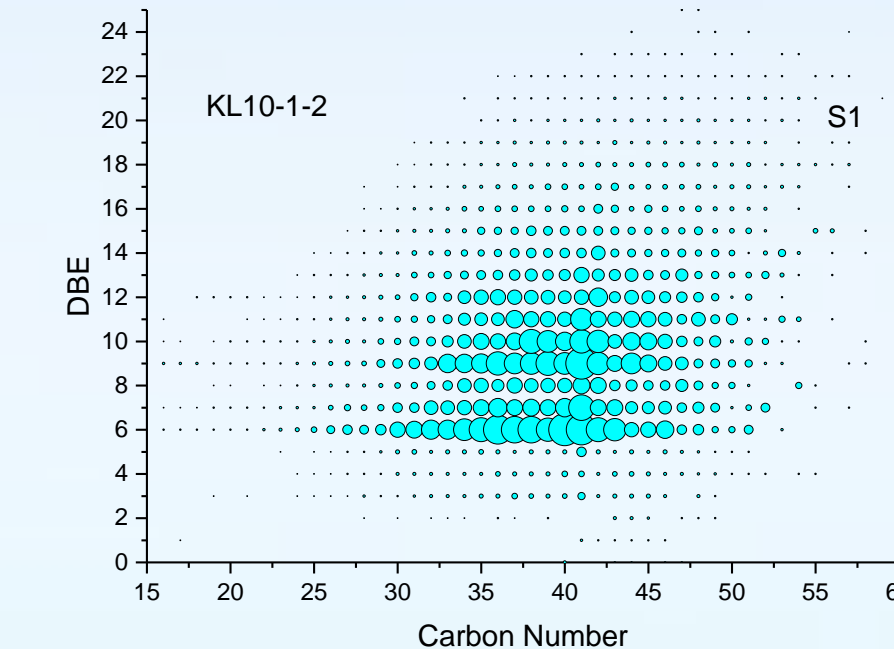


Figure 16. Oil from KL10-1

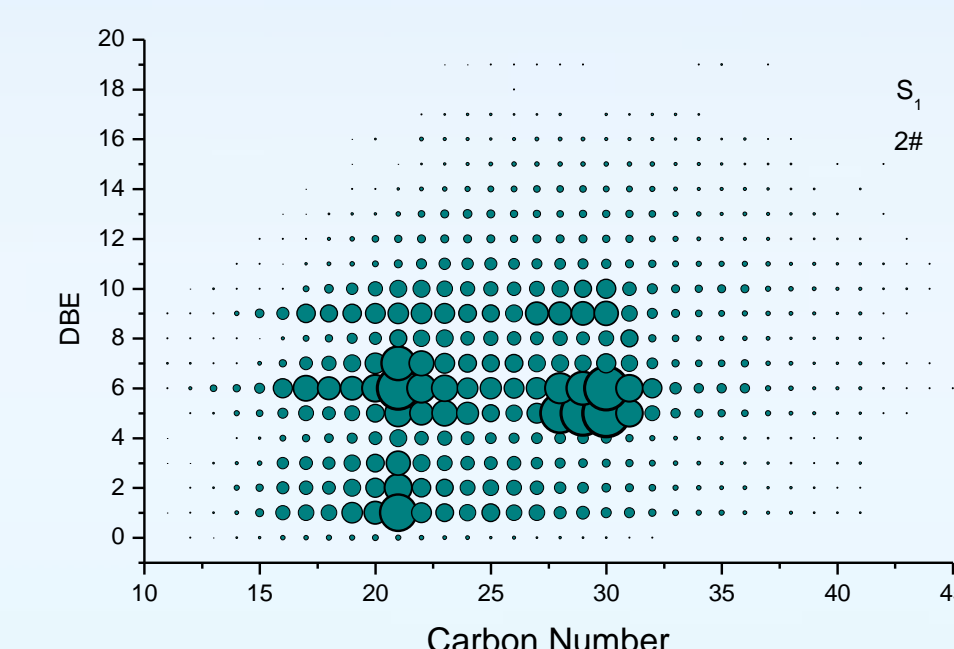


Figure 17. Oil from Jinxian

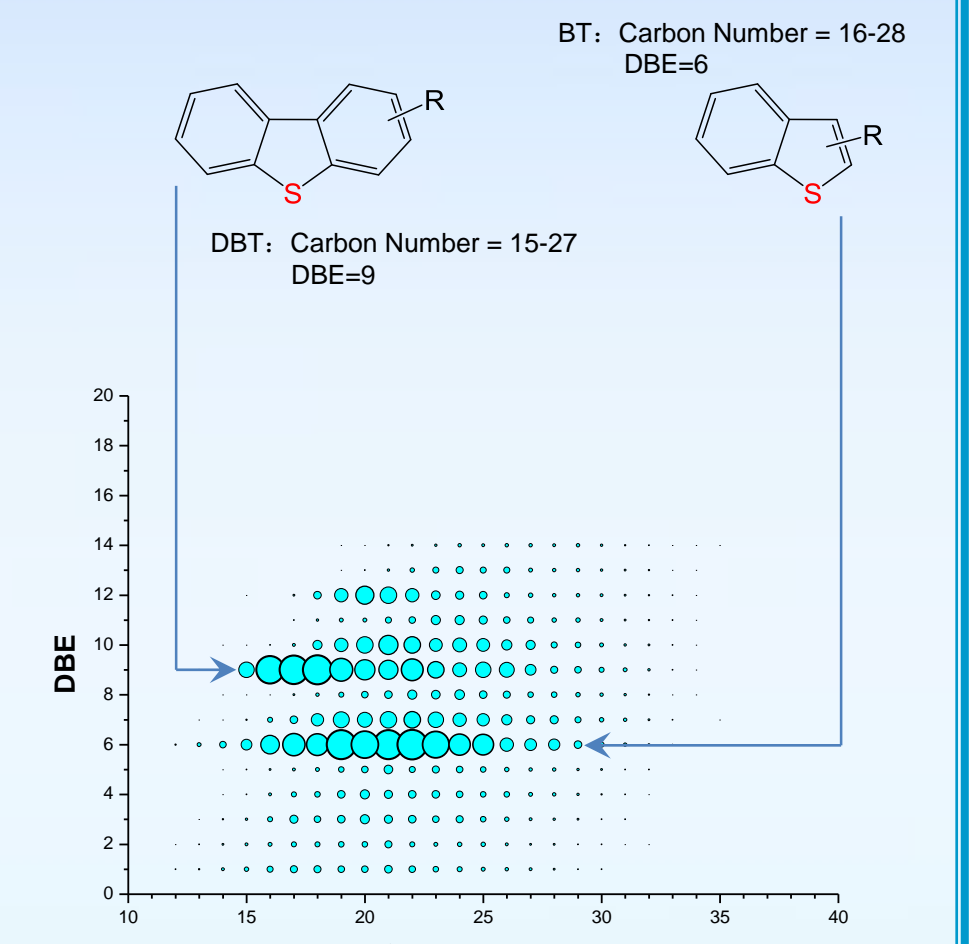


Figure 18. Oil from Tahe oilfield

4. Conclusion

Evaporation is greater than the injection in the enclosed environment and deposits overlying evaporites are often of high quality. Source rock have relatively high TOC contents and S₁+S₂ values. Brine lake facies may have some kind of good source rock in the research area.

Closed evaporation theory is the most probable origin of the region. High quality of source rock in Laizhouwan depression may has relationship with the high thermal gradient in the region.

(Figures 19,20 ,21)

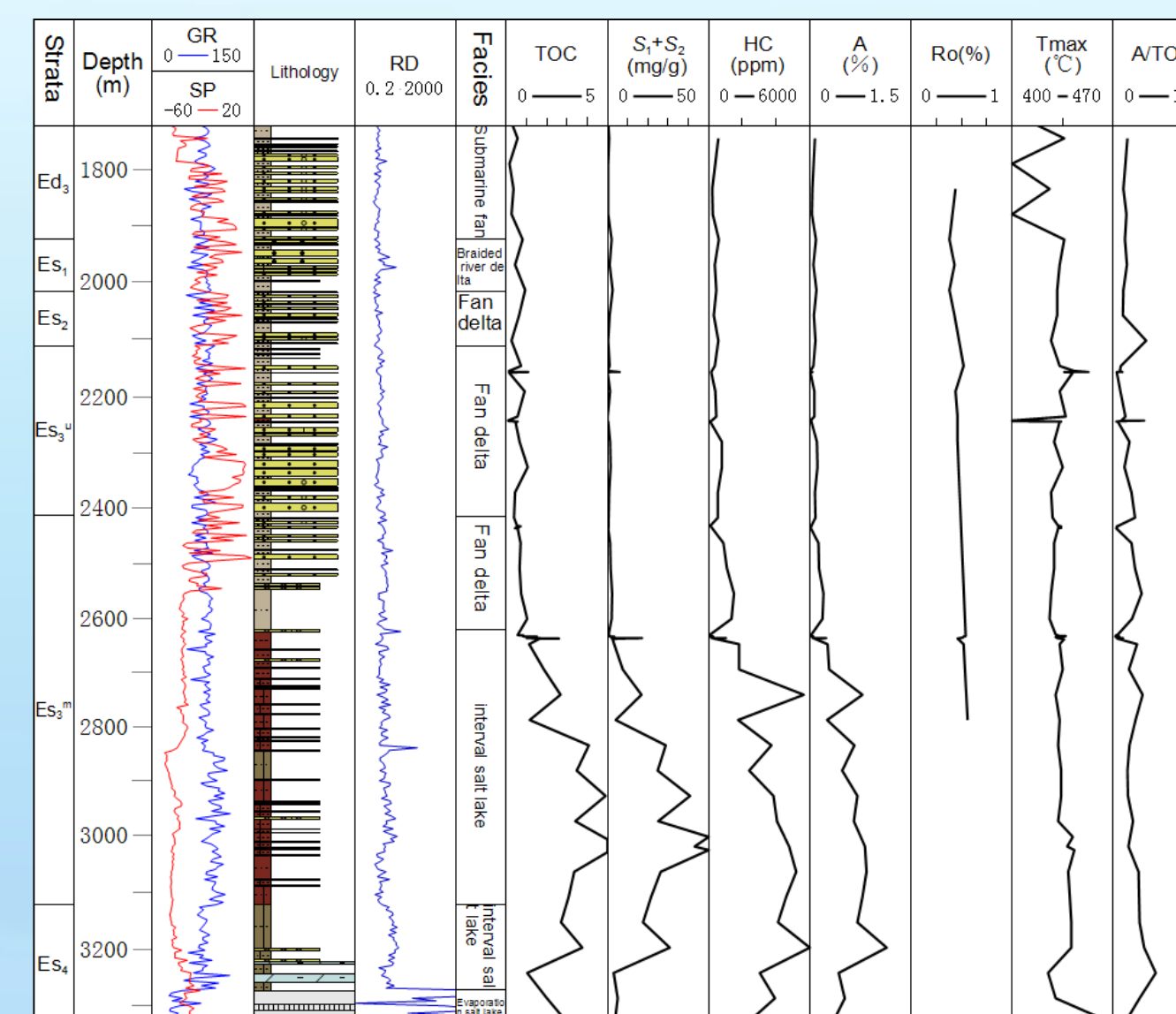


Figure 19. Comprehensive geochemical property of KL10-2-A

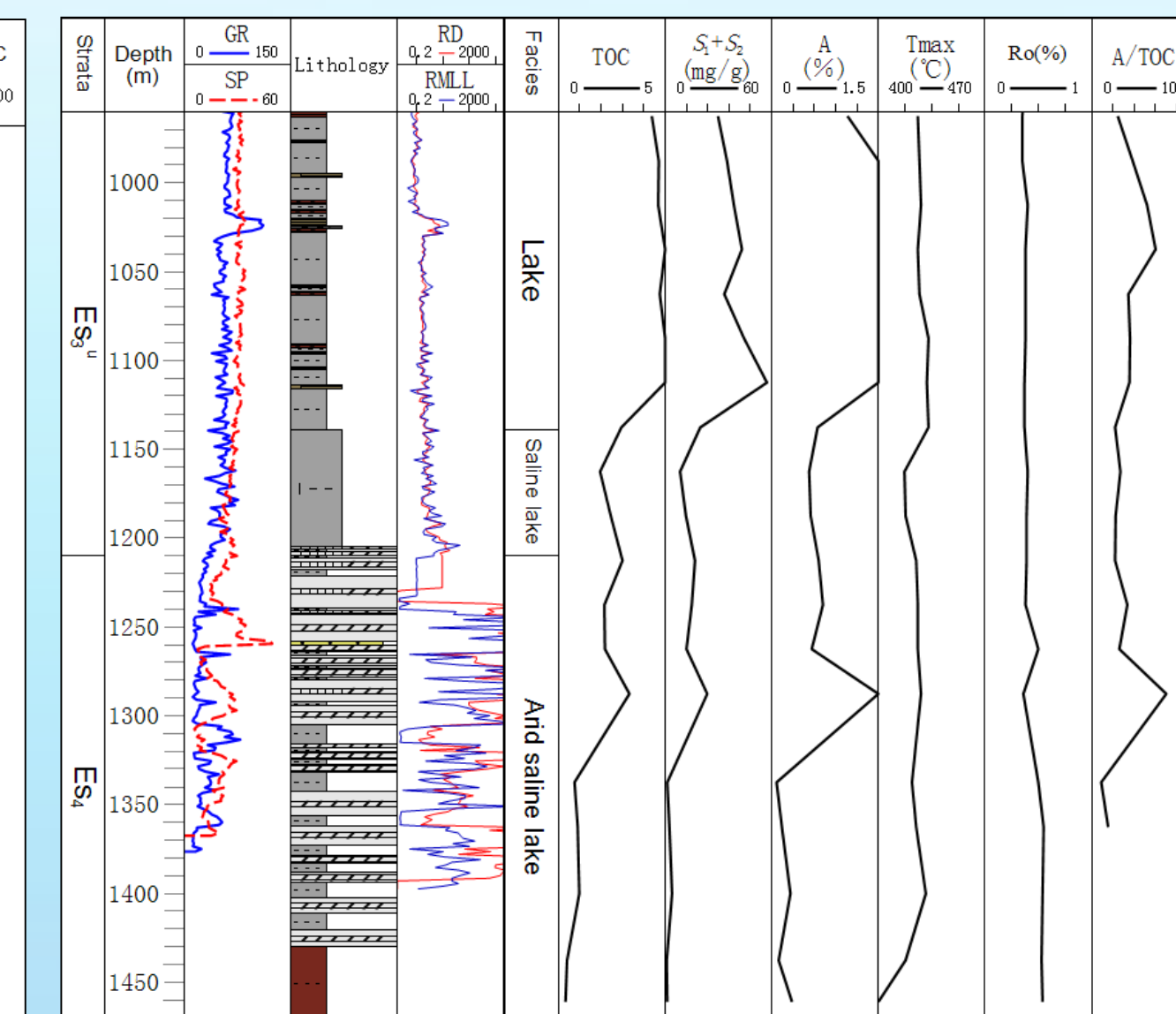


Figure 20. Comprehensive geochemical property of KL11-2-A

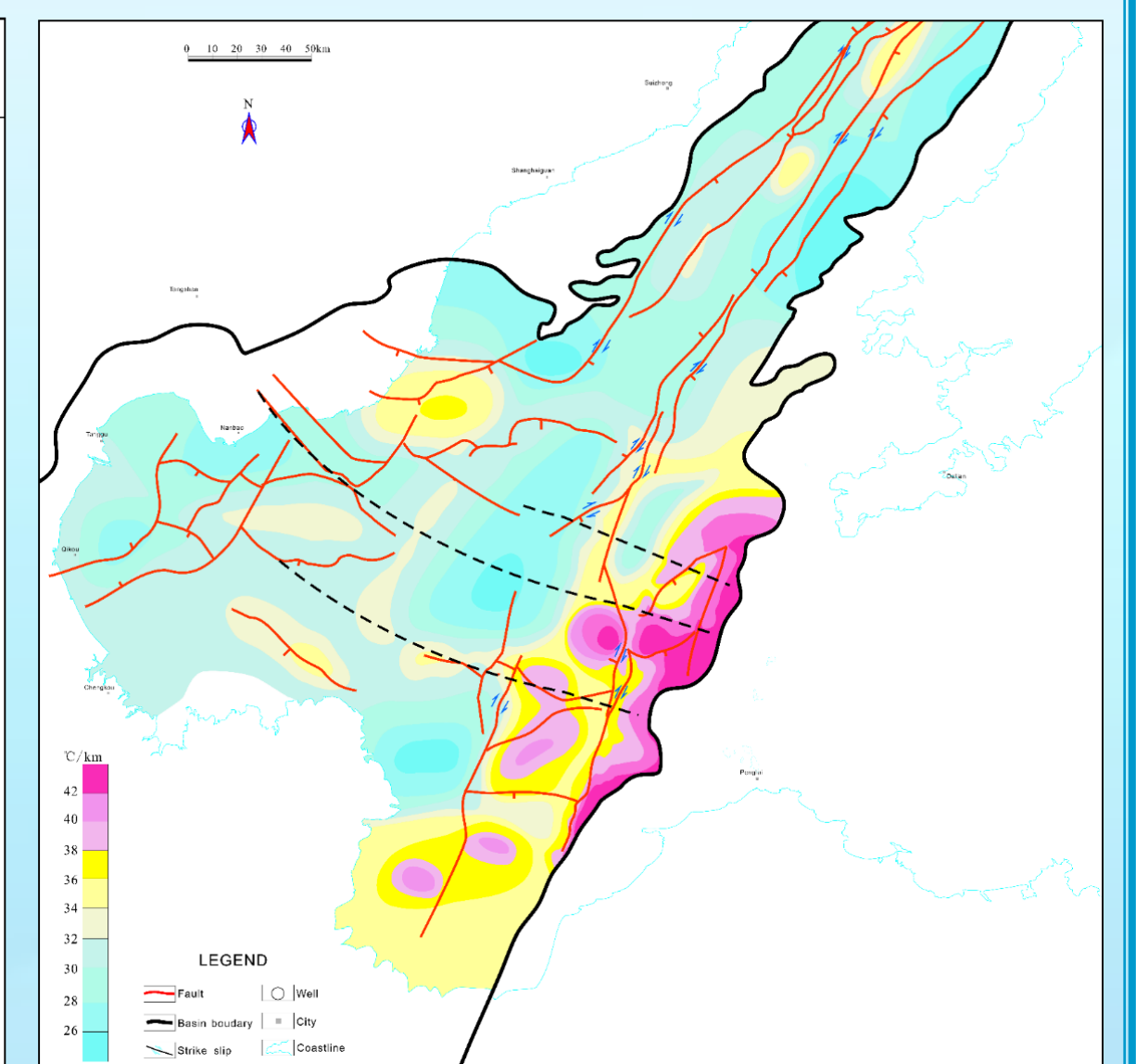


Figure 21. Thermal gradient contour map of Bohai sea area