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ORIGINAL ARTICLE

Some aspects of excellent marine source rock formation: implications on enrichment regularity of organic matter in continental margin basins

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Abstract Through the analysis of ocean organisms, the distribution characteristics and enrichment of organic matters in modern marine sediments and ancient marine strata, this paper shows that the main factors influencing the formation of excellent marine source rocks are the paleoclimate, biologic productivity, terrestrial organic matter, oxidation–reduction environment, sedimentation rate, and the type of the basin. In addition to those factors, high biologic productivity or high content of terrestrial organic matter input is a requirement for the enrichment of the organic matter in a marine environment. Reducing environment was favorable for organic matter accumulation and preservation in depositing and early diagenesis stage, which is an important element for the formation of high-quality marine source rocks. Paleoclimate also influences the marine source rocks formation, as humid subtropical and tropical climates are the most favorable regimes for the formation of marine source rocks. Wind transports some vascular plant materials into the marine environment. Furthermore, upwellings driven by steady wind can cause high biologic productivity, thus forming organic-C-rich mud. Suitable sedimentation rate is beneficial for marine organic matter accumulation. Moreover, the type of the basin also plays an important role in the development of marine source rocks. Silled basins with a positive water balance often act as nutrient traps, thus enhancing both productivity and organic matter preservations, while in open oceans, organic matter enrichment in sediments has just been found in the oxygen minimum layers.

Keywords Marine source rock · Controlling factor · Preservation condition · The Qiongdongnan Basin · Northern South China Sea

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1 Introduction

The formation conditions of excellent marine source rocks depend on the living environment of the original source organisms and the favorable preservation conditions of organic matter, which are influenced by the paleoclimate, biologic productivity, terrestrial organic matter input, redox environment, sedimentation rate and the type of the basin. The debate on whether the high organic matter abundance in marine sedimentary stratum is dependent on preservation conditions or production has already existed since the 1980s. The former considered the fact that organic matter gathers when the bottom water conditions were anoxic, and argued that it had nothing to do with biologic productivity (Tyson 1987a, b; Tyson and Pearson 1991). Meanwhile the latter believed that organic matter could assemble at the water column with high biologic productivity, and that it was the water depth rather than the dissolved oxygen that influenced the abundance of organic matter (Calvert and Pedersen 1992). However, attempt in to put separate emphasis on whether high organic matter abundance in marine sedimentary stratum depends on preservation conditions or high biological production cannot objectively reveal the formation mechanism of excellent marine source rocks. Besides the above two factors, input of terrestrial higher plants is also a significant factor to the formation of marine source rocks developed in the continental margin basin (Li et al. 2013; Deng 2012), where some of the world famous marine petroleum-rich provinces have developed in geological history. This realization, in turn, has led to the recognition that the developmental environment and pattern of marine source rocks in continental margin basins are still controversial or poorly understood. This article does not focus on which factor, preservation conditions or high biological production, is more crucial; it aims to discuss every factor that controls preservation conditions, production and the input of terrestrial organic matter such as the paleoclimate, biologic productivity, oxidation–reduction environment, sedimentation rate, the origin of organic matter and the type of the basin. Through the analysis of the above factors, this article wants to reveal the enrichment regularity of organic matter in the continental margin basins.

2 Paleoclimate

The paleoclimate change plays an important role in the formation of hydrocarbon source rocks. Favorable climate conditions include humid subtropical and tropical climates. The main paleoclimate factors are temperature, rainfall and wind. The influences of temperature and rainfall are proven by the following facts: a large number of algae breed when the climate is warm and humid, thus promoting the primary productivity of the ocean. At the same time, the lush vegetation on land plays a vital role in water and soil conservation, which reduces the clastic particle inflowing into the ocean, thus reducing dilution of organic matter by mineral matter, therefore keeping high organic matter content in sediments. When rainfall increases, the incremental air humidity promotes the growth and reproduction of plants. Another important climate factor, wind, functions mainly in the ocean basin. It has significant power in forming ocean circulation, especially the upwellings. Upwellings form when offshore wind blows surface water away, which is significant in the formation of excellent marine source rocks.

3 Biologic productivity

Pedersen and Calvert (1990) and Calvert et al. (1995) held the belief that biologic productivity in the water column was the most important factor in controlling the development of the marine source rocks. Calvert (1987) attributed the high organic matter abundance in marine sedimentary rocks to the high biologic productivity rather than the anoxic environment, which determined the distribution and accumulation of organic matter in sediments. Furthermore, biologic productivity can result in the creation of anoxic conditions of bottom water. This is due to the fact that the decomposition of abundant organic matter can deplete the dissolved oxygen in water, thus forming the anoxic environment of the bottom water.

High biologic productivity often relates to upwelling, which brings nutrients in the subsurface water to the sun-lit zone. Thus, it promotes high biological productivity. Examples are Peru–Chile (Burnett et al. 1983) and Namibia (Calvert and Price 1971). Moreover, upwelling can cause a high accumulation rate. In an upwelling area, 20 %–60 % of the organic matter in the surface seawater can reach the water depth of 100 m, while only 15 %–35 % can reach the same water depth in non-upwelling areas (Suess and Thiede 1983).

Many academics presented the mathematical model to estimate paleoproductivity in a sedimentary environment. For example, Dymond et al. (1992) and Francois et al. (1995) proposed the formula that uses sedimentation flux of Ba to calculate the primary productivity. Paytan et al. (1996) used the accumulation rate of BaSO4 to qualitatively analyzing the paleoproductivity. In addition, Murray and Leinen (1996) put forward the method that the Al/Ti value could be used to analyze the primary production qualitatively. The gradient leaching experiment tells us the residue mineral phase has more than 95 % of Ti and about 50 % of Al combined with biogenesis, so the Al/Ti value depends on the number of organism scavenging action, which can reflect primary production.

In order to reveal the relationship between paleoproductivity and organic matter enrichment conditions, this article has discussed the effect of primary production on Miocene marine source rocks using the analyses of several exploratory wells in the Qiongdongnan Basin of the northern South China Sea. The Miocene source rocks developed in the open oceanic environment in the Qiongdongnan Basin, where terrestrial input had little impact. At that rate, the Al/Ti value can present the efficiency of primary production. Al/Ti values of the source rocks in Huangliu formation, Sanya formation and Meishan formation have a good linear relation with the content of TOC (Fig. 1). The sample with a high Al/Ti value has a high organic matter abundance, so the primary production conditions control the quality of the marine source rocks.

4 Terrestrial organic matter

Terrestrial organic matter is an important biogenic matter of the marine source rocks in continental margin basins.

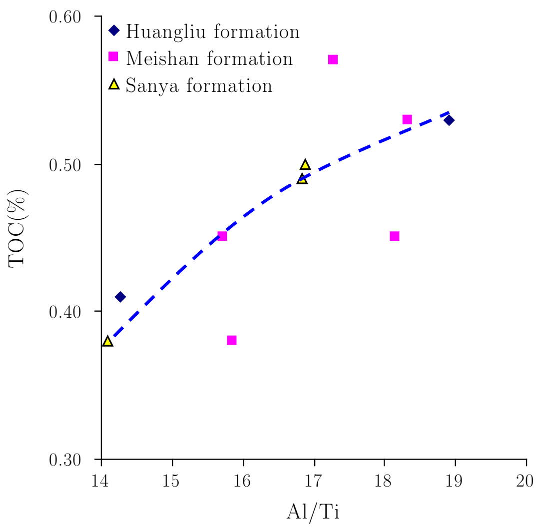


Fig. 1 Graph showing the relationship between Al/Ti value and TOC of Miocene source rocks in the Qiongdongnan Basin

The continental basin, where excellent marine source rocks formed, is mainly located below the estuary of a big river. Rivers can bring abundant terrestrial sediments, and as the waves and ocean currents have little destructive effect on the sedimentary formation of Continental margin, the delta-shore sedimentary system advances gradually into the ocean. As a result, the delta facies in offshore area and slope facies which are full of organic matter are considered to be the favorable places for the formation of source rocks.

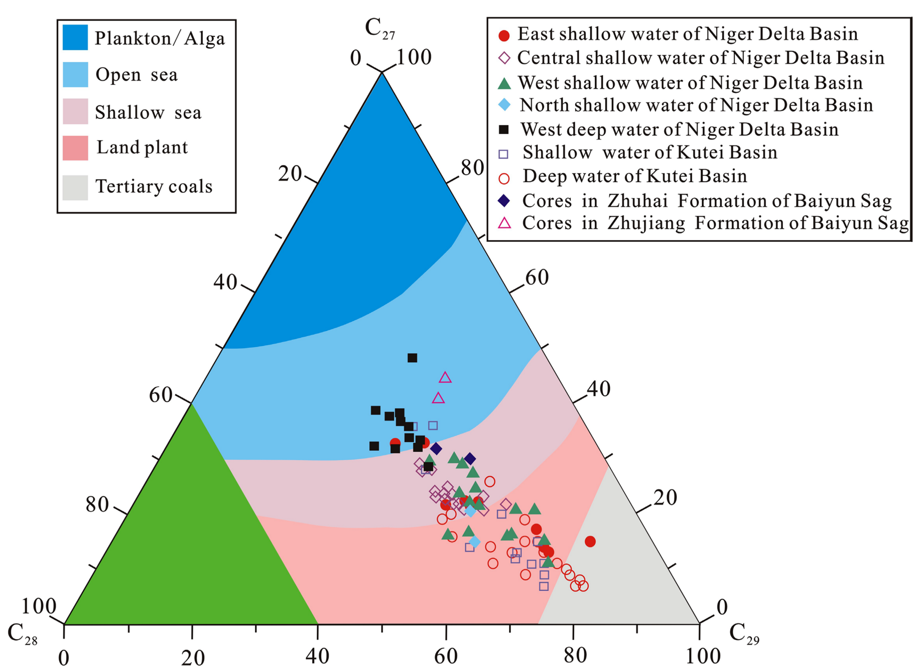
For example, take into account some of the delta basins in the continental margin. The distribution of C_{27}, C_{28} and C_{29} steranes in Crude oils in Niger Delta Basin and Kutei Basin show that most of the samples are dominated by C_{29} steranes (Fig. 2). This indicates that the origin of the organic matter is mainly terrestrial organic matter. Cores in the Zhuhai and Zhujiang formations in the Baiyun Sag of Pearl River Mouth Basin also have a relatively high content of C_{29} sterane (Fig. 2), indicating large amounts of terrestrial organic matter input.

Take into account another example, the Qiongdongnan Basin where there lacks a big river or a large size delta. The organic matter input of Oligocene source rocks is dominated by the terrestrial higher plants. The high content of oleanane that represents the terrestrial higher plants input was detected in the transitional facies source rocks of Yacheng Formation (Fig. 3), while the content of the semi-enclosed marine facies source rocks of Lingshui formation were significantly reduced. As the main origin of organic matter in the Oligocene source rocks is terrestrial higher plants, the amount of terrestrial organic matter determines the quality of source rocks. This fact explains the fact that the source rocks of Yacheng formation are the main source rocks in the Qiongdongnan Basin well.

5 Redox conditions

The preservation of organic matter is directly related to the oxic–anoxic conditions of deposition. In an oxygenated environment, the organic matter is partly degraded as it falls through the water column. An additional percentage of the carbon is consumed by the benthic fauna on the

Fig. 2 Ternary diagram showing C_{27}, C_{28} and C_{29} steranes of source rocks or crude oils in some delta basins



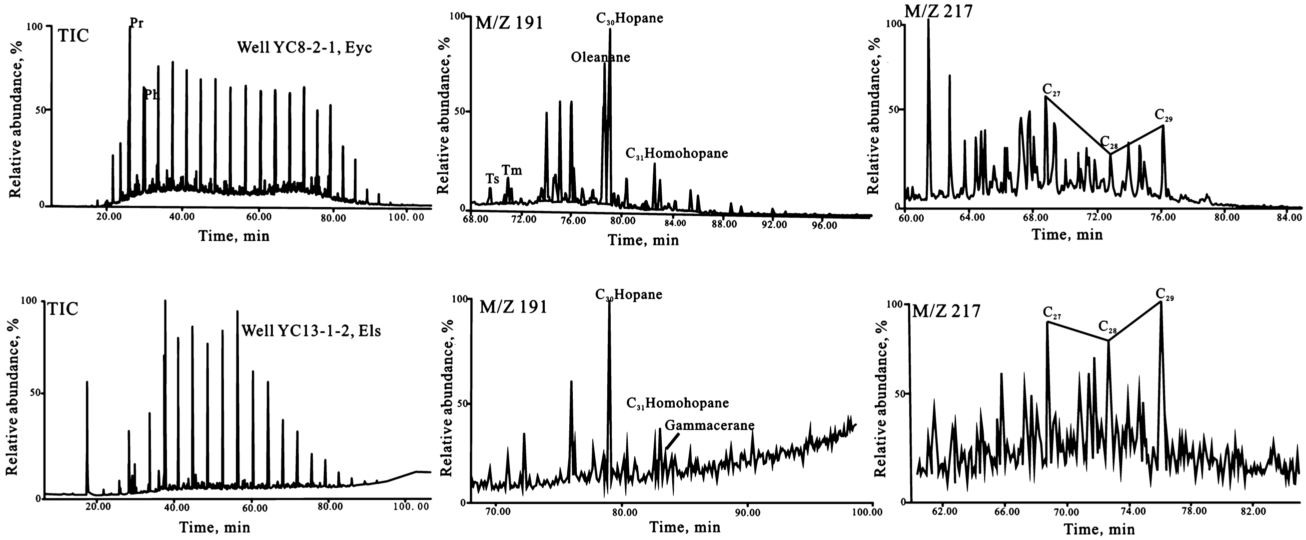


Fig. 3 Mass chromatograms showing the distribution of the n-alkane series (TIC), terpenoids (m/z 191) and steroids (m/z 217)in saturated hydrocarbons of core extracts in Oligocene source rocks in the Qiongdongnan Basin

seabottom. After that, worms or other burrowing organisms work it over in the sediments. Bioturbation caused by these organisms introduces oxygen into the sediments resulting in a high level of destruction of the less inert forms of carbon. In contrast, the anoxic environment frequently has hydrogen sulfide in the water column above the ocean bottom, which effectively kills all benthic organisms so that no oxidation of organic carbon occurs. Instead, bacterial sulfate reduction generally leads to form more hydrocarbon-like biomasses.

Demaison and Moore(1980)believed that oxygen contents of less than 0.5 ml/l of water resulted in good organic matter preservation. Inland silled basins with a positive-water-balance act as nutrient traps, thus enhancing the preservation of organic matter. Examples include the Black Sea (Degens and Ross 1974) and the Baltic Sea (Grasshoff 1975). The enrichment of organic matter in the open ocean is often related to the anoxic environment. Organic matter mainly gathers in the continental shelf or continental slope where oxygen content is below the level of 0.5 ml/l, such as at the northeastern Pacific Basin (Gross et al. 1972), Gulf of California (Van Andel 1964),and the Indian Ocean (Stackelberg 1972). Moreover, upwelling can form an anoxic layer. A typical example of this is the Peru Current.

According to several drilling data from the Qiongdongnan Basin of northern South China Sea, this paper uses the trace element indexes of the U/Th and Ni/Co value put forward by Tenger et al. (2005) to distinguish the formation environment of Miocene marine source rocks in the basin. The results show that the source rocks mainly developed in an oxic environment (Fig. 4), the reason being that drilling wells mainly distribute in shallow water areas (where the water depth is below 100 m). Therefore the preservation conditions of organic matter restrict the formation of excellent marine source rocks in the Qiongdongnan Basin.

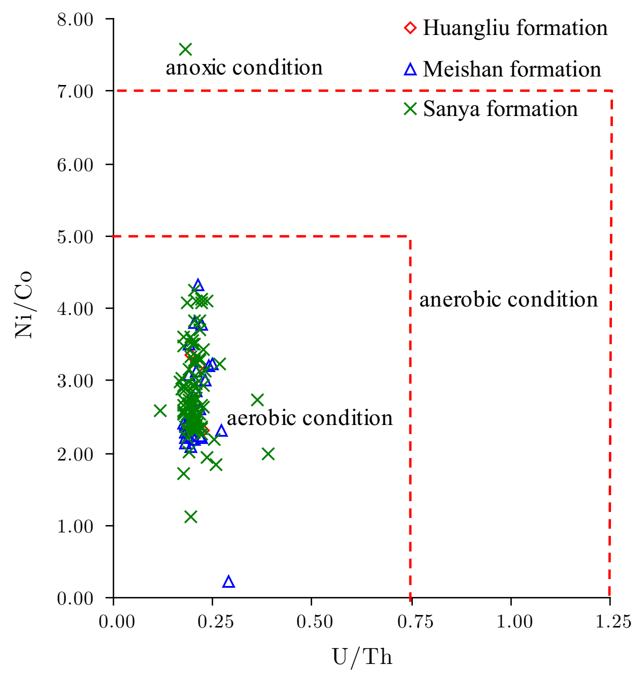


Fig. 4 Graph showing the relationship between U/Th value and Ni/Co value of Miocene marine source rocks in the Qiongdongnan Basin

6 Sedimentation rate

Sedimentation rate is an important factor when determining the accumulation of organic matter. International Deep Sea

Drilling Project (DSDP) of the core study found that there existed a certain correlation between the sedimentation rate and organic matter enrichment (Ibach 1982). Chen et al. (2006) studied the impact of sedimentation rate on organic matter enrichment by testing comparatively different frequencies and different injected doses in the laboratory. The results show that the organic carbon content first increases and then decreases as the deposition rate increases. The above phenomenon indicates that the organic matter can be easily diluted by a mass of inorganic particles when sedimentation rate is too fast, leading to the decrease of organic matter in sediments. On the contrary, if the deposition rate is too slow, organic matter can be gradually consumed by the oxygen in the water column, leading to the reduction of organic matter in sedimentary rocks. Therefore, suitable sedimentation rate is beneficial for the formation of organic- rich source rocks. Dilution of organic matter by mineral matter during deposition is a factor of source-sediment information that is related to the rate of sedimentation. Rapid deposition under oxic bottom-water generally leads to preservation of organic matter, but not to the formation of rich source beds. On the contrary, many ancient marine source rocks formed at regions with a low sedimentary rate (de Graciansky et al. 1984; Tyson 1987a, b). In other words, rich source beds seldom form where dilution of organic matter by mineral matter is excessive, but they commonly form where dilution of organic matter by mineral matter is meager.

This paper uses Site 1148 of deep sea drilling in the South China Sea Basin as an example to show the relationship between the sedimentation rate and organic matter. Site 1148 in the abyssal zone reveals low organic matter abundance of Miocene marine source rocks, the average TOC of which is less than 0.5 %. One of the important reasons of this is that the deposition rate in Miocene restricts the formation of marine source rocks. The low deposition rate makes the organic matter deplete in the water column rather than accumulate in the sea floor, which is to the disadvantage of the development of the marine source rocks (Fig. 5).

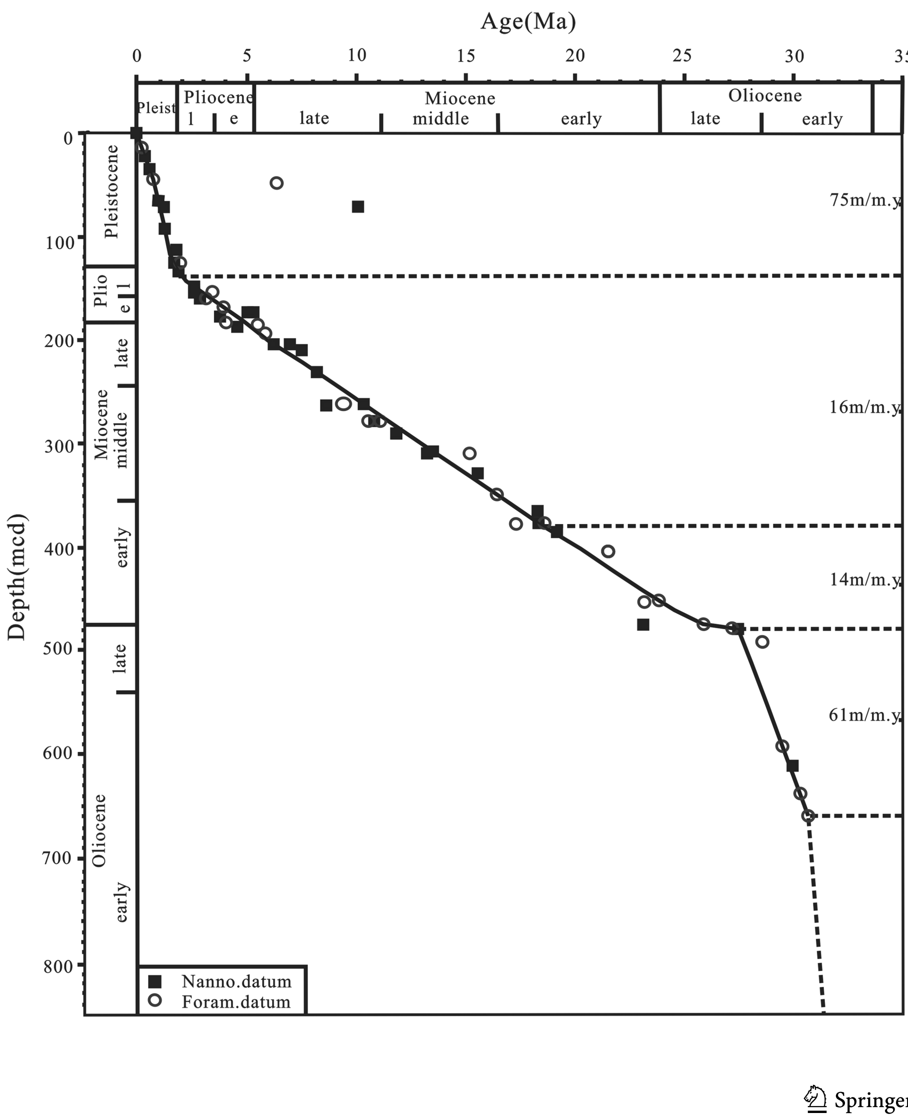


Fig. 5 Age-depth plot for site 1148 (Wang et al. 2000)

7 The type of the basin

7.1 The silled basins

In a silled embayment, the dissolved oxygen is commonly depleted below the sill-depth of the water column. This is due to the fact that the sill prevents the horizontal circulation of water outside the embayment from moving into the embayment, thus enhancing water stratification. Vertical currents may be prevented from moving into the bottom water by persistent density-stratification of the water-mass, which is apt to form an anoxic environment of the bottom water, which is beneficial for the enrichment of the organic matter (Fig. 6). Basins with a positive-water-balance can act as nutrient traps, which enhance both the productivity and preservation of organic matter. A typical example of an anoxic landlocked basin with a positive-water-balance is the Black Sea, the largest anoxic land-locked basin in the world. Mediterranean Sea water of 38.5 ‰ salinity flows into the Black Sea, and mixes with the Black Sea water. The mixed water, which has approximately 22 ‰ salinity, sinks into the deep water and becomes anoxic water mass, so that the Black Sea contains little dissolved oxygen below the water depth 150 m. It is therefore favorable for the preservation of organic matter.

7.2 The open ocean

Modern source sediments are accumulating in unrestricted basins in shelves, slopes, rises, and on abyssal plains. Ancient source sediments of this type also formed in such areas mentioned above, buy they also formed in epeiric

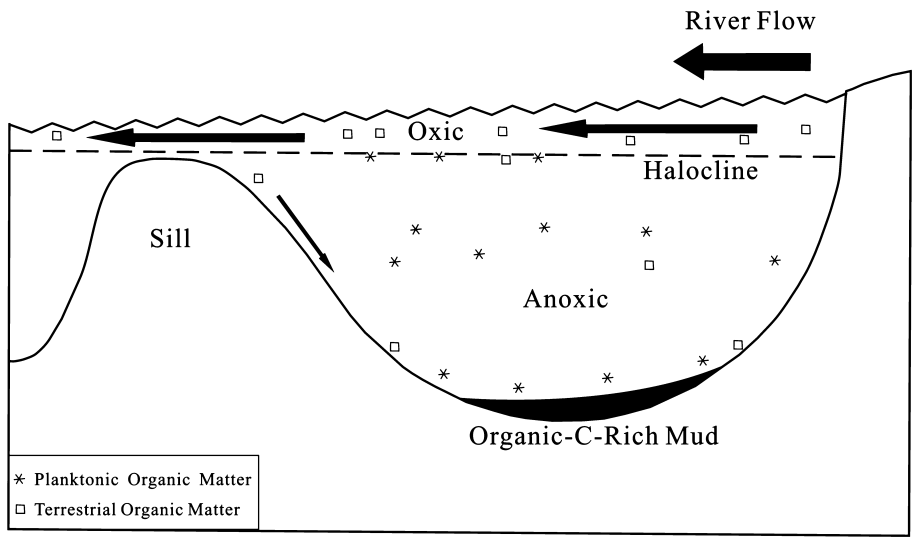


Fig. 6 The enrichment model of organic matter of anoxic silled basin

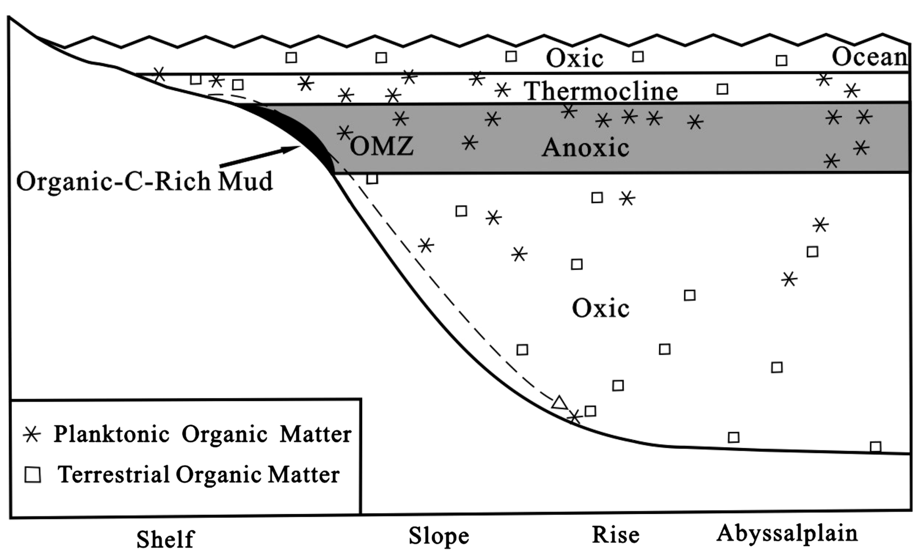


Fig. 7 The enrichment model of organic matter of the open ocean

seas. Large volumes of anoxic water do exist in the oxygen minimum layers of open oceans, such as the Indian Ocean. The organic matter in open oceans commonly enriches in the oxygen minimum layers where the water mass is anoxic, rather than in the other zones (Fig. 7). Below the oxygen-minimum zone of the oceans, the concentration of dissolved oxygen increases rapidly until it approaches saturation. This oxygenated water in the deep sea is derived from polar seas. Therefore the oxygen-minimum zone with anoxic environment is the best area to formation of source sediments.

8 Conclusions

(1) Paleoclimate change plays an important role in the formation of marine source rocks. The main paleoclimate factors include temperature, rainfall, and wind. The favorable climate conditions include humid subtropical and tropical climates. Upwellings formed by wind lead to high biological productivity and favorable preservation conditions of organic matter, which is significant in the formation of marine excellent source rocks.

(2) High biologic productivity is a requirement in the enrichment of organic matter in a marine environment. Source rocks with high organic matter abundance commonly develop in the high biological productivity zone.

(3) Terrestrial organic matter is an important origin in continental margin basins, where high quality source rocks often formed when there big rivers or delta developed.

(4) An anoxic environment is favorable for organic matter accumulation and preservation in depositing and the early diagenesis stage, while the relative oxygenated environment is not. As a result, the relative anoxic environment is an important element for the formation of excellent marine source rocks.

(5) Sedimentation rate also influences the enrichment of organic matter. It can be easily diluted by a mass of inorganic particles when sedimentation rate is too fast, leading to the reduction of organic matter in sediments. On the contrary, if the deposition rate is too slow, organic matter can be gradually consumed by oxygen in the water column, resulting in the decrease of organic matter in sedimentary rocks. Therefore, suitable sedimentation rate is beneficial for the formation of organic-rich source rocks.

(6) The type of the basin also plays an important role in development of marine source rocks. Silled basins with a positive water balance often act as nutrient traps, thus enhancing both the productivity and preservation of organic matter, while in open oceans, organic matter enrichment in sediments is commonly found in the oxygen minimum layers.

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References

Burnett WC, Roe KK, Piper DZ (1983) Upwelling and phosphorite formation in the ocean. In: Suess E, Thiede J (eds) Coastal upwelling: its sediment record, Part A. Plenum Press, New York, pp 377–397

Calvert SE (1987) Oceangraphic controls on the accumulation of organic matter in marine sediments. In: Brook J, Fleet AJ (eds) Marine petroleum source rock. Blackwell, London, pp 137–151

Calvert SE, Pedersen TF (1992) Organic carbon accumulation and preservation in marine sediments: how important is anoxia? In: Whelan JK, Farrington JW (eds) Productivity, accumulation and preservation of organic matter in recent and ancient sediments. Columbia University Press, New York, pp 231–263

Calvert SE, Price NB (1971) Upwelling and nutrient regeneration in the Benguela current, October 1971. Deep-Sea Res 18:505–523

Calvert SE, Pedersen TF, Naidu PD, von Stackelberg U (1995) On the organic carbon maximum on the continental slope of the eastern Arabian Sea. J Mar Res 53:269–296

de Graciansky PC, Deroo G, Herbin JP, Montadert L, Müller C, Schaaf A, Sigal J (1984) Ocean-wide stagnation episode in the Late Cretaceous. Nature 308:346–349

Degens ET, Ross DA (eds) (1974) The Black Sea—geology, chemistry and biology. American Association of Petroleum Geologists Mem, vol 20, p 633

Deng Y (2012) River-gulf system—the major location of marine source rock formation. Pet Sci 9:281–289

Dymond J, Suess E, Lyle L (1992) Barium in deep-sea sediment: a geochemical proxy for paleoproductivity. Paleoceanography 7:163–181

Francois R, Honjo S, Manganini SJ, Ravizza GE (1995) Biogenic barium fluxes to the deep sea: implications for paleoproductivity reconstruction. Global Biogeochem Cycles 9:289–303

Grasshoff K (1975) The hydrochemistry of landlocked basins and fjords. In: Riley JP, Skirrow J (eds) Chemical oceanography, 2nd edn. Academic Press, New York, pp 456–597

Gross MG, Carey AG, Fowler GA, Kulm LD (1972) Distribution of organic carbon in surface sediment, Northeast Pacific Ocean. In: Pruter AT, Alverson DL (eds) The Columbia River Estuary and adjacent ocean waters: bioenvironmental studies. University of Washington Press, Seattle, pp 254–264

Ibach LEJ (1982) Relationship between sedimentation rate and total organic carbon content in ancient marine sediments. AAPG Bull 66:170–188

Chen J, Zhang S, Sun S, Wu Q (2006) Main factors influencing marine carbonate source rock formation. Acta Geol Sin 80:467–472 (in Chinese with English abstract)

Li W, Zhang Z, Li Y, Liu C, Fu N (2013) The main controlling factors and developmental models of Oligocene source rocks in the

Qiongdongnan Basin, northern South China Sea. Pet Sci 10:161–170

Murray RW, Leinen M (1996) Scavenged excess Al and its relationship to bulk Ti in biogenic sediment from the central equatorial Pacific Ocean. Geochim Cosmochim Acta 60:3869–3878

Paytan A, Kastner M, Chavez FP (1996) Glacial to interglacial fluctuations in productivity in the Equatorial Pacific as indicated by marine barite. Science 274:1355–1357

Pedersen TF, Calvert SE (1990) Anoxia vs Productivity: what controls the formation of organic-carbon-rich sediments and sedimentary rock? AAPG Bull 74:454–466

Stackelberg VU (1972) Faziesverteilung in Sedimentendes Indisch–Pakistanischen Kontinentalrandes (Arabisches Meer.): 'Meteor' Forschungsergeb., Reihe C, 1–73

Suess E, Thiede J (1983) Introduction. In: Suess E, Thiede J (eds) Coastal upwelling: sediment record, Part A. Plenum Press, New York, pp 1–10

Tenger, Liu W, Xu Y, Chen J (2005) Correlative study on parameters of inorganic geochemistry and hydrocarbon source rocks formative environment. Adv Earth Sci 20:193–200 (in Chinese with English abstract)

Tyson RV (1987a) The genesis and palynofacies characteristics of marine petroleum source rocks. In: Brooks J, Fleet AJ (eds) Marine petroleum source rocks, vol 26. Geological Society of London Special Publication, London, pp 47–67

Tyson RV (1987b) The genesis and palynofacies characteristics of marine petroleum source rocks. In: Brooks J, Fleet AJ (eds) Marine petroleum source rocks **26**. Geological Society of London Special Publication, London, pp 251–261

Tyson RV, Pearson TH (1991) Modern and ancient continental shelf anoxia: an overview. In: Tyson RV, Pearson TH (eds) Modern and ancient continental shelf anoxia **58**. Geological Society of London Special Publication, London, pp 1–24

Van Andel TH (1964) Recent marine sediments of Gulf of California. In: van Andel TH, Shor GG (eds) Marine geology of the Gulf of California. American Association of Petroleum Geologists, Tulsa, pp 216–310

Wang P, Prell WL, Blum P (2000) Proceedings of the Ocean Drilling Program, Initial Reports volume 184