Oil Shale, 2025, Vol. 42, No. 1, pp. 62–78
doi: https://doi.org/10.3176/oil.2025.1.03
ISSN 0208-189X

Environmental differences associated with Eocene lithology formation in the Fushun Basin, northeast China: insights from sedimentary organic facies

Yueyue Bai[a], Pingchang Sun[b]*, Zhaojun Liu[b], Junxian Wang[c], Yinbo Xu[d]

[a] SinoProbe Laboratory, Chinese Academy of Geological Sciences, Beijing 100094, China
[b] College of Earth Sciences, Jilin University, Changchun, Jilin 130061, China
[c] Beijing Research Institute of Uranium Geology, Beijing 100029, China
[d] Oil and Gas Survey, China Geological Survey, Beijing 100083, China

Received 21 June 2024, accepted 10 January 2025, available online 14 January 2025

Abstract. *The delineation of sedimentary organic facies is crucial for understanding the oil and gas generation in hydrocarbon source rocks. The Fushun Basin, characterized by abundant dark-colored sedimentary rocks rich in organic matter, serves as a prototypical region for establishing organic facies. This study employs maceral analysis on a comprehensive set of organic geochemical data to investigate the origins of organic matter-rich mudstones, utilizing the perspective of sedimentary organic facies. The organic matter types in the Fushun Basin transitioned from the Guchengzi Formation to the Xiloutian Formation, evolving from type* II_2 *and I to type* II_1 *and I, and subsequently to type* II_1*. Organic matter in the coal seams of the Guchengzi Formation mainly originates from terrestrial vascular plants, while in the oil shales of both the Jijuntun Formation and Xiloutian Formation, it primarily derives from lake algae. The sedimentary environment shifted from a peat swamp to a semi-deep lake, then to a deep lake, and ultimately to a shallow lake. Depending on the lake's openness or closure, the organic facies are classified into wetland-forest (swamp), open-basin lake-alginite, and closed-basin lake-alginite facies. This suggests that the rapid accumulation of abundant higher plants in the shallow-water environment has facilitated coal seam deposition, while the extensive enrichment of algae in the deep-water environment has contributed to the formation of thick oil shale layers in the Fushun Basin.*

Keywords: *coal, oil shale, organic facies, Fushun Basin, Eocene.*

* Corresponding author, sunpingchang711@126.com

1. Introduction

The analysis of organic facies represents an effective approach for assessing the origin and distribution of hydrocarbon source rocks. This method has been widely utilized across various domains within the study of hydrocarbon source rocks, encompassing the examination of petrological features, quality evaluation, organic matter accumulation and preservation, and the reconstruction of paleo-sedimentary environments [1–3]. Oil and gas geochemists primarily evaluate the potential of source rocks to generate hydrocarbons using indicators such as the hydrogen index, hydrocarbon generation potential, and total organic carbon (TOC) content. These indicators also function as the primary criteria for classifying organic facies [4–6].

The organic matter-rich Eocene strata in the Fushun Basin encompass coal seams in the Guchengzi Formation (Fm), thick oil shale layers in the Jijuntun Fm, and thin oil shale layers in the Xiloutian Fm. Previous research has predominantly concentrated on the paleoclimate evolution and conditions conducive to organic matter enrichment in the coal-bearing strata of the Guchengzi Fm and the oil shale-bearing strata of the Jijuntun Fm [7–10]. A series of studies has confirmed that the coals (Guchengzi Fm) and oil shales (Jijuntun Fm) in the basin formed under warm and humid paleoclimatic conditions, with precipitation concentrated in the range of 400 to 1300 mm. Coal seams represent freshwater swamp sediments formed in oxidizing environments of deep freshwater lakes, while oil shale formed in oxygen-deficient reducing environments [7, 8, 10–12]. Scholars have undertaken comprehensive investigations into the impact of paleoenvironmental factors on the organic matter in the Fushun Basin. Nevertheless, an integrated analysis of both the sedimentary environment and the characteristics of organic matter is crucial for assessing hydrocarbon source rocks and understanding the mechanisms of organic matter enrichment.

The Eocene Fushun Basin is rich in various energy mineral resources, encompassing coal seams, carbonaceous shales, and oil shales [13, 14]. Identifying the origins of organic matter and the depositional environments of these resources is crucial for understanding their accumulation. This study examines the sedimentary organic facies of organic matter-rich sedimentary rocks across different strata of the Eocene Fushun Basin, employing three key parameters: organic matter content, organic matter source, and depositional environment. The objective is to furnish a geological foundation for the exploration of the ore-forming processes in shale oil and coal as energy mineral resources.

2. Geological setting

The Fushun Basin, situated at the western terminus of the Dunhua–Mishan Fault Zone, represents a major Cenozoic rift basin. It is of paramount importance as a leading industrial center for coal and oil shale extraction in China, boasting an extensive mining legacy [15]. The Eocene Fushun Basin is located between latitudes 40–45° N (Fig. 1a).

The Dunhua–Mishan Fault Zone stretches in a NE–SW direction, showcasing the formation of numerous graben basins along its path, including the Fushun, Huadian, Dunhua, and Jixi basins [16]. Investigating the sedimentary organic facies in the Fushun Basin is crucial for formulating a model that represents the sedimentary organic facies of continental basins across northeast Asia.

The Paleogene strata of the Fushun Basin display notable variability in thickness. This heterogeneity is particularly evident in the sedimentation patterns of the Xiloutian, Jijuntun, Guchengzi, and Lizigou Fms. In the Lizigou Fm, tuffaceous limestone and coal deposits are predominant, with thicknesses varying from 6.9 to 115 m. The Guchengzi Fm is predominantly made up of coal seams, interspersed with carbonaceous mudstones, and ranges from 0.6 to 157 m in thickness. The Jijuntun Fm is distinguished by extensive oil shale deposits, with thicknesses spanning from 25 to 362 m. The Xiloutian Fm, consisting primarily of gray-green mudstones, along with carbonate and brown oil shale sediments, shows a varying thickness from 120 to 530 m [15]. Together, these formations constitute a continuous sequence of continental sedimentation, offering valuable empirical evidence for the study of organic-facies sedimentation in the basin.

3. Materials and methods

The target layer of the LFD-1 well in the Fushun Basin was sampled, with a total of 58 specimens collected and analyzed. The LFD-1 well includes the entire Guchengzi Fm (486.5–558.9 m), Jijuntun Fm (401.5–486.5 m), and Xiloutian Fm (294.7–401.5 m). All 58 samples were analyzed to determine their TOC content, Rock-Eval pyrolysis, and maceral composition, employing various methods. The TOC content was measured with a LECO-230 carbon-sulfur analyzer. Rock-Eval pyrolysis was performed utilizing the Rock-Eval 6 rock pyrolyzer to determine the quantities of free hydrocarbons (S_1), pyrolytic hydrocarbons (S_2), and the temperature at the peak of the S_2 curve (T_{max}). Maceral components in coals, carbonaceous mudstones, oil shales, and mudstones were examined using a Zeiss transmitted/reflected fluorescence microscope. This analysis was conducted under alternating conditions of reflected white light and fluorescence at 50× magnification [19]. At least 500 points were observed for each sample to ensure precision in assessing microscopic component content (volume percentage, % mmf), excluding mineral-based materials. The above experimental dataset was sourced from Li et al. [17] and the analysis was conducted in the Key Laboratory for Oil Shale and Paragenetic Minerals of Jilin Province.

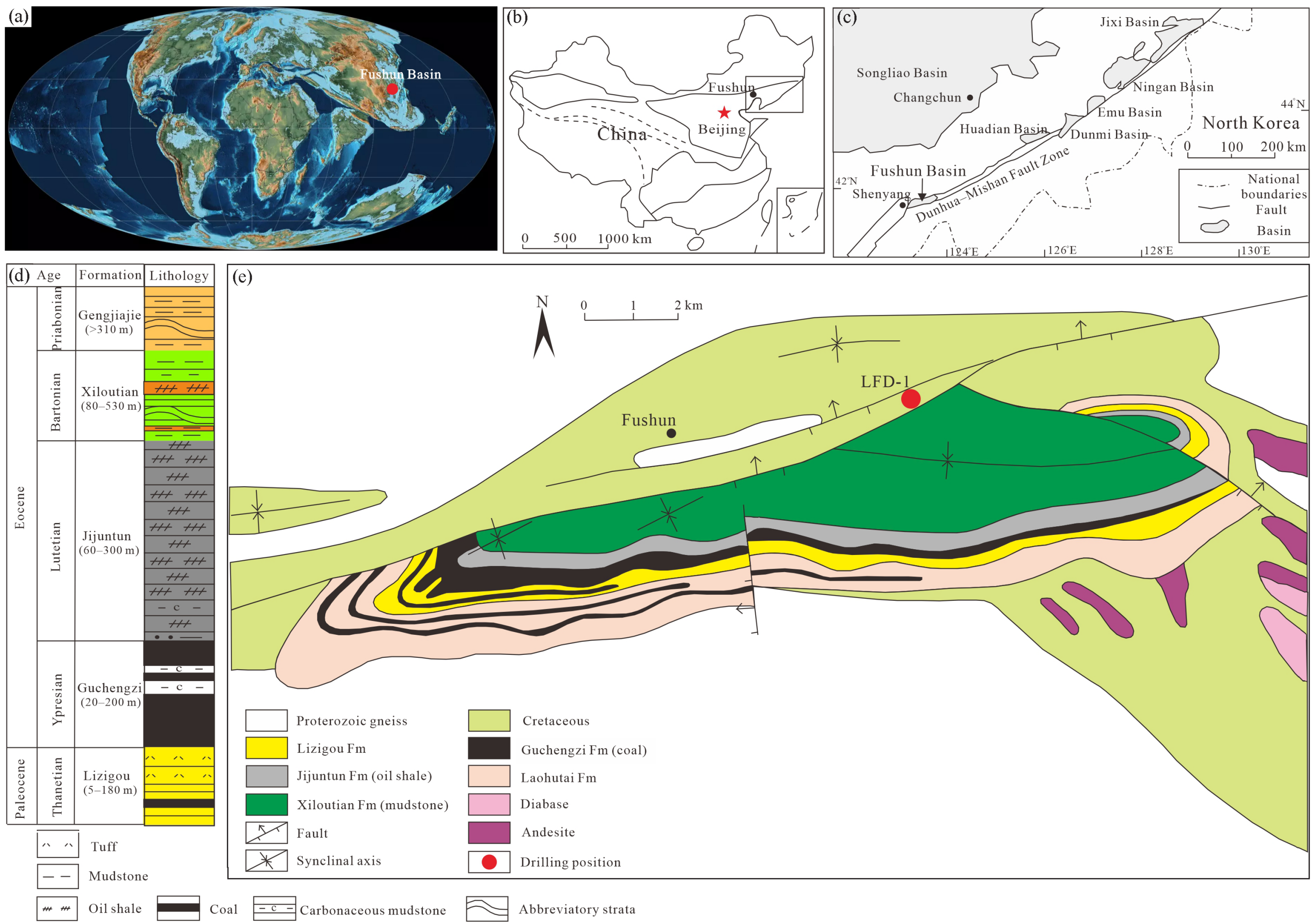

Fig. 1. Regional geological map of the Fushun Basin, northeast China: (a) location on a global map (50 Ma), (b) location in China [15, 17, 18], (c) location in the Dunhua–Mishan Fault Zone [15], (d) stratigraphic column [16], (e) geological structural units [15].

4. Results

4.1. TOC content

The samples of coals, carbonaceous mudstones, oil shales, and mudstones collected from the Paleogene Fushun Basin were analyzed for their TOC content (Fig. 2). The test results revealed that the coal of the Guchengzi Fm has the highest TOC content, ranging from 38.2 to 66.2 wt% (average 51.5 wt%). The carbonaceous mudstones of this formation also exhibit significant TOC content, varying from 13.6 to 37.7 wt% (average 31.3 wt%). The TOC contents of oil shales of the Jijuntun and Xiloutian Fms are relatively similar, ranging from 5.2 to 32.3 wt% (average 11.2 wt%) and 6.8 to 11.7 wt% (average 9.3 wt%), respectively. The mudstones of the Xiloutian Fm contain the lowest TOC content, ranging from 0.5 to 5.5 wt% (average 3.0 wt%).

4.2. Rock-Eval pyrolysis

Coals, carbonaceous mudstones, oil shales, and mudstones collected from the Eocene strata of the Fushun Basin were analyzed using a Rock-Eval 6 pyrolysis analyzer. The coal samples from the Guchengzi Fm exhibited a high potential for hydrocarbon production, with $S_1 + S_2$ values ranging from 98.1 to 164.4 mg/g (average 127.7 mg/g). The carbonaceous mudstones of this formation ranked second in terms of hydrocarbon potential, with $S_1 + S_2$ values ranging from 45.5 to 96.9 mg/g (average 82.9 mg/g). The oil shales of the Jijuntun and Xiloutian Fms demonstrated $S_1 + S_2$ values ranging from 24.9 to 310.8 mg/g (average 79.9 mg/g) and 54.6 to 99.2 mg/g (average 77.5 mg/g), respectively. The mudstones of the Xiloutian Fm displayed the lowest hydrocarbon generation potential, with $S_1 + S_2$ values ranging from 0.9 to 40.0 mg/g (average 17.3 mg/g).

Upon performing a correlation analysis of the TOC content and $S_1 + S_2$ values of the samples obtained from the Eocene Fushun Basin (Fig. 3), a relatively weak correlation was observed across all the samples ($R^2 = 0.66$). Nevertheless, upon examining the correlation by the types of organic matter-rich sediments in the study area, it became evident that coals and carbonaceous mudstones displayed a highly significant positive correlation between the TOC content and $S_1 + S_2$ values ($R^2 = 0.99$), albeit with a less steep correlation curve. Additionally, mudstones and oil shales exhibited an excellent positive correlation between the TOC content and $S_1 + S_2$ values ($R^2 = 0.97$), but with a steeper correlation curve.

The hydrogen index (HI) serves as a valuable tool for evaluating the oil-generating potential of organic matter within organic-rich mudstones and for classifying its types [20]. Among the oil shales of the Jijuntun and Xiloutian Fms, the highest HI values were observed, ranging from 486 to 954 mg HC/g TOC (average 679 mg HC/g TOC). The mudstones of the Xiloutian Fm followed, with HI values spanning from 100 to 727 mg HC/g TOC (average

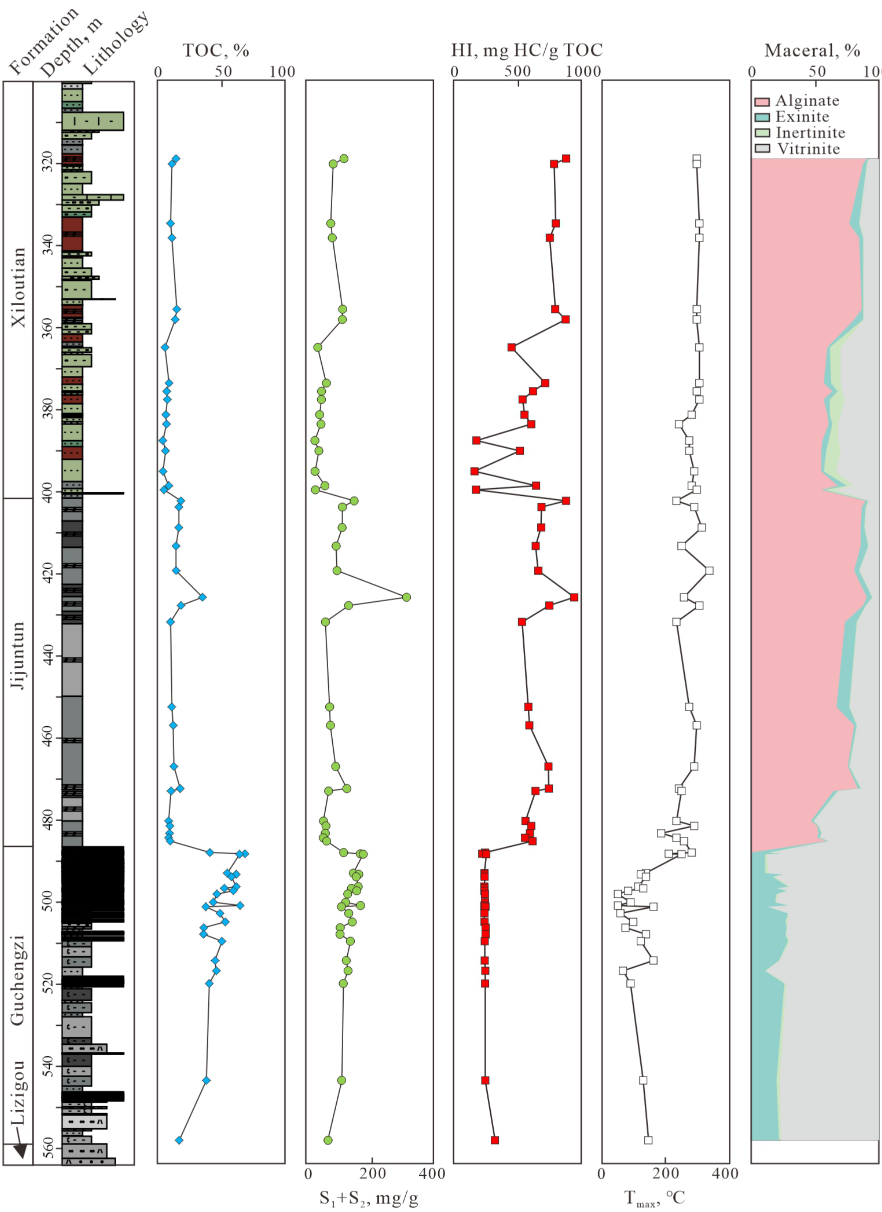

Fig. 2. Vertical variations in the TOC, Rock-Eval, and maceral data of the selected samples from the Eocene Fushun Basin [17].

424 mg HC/g TOC). The carbonaceous mudstones of the Guchengzi Fm exhibited HI values between 255 and 338 mg HC/g TOC (average 280 mg HC/g TOC), while the coals of the Guchengzi Fm showed lower HI values,

ranging from 200 to 263 mg HC/g TOC (average 248 mg HC/g TOC). The mudstones of the Xiloutian Fm followed, with T_{max} values spanning from 406 to 442 °C (average 427 °C), indicating that the sediments rich in organic matter are typically at an immature to low-maturity thermal evolution stage.

4.3. Maceral composition

The maceral analysis of coals, carbonaceous mudstones, oil shales, and mudstones collected from the study area was conducted using a transmitted fluorescence microscope. By comparing the relative content of maceral components, remarkable similarities between the coals and carbonaceous mudstones of the Guchengzi Fm were observed. Notably, vitrinite constituted the predominant fraction, accounting for approximately 70–89% (average 77%), followed by exinite at 11–29% (average 22 %). The relative abundance of both alginite and inertinite was less than 5%. The maceral components in the oil shales of the Jijuntun and Xiloutian Fms exhibited a general similarity, with alginite being the predominant content, accounting for approximately 47–91% (average 76%). This was followed by vitrinite content, constituting about 5–51% (average 20%). Both exinite and inertinite components were present at levels below 5%. The maceral components of the mudstones and oil shales of the Xiloutian Fm exhibited a striking similarity. Alginite was the most abundant, forming 55–68% (average 58%), followed by vitrinite, which constituted 20–35% (average 30%). Inertinite accounted for approximately 3–11% (average 7%), while the relative content of exinite was notably low, at less than 5%.

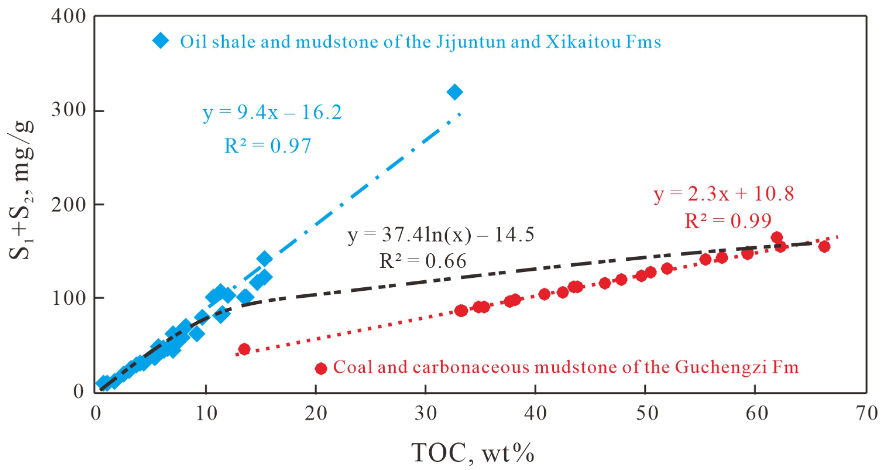

Fig. 3. Correlation between the $S_1 + S_2$ values and TOC content of the sedimentary samples from the Fushun Basin.

5. Discussion

5.1. Organic matter source

The analysis of organic matter sources is essential for investigating the enrichment of organic matter and sedimentary organic facies [5, 20]. Thorough examination of organic geochemical parameters and identification of maceral components provide a reliable approach to studying the origins of organic matter [21]. Based on a systematic analysis of the TOC content, Rock-Eval pyrolysis parameters, and maceral component identification data, this study distinguishes the types and sources of organic matter-rich sediments (including coals, carbonaceous shales, oil shales, and mudstones) in the Eocene Fushun Basin.

Upon examining the crossplot of T_{max}–HI (Fig. 4), it becomes evident that the majority of sample points from the coals and carbonaceous mudstones of the Guchengzi Fm are situated within the type II_2-kerogen zone, while a small number of samples are located within the type II_1-kerogen zone. Furthermore, an analysis of the maceral components reveals that these samples primarily consist of exinite, vitrinite, and inertinite groups, originating mainly from terrestrial vascular plants, with a minor presence of telalginite fibers. These observations imply that the organic matter in the coals and carbonaceous mudstones of the Guchengzi Fm is primarily derived from terrestrial vascular plants.

The oil shale samples from the Jijuntun Fm are predominantly located within the type I-kerogen zone, with additional samples within the type II_1-kerogen zone (Fig. 4). The type I-kerogen zone is primarily composed of high-quality oil shales (i.e., those with high oil yield), whereas the type II_1-kerogen zone predominantly includes mainly lower-quality oil shales (i.e., those with low oil yield). The predominant maceral component in the Jijuntun oil shale is lamalginite algae, accounting for 71.1% of all maceral components, followed by terrestrial organic matter mixed with exinite, vitrinite, and inertinite groups, with an average relative content of 26.7%. The deposition period characterized by a relatively low abundance of lamalginite algae (with an average relative content of 53.2%) corresponds to the formation of poor-quality oil shales. In contrast, the deposition period marked by a high concentration of lamalginite algae (with an average relative content of 80.1%) aligns with the development of high-quality oil shales. These findings suggest that lake algae serve as the primary source of organic matter in high-quality oil shales, while poor-quality oil shales originate from a mixed source, predominantly composed of lake algae and terrestrial vascular plants, with lake algae making a significant contribution.

The organic matter-rich sediments of the Xiloutian Fm predominantly consist of dark-colored mudstones and thin-layer oil shales. The organic matter in these dark mudstones displays a rich variety of compositions, mainly comprising type II_1 kerogen, with occasional occurrences of type II_2 kerogen and a limited presence of type I kerogen (Fig. 4). Furthermore, in comparison to the oil shales of the Jijuntun Fm, there is a reduction in the relative content of lamalginite algae, averaging 56.1%. In contrast, the contribution from terrestrial organic matter, including exinite, vitrinite, and inertinite groups, is higher, averaging 41.1%. These findings suggest that the primary source of organic matter in the dark-colored mudstones of the Xiloutian Fm is a blend of lacustrine algae and terrestrial vascular plants.

However, there has been a rise in the contribution of the organic matter originating from terrestrial vascular plants, as opposed to that from the oil shales of the Jijuntun Fm. The oil shales of the Xiloutian Fm predominantly contain type I kerogen, with a minor presence of type II_1 kerogen (Fig. 4). Additionally, lamalginite algae constitute the primary organic matter source in these oil shales, with an average content of 82.2%. In contrast, the contribution from terrestrial organic matter, including exinite, vitrinite, and inertinite, is significantly lower, averaging just 15.2%. These findings suggest that lake algae mainly served as the source of organic matter in the oil shales of the Xiloutian Fm.

In contrast to the Jijuntun Fm, which is characterized by its thick layers of oil shale, the Xiloutian Fm comprises a series of high-frequency interbedded deposits, featuring dark-colored mudstones and thin layers of oil shale. Moreover, the organic matter in the dark mudstones and oil shales of the Xiloutian Fm suggests that this formation underwent a high-frequency paleolake ecological evolution.

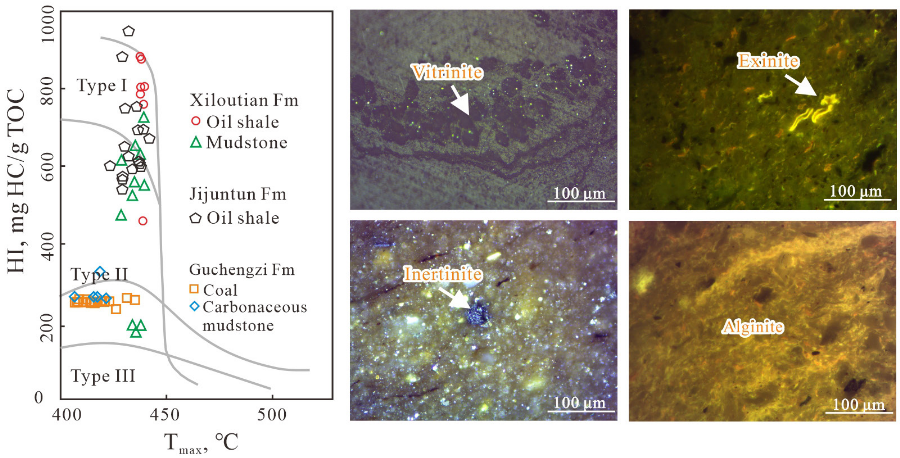

Fig. 4. Types of organic matter and characteristics of micro-components in the organic matter-rich mudstones of the Fushun Basin [17].

5.2. Type of sedimentary organic facies

Various regions adhere to distinct criteria for classifying sedimentary organic facies. In this study, we adopted the methodology suggested by Yao et al. [22], utilizing the proportions of maceral components (such as inertinite, vitrinite, exinite, and alginite) as the principal classification parameter [23]. By incorporating the characteristics of the depositional environment, we delineated the sedimentary organic facies of the various types of organic matter-rich sediments in the Eocene Fushun Basin (Fig. 5). The application

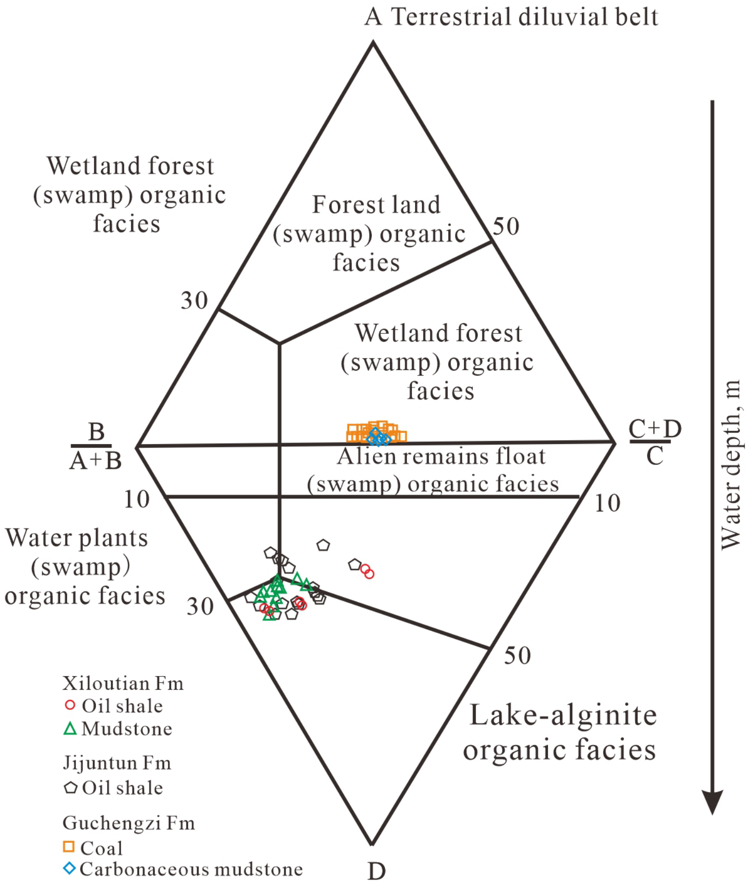

Fig. 5. Organic facies division of various types of organic matter-rich sedimentary rocks in the Eocene Fushun Basin. A – inertinite, B – vitrinite, C – sporinite, D – alginate. The upper delta represents drier conditions towards A. When D is <10%, C and D merge in the triangle. The lower triangle represents the underwater environment, with direction D indicating the deepening of the water body. When D is >10%, A and B merge in the triangle.

of this classification technique enhances our comprehension of the theoretical underpinnings associated with coal and oil shale formation.

The coals and carbonaceous mudstones of the Guchengzi Fm are located within the organic facies of a wetland-forest (swamp), while the mudstones and oil shales of the Jijuntun and Xiloutian Fms are deposited in the region of lake-alginite organic facies (Fig. 5). These findings suggest that the coals and carbonaceous mudstones of the Guchengzi Fm were deposited in a swamp environment at the lake's periphery, resulting in the formation of humic-sapropel type coal seams as the lake's depth diminished. The thickness of each coal seam remains relatively consistent, with grass ferns serving as the primary source of organic matter, accompanied by a mixed growth of woody plants. Owing to its proximity to the lake edge, this region experienced strong water flow, leading to the decomposition of robust plants and the formation of peat mires dominated by matrix humus bodies. The abundant terrestrial vegetation also contributed to the significant presence of exinite components. Carbonaceous mudstones likely formed during the transition from swamp to shallow lake or in shallow-water environments, with comparatively minimal alteration in the predominant vegetation cover.

During the deposition of mudstones and oil shales in the Jijuntun and Xiloutian Fms, the sedimentary environment was characterized by shallow lake and semi-deep to deep lake environments, with algae as the dominant organic maceral component. The lake during this period was notably deeper, resulting in high paleoproductivity and substantial accumulation of algae, which led to exceptionally high oil potential.

5.3. Modeling sedimentary organic facies

Due to the distribution characteristics and depositional environments of the Eocene organic matter-rich mudstone system in the Fushun Basin, from the Guchengzi to the Xiloutian Fm, the lakes underwent a transformation from peat swamps to semi-deep to deep lakes, and then to shallow lakes. Typically, distinct sedimentary organic facies display specific zonal patterns. Furthermore, depending on the degree of openness or closure of these lakes, a changing pattern in sedimentary organic facies is evident in this study area. This transition is characterized by the evolution of wetland-forest (swamp) organic facies into open-basin lake-alginite organic facies, and eventually into closed-basin lake-alginite organic facies.

The investigation into the vertical distribution of sedimentary organic matter facies indicates that the fine-grained sediments in the Guchengzi Fm are predominantly composed of wetland-forest (swamp) organic facies. Throughout this era, the region experienced a subtropical humid climate, with a mean annual temperature (MAT) fluctuating between 14.20 and 16.63 °C and a mean annual precipitation (MAP) varying from 968.40 to 1310.63 mm. These conditions fostered intense chemical weathering [17, 18, 24]. The organic matter is classified as type II_2 kerogen and predominantly originates from terrestrial vascular plants. Due to their oxygen content, shallow lacustrine water bodies can induce oxidation and decomposition of organic matter. Nonetheless, an excess of organic material exceeds its rate of utilization [7], resulting in the formation of coal and carbonaceous mudstones with a high TOC content of organic matter and hydrocarbon generation potential.

The fine-grained sediments in the Jijuntun Fm predominantly exhibit the characteristics of open-basin lake-alginite organic facies. These sediments were deposited under a subtropical to warm temperate transitional humid climate, with MAT ranging from 12.21 to 14.58 °C and MAP varying between 585.38 and 941.41 mm, accompanied by intense chemical weathering [17, 18, 24, 25]. The sediments mainly contain type I kerogen, which originates chiefly from algal sources. Additionally, the shift from swamp to shallow lake conditions in the basin led to an expansion of accommodation space and a decrease in environmental oxygen levels. Collectively, these factors facilitated the preservation of organic matter within the sediments [8], forming high-quality oil shales characterized by a high TOC content of organic matter and significant hydrocarbon generation potential.

Thin strata of argillaceous limestone were deposited in the Xiloutian Fm, signifying the establishment of a predominantly enclosed lacustrine system during that era, characterized by relatively high water salinity [26]. The dominant organic facies were closed-basin lake-alginite organic facies, primarily indicative of shallow lakes and, in some areas, semi-deep to deep lakes. The paleoclimate during this era was warm temperate, with a semi-humid to semi-arid environment (MAT of 12.08–15.71 °C and MAP of 556.49–968.64 mm), exhibiting moderate to strong chemical weathering [18]. The organic matter in the argillaceous limestones was mainly type I and type II_1 kerogen, with lake algae serving as the primary source of organic matter.

The thick-layered mudstones in the Xiloutian Fm were deposited in a shallow lake environment that transitioned from an open to a closed system. This transitional phase was characterized by a gradual decrease in lake levels and a shift from freshwater to saline conditions [8], leading to increased water salinity. Consequently, the progressive development of salinity stratification in the water body enhanced its reductivity [26]. However, increased influx of terrestrial debris diluted the organic matter in the lakes, resulting in suboptimal preservation conditions. Despite these circumstances, terrestrial higher-plant organic matter continued to be transported into the lake, thereby contributing to the formation of lake-alginite water plant (swamp) organic facies, with mudstones containing relatively low organic matter.

During the formation of oil shales in the Xiloutian Fm, the lake existed in a semi-deep to deep, closed system. The salinity of the lake increased due to the warm temperate, semi-arid climate (MAT of 9.90–13.81 °C and MAP of 568.64–883.86 mm) [18]. This led to salinity stratification and a significantly reduced aquatic environment, creating ideal conditions for the preservation of organic matter. Moreover, the limited supply of terrestrial organic matter and minimal degradation facilitated the accumulation of lake algae under

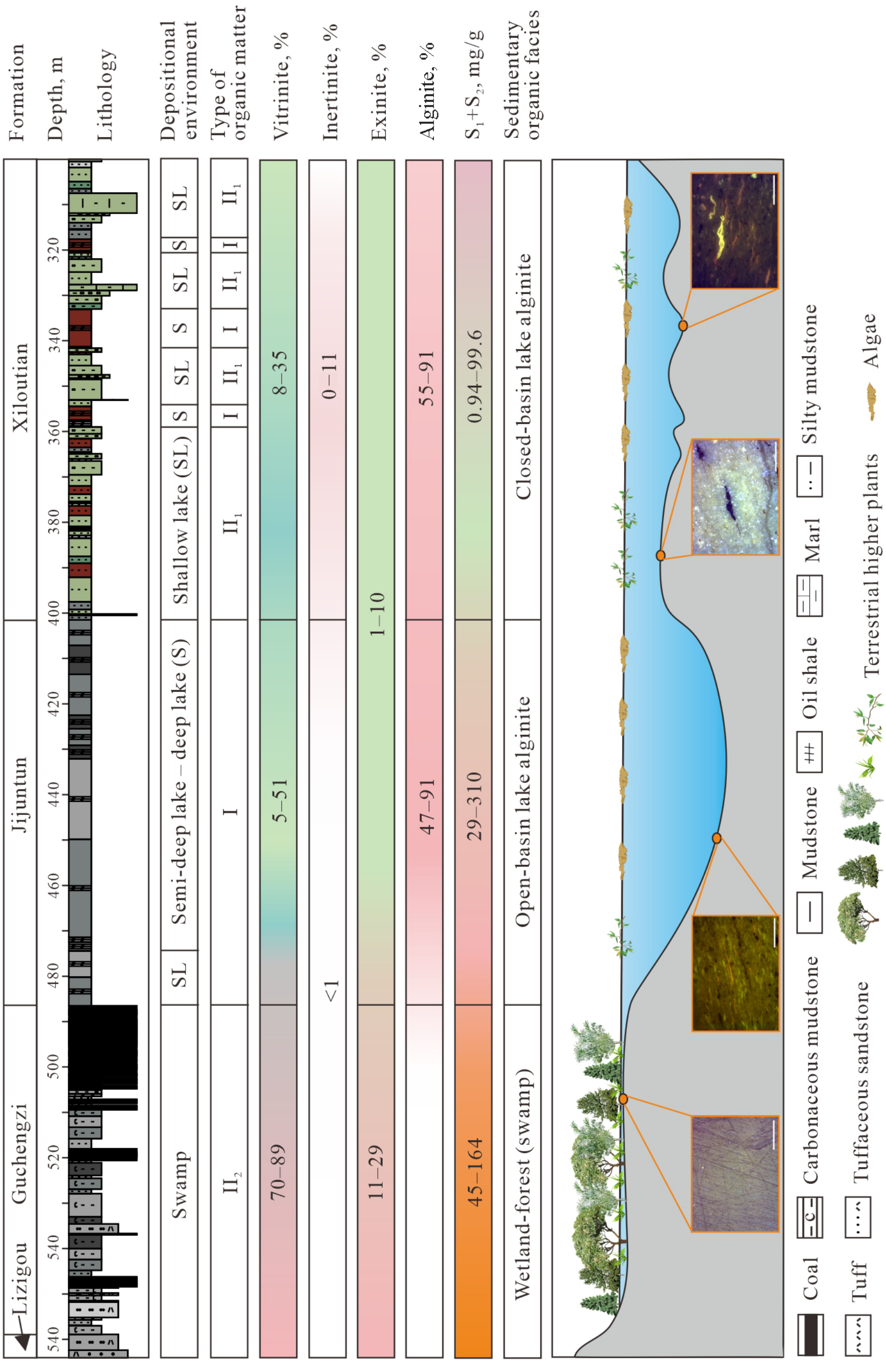

Fig. 6. Evolutionary model of sedimentary organic facies in the Eocene Fushun Basin.

favorable preservation conditions, ultimately leading to the deposition of brown oil shales characterized by lake-alginite organic facies.

6. Conclusions

Organic geochemistry and micro-compositional techniques are utilized to investigate the variations and origins of sedimentary organic facies, shedding light on the mechanisms of organic matter aggregation within the Eocene organic matter-rich mudstones of the Fushun Basin. In this basin, from the Guchengzi to the Xiloutian Fm, the organic matter types have undergone a transitional evolution from type II_2 and I to type II_1 and I, and subsequently to type II_1. Notably, coal seams and charcoal mudstones predominantly derive their organic matter from terrestrial vascular plants, while oil shales originate mainly from lacustrine algae. Mudstone samples reveal a higher contribution of organic matter from terrestrial vascular plants compared to oil shales, yet the latter continue to be predominantly sourced from lacustrine algae.

From the Guchengzi to the Xiloutian Fm in the Fushun Basin, the sedimentary organic facies have shifted from wetland-forest (swamp) organic facies to those dominated by algae in an open-basin lake, and subsequently to those in a closed-basin lake. Specifically, the coals and charcoal mudstones of the Guchengzi Fm were formed in wetland-forest (swamp) organic facies, while the oil shales of both the Jijuntun and Xiloutian Fms were deposited in semi-deep to deep lake environments, characterized by open-basin and closed-basin lake-alginite organic facies. Moreover, the mudstones of the Xiloutian Fm were deposited in a shallow lake environment within a closed-basin lake.

Author contribution

Yueyue Bai primarily established the article's framework, drafted the initial version, and carried out revisions. Pingchang Sun contributed to establishing the article's framework. Zhaojun Liu and Junxian Wang were responsible for data organization. Yinbo Xu was involved in creating the figures. All authors participated in the overall modifications and polishing of the article.

Data availability statement

The data used in this manuscript are available in the published article at the following DOI: https://doi.org/10.1016/j.palaeo.2022.111099.

Acknowledgments

This work was supported by the Foundation of China Geological Survey Project (grants No. DD20230008 and No. DD20221643). The authors would like to express their gratitude to EditSprings (https://www.editsprings.cn) for the expert linguistic services provided. We thank the editors and reviewers for their useful feedback that improved this paper. The publication costs of this article were partially covered by the Estonian Academy of Sciences.

References

1. Fowler, M. G., Stasiuk, L. D., Hearn, M., Obermajer, M. Evidence for *Gloeocapsomorpha prisca* in Late Devonian source rocks from southern Alberta, Canada. *Org. Geochem.*, 2004, **35**(4), 425–441. https://doi.org/10.1016/j.orggeochem.2004.01.017
2. Ercegovac, M., Kostić, A. Organic facies and palynofacies: nomenclature, classification and applicability for petroleum source rock evaluation. *Int. J. Coal Geol.*, 2006, **68**(1–2), 70–78. https://doi.org/10.1016/j.coal.2005.11.009
3. Lewan, M. A., Kotarba, M. J., Curtis, J. B., Więcław, D., Kosakowski, P. Oil-generation kinetics for organic facies with type-II and -IIS kerogen in the Menilite Shales of the Polish Carpathians. *Geochim. Cosmochim. Acta*, 2006, **70**(13), 3351–3368. https://doi.org/10.1016/j.gca.2006.04.024
4. Demaison, G., Murris, R. J. (eds). *Petroleum Geochemistry and Basin Evaluation*. American Association of Petroleum Geologists, Tulsa, 1984.
5. Jones, R. W. *Organic Facies*. Academic Press, London, 1987.
6. Tuweni, A. O., Tyson, R. V. Organic facies variations in the Westbury Formation (Rhaetic, Bristol Channel, SW England). *Org. Geochem.*, 1994, **21**(10–11), 1001–1014. https://doi.org/10.1016/0146-6380(94)90064-7
7. Strobl, S. A. I., Sachsenhofer, R. F., Bechtel, A., Gratzer, R., Gross, D., Bokhari, S. N. H., Liu, R., Liu, Z. J., Meng, Q. T., Sun, P. C. Depositional environment of oil shale within the Eocene Jijuntun Formation in the Fushun Basin (NE China). *Mar. Pet. Geol.*, 2014, **56**, 166–183. https://doi.org/10.1016/j.marpetgeo.2014.04.011
8. Strobl, S. A. I., Sachsenhofer, R. F., Bechtel, A., Meng, Q. T. Paleoenvironment of the Eocene coal seam in the Fushun Basin (NE China): implications from petrography and organic geochemistry. *Int. J. Coal Geol.*, 2014, **134–135**, 24–37. https://doi.org/10.1016/j.coal.2014.10.001
9. Xu, S. C., Liu, Z. J., Zhang, P., Boak, J. M., Liu, R., Meng, Q. T. Characterization of depositional conditions for lacustrine oil shales in the Eocene Jijuntun Formation, Fushun Basin, NE China. *Int. J. Coal Geol.*, 2016, **167**, 10–30. https://doi.org/10.1016/j.coal.2016.09.004
10. Chen, Z., Ding, Z., Tang, Z., Yang, S., Wang, X., Cui, L. Paleoweathering and paleoenvironmental change recorded in lacustrine sediments of the early to

middle Eocene in Fushun Basin, Northeast China. *Geochem. Geophys. Geosyst.*, 2017, **18**(1), 41–51. https://doi.org/10.1002/2016GC006573

11. Wang, Q., Ferguson, D. K., Feng, G. P., Ablaev, A. G., Wang, Y. F., Yang, J., Li, Y. L., Li, C. S. Climatic change during the Palaeocene to Eocene based on fossil plants from Fushun, China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 2010, **295**(1–2), 323–331. https://doi.org/10.1016/j.palaeo.2010.06.010
12. Quan, C., Liu, Y. S., Utescher, T. Paleogene evolution of precipitation in northeastern China supporting the middle Eocene intensification of the east Asian monsoon. *Palaios*, 2011, **26**(11), 743–753. https://doi.org/10.2110/palo.2011.p11-019r
13. Xie, W., Tan, J., Wang, W., Schulz, H.-M., Liu, Z., Kang, X., Wang, Y., Shahzad, A., Jan, I. U. Middle Jurassic lacustrine source rocks controlled by an aridification event: a case study in the northern Qaidam Basin (NW China). *Int. J. Coal Geol.*, 2021, **242**, 103779. https://doi.org/10.1016/j.coal.2021.103779
14. Xie, W., Jia, J., Mansour, A., Wang, X. Hydrocarbon generation and migration in the Fuxin Basin during the Cretaceous evolution of the North China Craton, NE China. *Geomech. Geophys. Geo-Energy Geo-Resour.*, 2023, **9**(1), 148. http://dx.doi.org/10.1007/s40948-023-00687-0
15. Hong, Y., Yang, Z. Q., Wang, S. T., Sun, X. Q., Du, N. Q., Sum, M. R., Li, G. Y. *Study on the Strata and Paleontology of Fushun Coalfield, Liaoning Province*. Science Press of China, Beijing, 1980.
16. Meng, Q. T., Liu, Z. J., Bruch, A. A., Liu, R., Hu, F. Palaeoclimatic evolution during Eocene and its influence on oil shale mineralisation, Fushun Basin, China. *J. Asian Earth Sci.*, 2012, **45**, 95–105. https://doi.org/10.1016/j.jseaes.2011.09.021
17. Li, Y. J., Sun, P. C., Liu, Z. J., Bai, Y. Y., Ma, L., Wang, J. X. Quantitative reconstruction of atmospheric pCO_2 sources during Eocene hyperthermal events based on data from the Fushun Basin, northeast China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 2022, **601**, 111099. https://doi.org/10.1016/j.palaeo.2022.111099
18. Li, Y. J., Sun, P. C., Falcon-Lang, H. J., Liu, Z. J., Zhang, B., Zhang, Q., Wang, J. X., Xu, Y. B. Eocene hyperthermal events drove episodes of vegetation turnover in the Fushun Basin, northeast China: evidence from a palaeoclimate analysis of palynological assemblages. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 2023, **610**, 111317. https://doi.org/10.1016/j.palaeo.2022.111317
19. Taylor, G. H., Teichmüller, M., Davis, A., Diessel, C. E. K., Littke, R., Robert, P. *Organic Petrology*. Gebrüder Borntraeger, Berlin, Stuttgart, 1998.
20. Sun, P. C., Sachsenhofer, R. F., Liu, Z. J., Strobl, S. A., Meng, Q. T., Liu, R., Zhen, Z. Organic matter accumulation in the oil shale- and coal-bearing Huadian Basin (Eocene; NE China). *Int. J. Coal Geol.*, 2013, **105**, 1–15. https://doi.org/10.1016/j.coal.2012.11.009
21. Bai, Y. Y., Liu, Z. J., Sun, P. C., Liu, R., Hu, X. F., Zhou, R. J., Xu, Y. B., Zhao, H. Q., Wang, J. P. Diverse sedimentary conditions during deposition of coal and oil shale from the Meihe Basin (Eocene, NE China). *J. Sediment. Res.*, 2017, **87**(10), 1100–1120. https://doi.org/10.2110/jsr.2017.60

22. Yao, S. P., Zhang, K., Hu, W. X., Fang, H. F., Jiao, K. Sedimentary organic facies of the Triassic Yanchang Formation in the Ordos Basin. *Oil Gas Geol.*, 2009, **30**(1), 74–89. https://doi.org/10.3321/j.issn:0253-9985.2009.01.011
23. Zhang, P. L., Meng, Q. T., Liu, Z. J., Hu, F., Xue, M. A comparative study of oil shale-bearing intervals in the Lower Cretaceous Jiufotang Formation in the Beipiao Basin, northeast China based on sedimentary organic-facies theory. *Oil Shale*, 2020, **37**(1), 32–50. https://doi.org/10.3176/oil.2020.1.02
24. Li, Y. J., Sun, P. C., Liu, Z. J., Bai, Y. Y., Xu, Y. B., Ma, L., Liu, R. Eocene hyperthermal events in the terrestrial system: geochronological and astrochronological constraints in the Fushun Basin, NE China. *Mar. Pet. Geol.*, 2022, **139**, 105604. https://doi.org/10.1016/j.marpetgeo.2022.105604
25. Wang, Z., Sun, P. C., Du, J. F., Li, Y. J., Wang, J. X., Hou, L. Y., Xu, Y. B., Bai, Y. Y. Eocene paleoclimate evolution under the background of warmhouse–hothouse conditions in the continental Fushun Basin: implications from magnetic susceptibility and color reflectance. *ACS Omega*, 2022, **7**(28), 24614–24625. https://doi.org/10.1021/acsomega.2c02445
26. Li, Y. J., Sun, P. C., Liu, Z. J., Xu, Y. B., Liu, R., Ma, L. Factors controlling the distribution of oil shale layers in the Eocene Fushun Basin, NE China. *Mar. Pet. Geol.*, 2021, **134**, 105350. https://doi.org/10.1016/j.marpetgeo.2021.105350