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Transmission mechanism from orbital forced climate change to organic matter and shale oil enrichment

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The gravitational interactions among major planets in the solar system influence Earth's orbital parameters, which in turn cause the solar insolation received on Earth to exhibit multi-scale rhythms. These include the well-known long and short eccentricity, obliquity, and precession cycles, as well as their amplitude modulation cycles. Solar insolation further drives the formation of sedimentary cycles by influencing continental weathering, precipitation and evaporation, nutrient supply, primary productivity, and organic matter preservation conditions. These processes operate in both marine and lacustrine systems, and then formed well-laminated black shales. Typical orbital cycles have been found in the Cretaceous black shale of the Qingshankou Formation in the Songliao Basin. Taking the GY8HC well in the Gulong Sag of the Songliao Basin, NE China, as an example, this study utilized high-precision zircon U-Pb ages from volcanic ashes and AstroBayes method to estimate sedimentation rates. Through spectral analysis of high-resolution total organic carbon content (TOC), laboratory-measured free hydrocarbons (S1), hydrocarbons formed during pyrolysis (S2), and mineral contents, the enrichment characteristics and controlling factors of shale oil in an overmature area were investigated. The results indicate that: (1) TOC, S1, and S2 associated with shale oil enrichment exhibit a significant 173 ka obliquity amplitude modulation cycle; (2) Quartz and illite/smectite mixed-layer contents related to lithological composition show a significant 405 ka long eccentricity cycle; (3) Comparative studies with the high-maturity GY3HC well and moderate-maturity ZY1 well reveal distinct in-situ enrichment characteristics of shale oil in the overmature Qingshankou Formation, with a significant positive correlation to TOC, indicating that high TOC is a key factor for shale oil enrichment in overmature areas; (4) The sedimentary thickness of 12–13 m corresponding to the 173 ka cycle can serve as the sweet spot interval height for shale oil development in the study area, falling within the optimal fracture height range (10–15 m) generated during hydraulic fracturing of the Qingshankou shale. Orbitally forced climate changes not only controlled the sedimentary rhythms of organic carbon burial and lithological composition in the Songliao Basin but also influenced the enrichment characteristics and sweet spot distribution of Gulong shale oil.