

**PS Lacustrine Environment and Organic Matter Enrichment Mechanism for Source Rock
of the Third Member of the Eocene Shahejie Formation in the Raoyang Sag,
Bohai Bay Basin, Eastern China***

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Abstract

The third (E_{s3}) member of the Eocene Shahejie Formation is the main hydrocarbon source rock interval in the Raoyang Sag of Bohai Bay Basin. The controlling factors of source rocks formation are investigated with geochemical methods of 60 samples from three wells to reconstruct lacustrine environment during the deposition of E_{s3} . The clay assemblages of source rocks defined based on X-ray diffraction analyses exhibit the significant kaolinite accumulation in the lower E_{s3} and the illite accumulation in the upper E_{s3} . This phenomenon indicates that the paleoclimate gradually changed from humid to arid during the deposition of E_{s3} . The indicators of water salinity such as Sr/Ba, B/Ga and gammacerane index suggest freshwater lakes with unstable thermocline during the lower E_{s3} deposition, saline lakes with salinity stratified water column during the deposition of the upper E_{s3} . Carbon isotopic signatures of organic matters and carbonates ($\delta^{18}C_{om}$ and $\delta^{13}C_{carb}$), elements P and Ba are used as paleoproductivity proxies show that the paleoproductivity level had no clear periodical variation during the E_{s3} deposition. North American shale composite-normalized rare earth elements (REEs) patterns display sloping LREE trends and flat HREE trends with no obvious depletion of Ce (δCe ranges from 0.72 to 0.92, with average of 0.85) and Eu (δEu ranges from 0.93 to 1.05, with average of 0.98), thus the results can be taken as indicative of the anoxic depositional environment and low sedimentary rate of source rocks during the deposition of E_{s3} . Furthermore, Pristane/Phytane ratio, enrichment factors of trace elements Mo and U display obvious variation along with the strata changes, and distinguish the redox gradation of environmental conditions. The Pr/Ph ratio for the lower E_{s3} varies greatly from 0.46 to 1.41 with average of 1.01, a relatively low and narrow range of 0.1 to 0.36 with average of 0.19 for the upper E_{s3} . In addition, the enrichment of Mo and U occurs in the samples of the upper E_{s3} . These redox proxies indicate that the organic matters preservation conditions of the upper E_{s3} are more ideal than those of the lower E_{s3} . On the other hand, a positive correlation between $\Delta\delta^{13}C$ (difference between $\delta^{13}C$ values of carbonates and organic matters) and hydrogen index values proposes that enhanced anoxia triggered formation of the source rocks during the deposition of E_{s3} . This study may have important implications for source rock prediction in other lacustrine fault basins.



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Introduction

In this study, we present a detailed and high-resolution geochemical analysis of lacustrine source rocks of the third member (Es_3) of the Eocene Shahejie Formation in the Raoyang Sag to reveal the environmental and ecological changes that have occurred through geologic time. The aim of this study is to identify the factors that influence source rock formation and to construct depositional models of source rocks in the Raoyang Sag during the deposition of Es_3 , which may guide hydrocarbon exploration in the Raoyang Sag and other subbasins of the Bohai Bay Basin.

Geological Setting

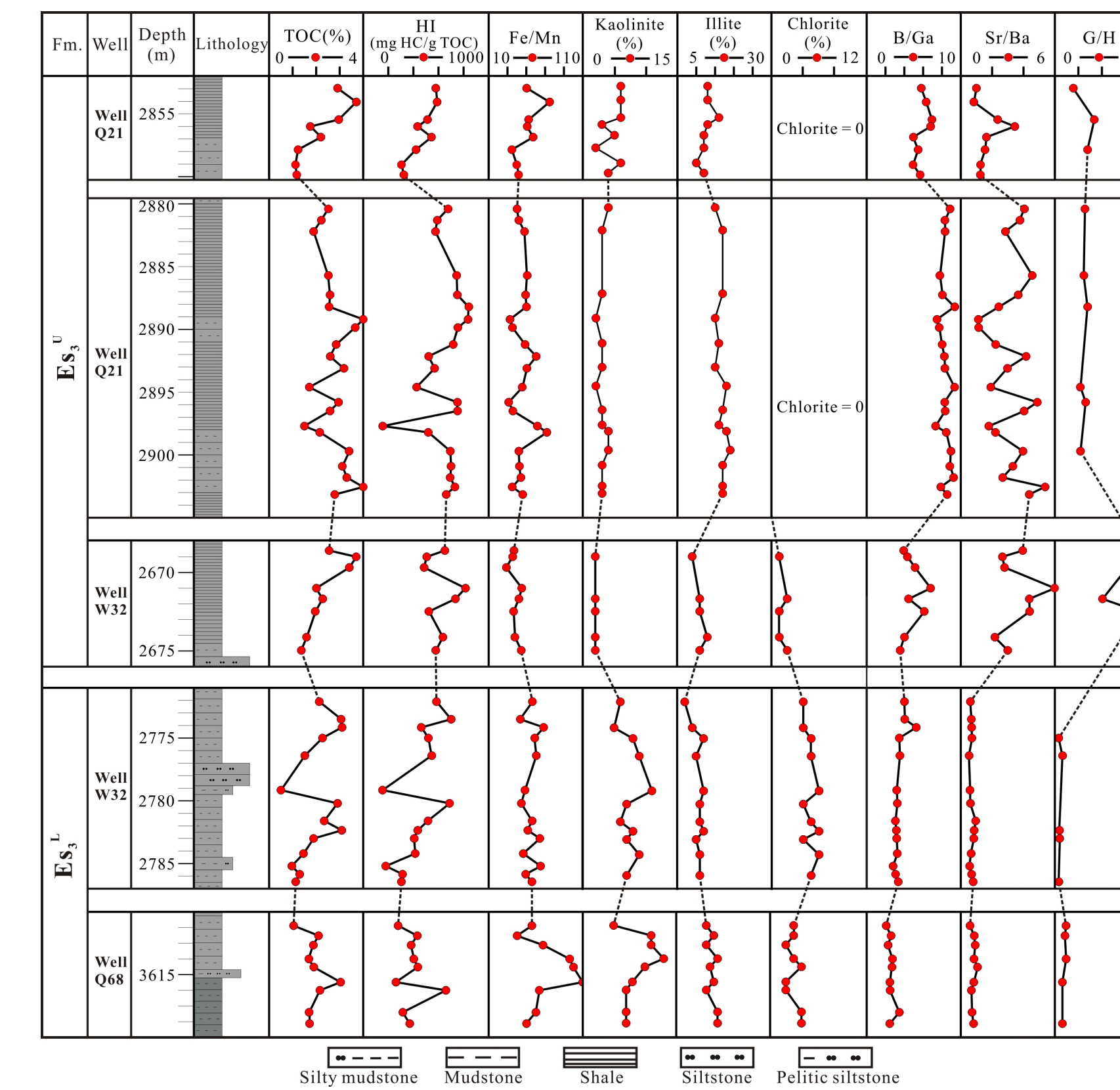
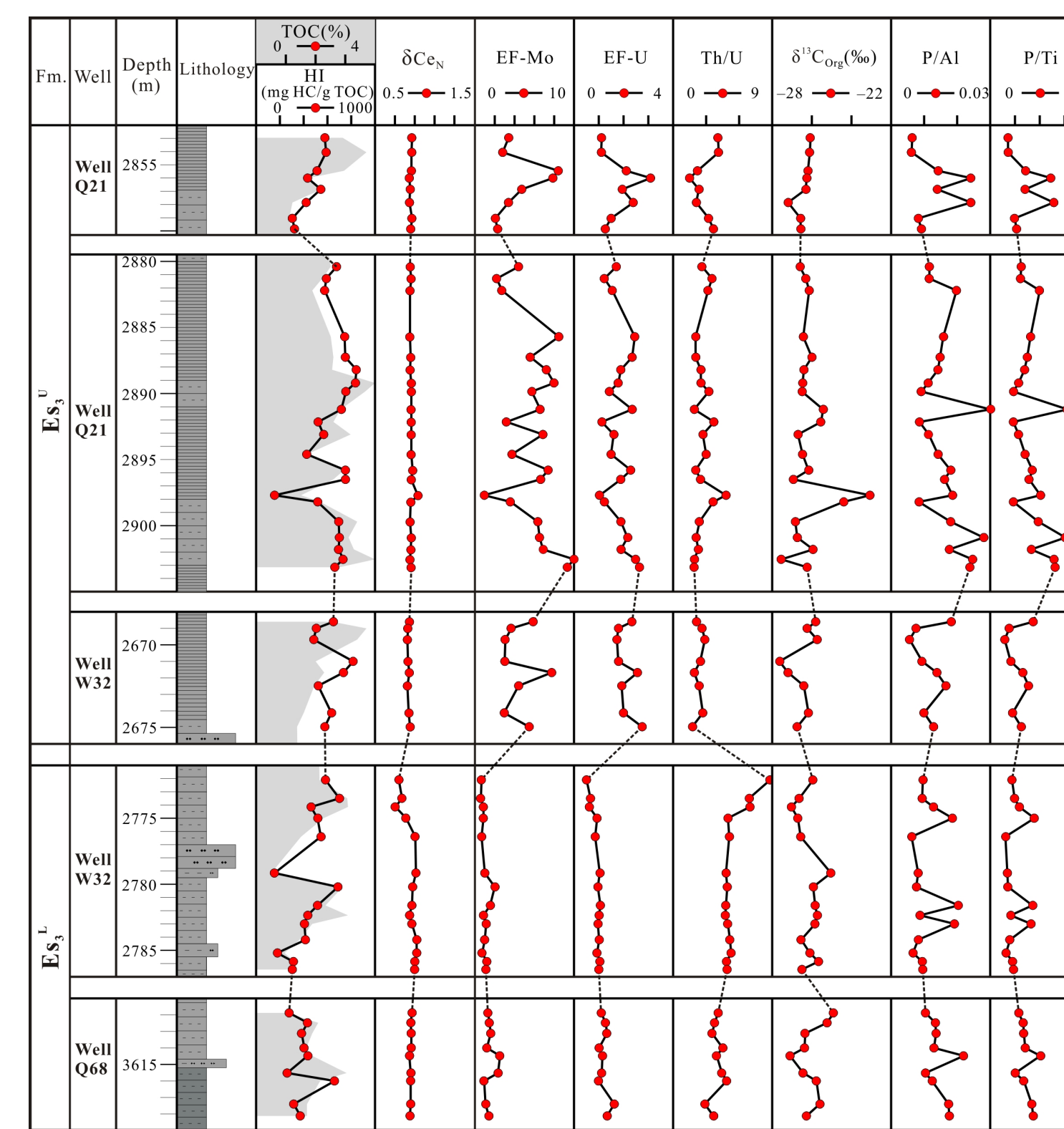
The Raoyang Sag is in the south-central area of the Jizhong subbasin of the Bohai Bay Basin of east China. It is a NE-trending Cenozoic half-graben that is bounded by the Xianxian salient to the east and the Gaoyang low salient to the west and is located in the centre of the Jizhong subbasin. The Es_3^L member is dominated by dark-grey lacustrine mudstone that is interbedded with sandstone formed in fluvial-deltaic environments. The Es_3^L member is conformably overlain by the Es_3^U member, which consists of predominantly dark-grey lacustrine mudstone and shale.

Palaeoclimate Condition and Water Salinity

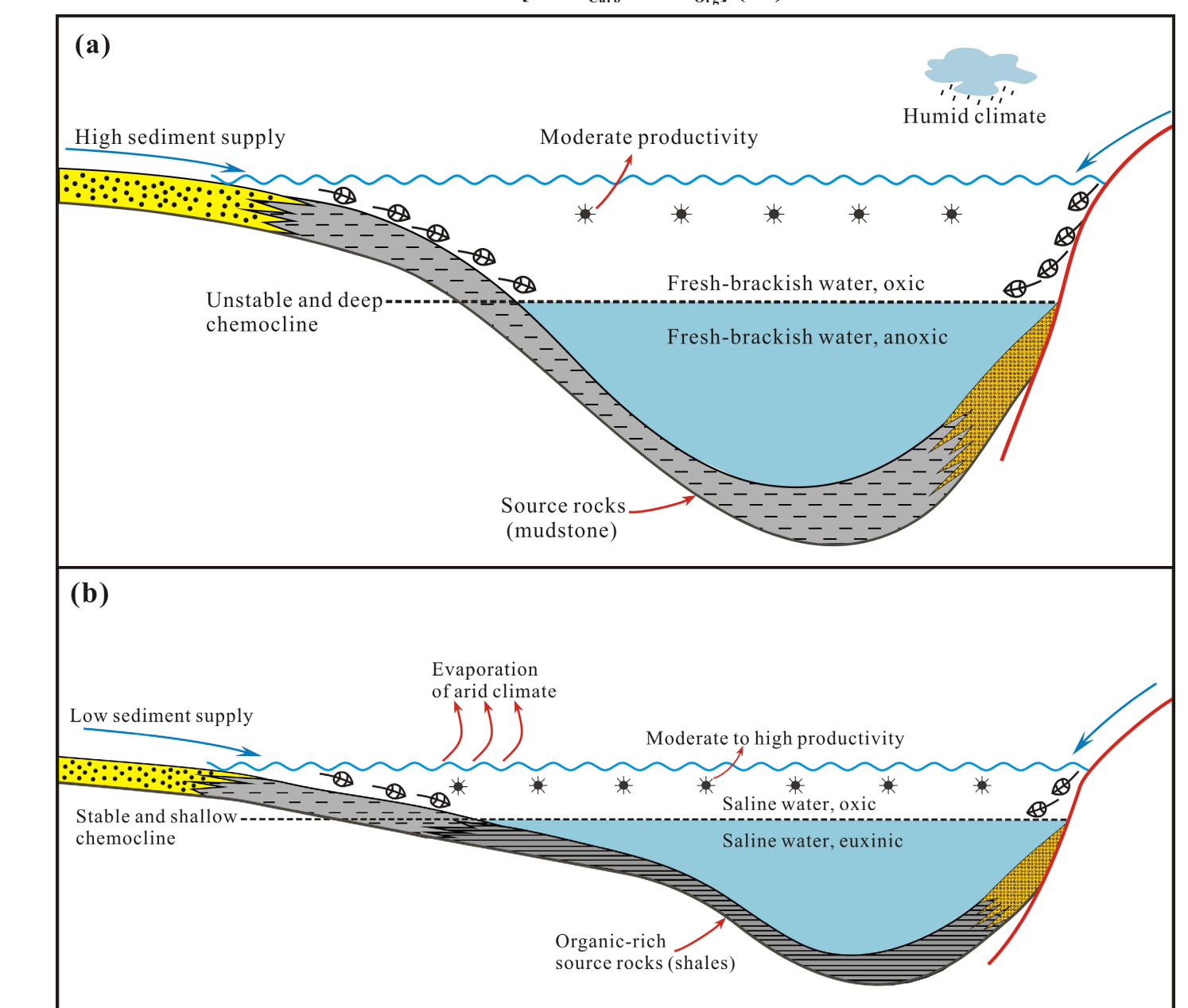
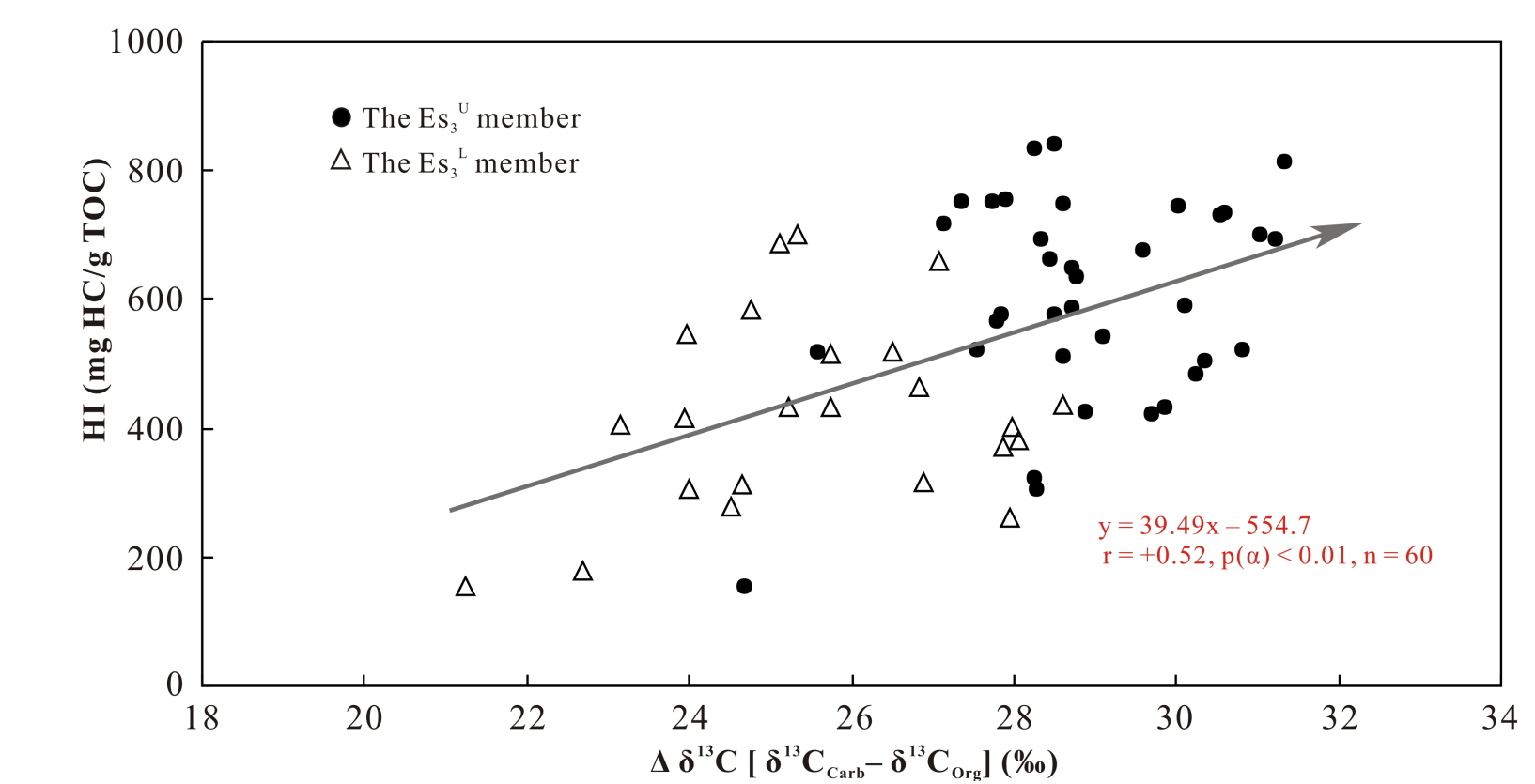
According to the XRD results of 60 samples from 3 wells, the clay assemblages of source rocks exhibit the significant kaolinite accumulation in the Es_3^L member and the illite accumulation in the Es_3^U member. Moreover, Fe/Mn ratio is relatively high in the Es_3^L member. The samples from the Es_3^U members have obviously higher ratios of gammacerane/C30 hopane (gammacerane index = G/H), B/Ga and Sr/Ba, suggesting saline water conditions with stratified water columns.

Palaeoproductivity and Redox Conditions

The P/Al and P/Ti ratios show consistent changes in the samples of Es_3 . The P/Al and P/Ti records reveal slightly higher values in the Es_3^U member, with averages of 0.015 and 0.30, respectively, than in the Es_3^L member, with averages of 0.012 and 0.24, respectively. According to the isotopic analysis, the $\delta^{13}C_{Org}$ values are mainly approximately -26.0‰ , with small variations from the Es_3^L member to the Es_3^U member in the Raoyang Sag. This indicates that the palaeoproductivity of the Es_3^U member is slightly higher than that of the Es_3^L member. In the Es_3^U member, the obviously high values of EF-Mo and EF-U are in accordance with the low ratios of Th/U and Pr/Ph and reflect euxinic conditions in the water column. However, in the Es_3^L member, the low values of EF-Mo and EF-U combined with the relatively high ratios of Th/U and Pr/Ph suggest less anoxic (non-sulfidic) conditions in the water column. In addition, North American shale composite-normalized rare earth elements (REEs) patterns display sloping LREE trends and flat HREE trends with no obvious depletion of Ce and, thus the results also can be taken as indicative of the anoxic depositional environment and high sedimentary rate of source rocks during the deposition of Es_3 .



Furthermore, $\Delta\delta^{13}C$ (i.e., the difference between the $\delta^{13}C$ values of carbonates and organic matter) and HI values exhibit an obvious positive correlation in Es_3 . This suggests that anoxic and stagnant bottom water is the major factor that controlled the accumulation of organic-rich sediments during the deposition of Es_3 in the Raoyang Sag.



Conclusions

We have summarized two models for source rock formation. The lakes of the Raoyang Sag had a moderate palaeoproductivity level and less anoxic (non-sulfidic) conditions during the Es_3^L member deposition but a slightly enhanced palaeoproductivity level and euxinic bottom water conditions (sulfidic) during the Es_3^U member deposition.

