

GEOCHEMICAL FEATURES AND GENETIC MECHANISM OF DEEP-WATER SOURCE ROCKS IN THE SENEGAL BASIN, WEST AFRICA

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Abstract: This paper discusses the maturity of source rocks of the Senegal basin through basin simulation, so as to get a better understanding of oil–source correlation. Based on the analysis of pyrolysis chromatography and TOC data of core samples taken from 11 wells, the model of Cenomanian–Turonian marine sediment-organic facies was established, and the genetic mechanism of high-quality source rocks was clarified. The results show that source rocks in the Senegal Basin may occur in the Aptian–Albian of Lower Cretaceous and Cenomanian–Turonian of Upper Cretaceous. One is hybrid organic facies in the shallow carbonate platforms in the shelf area and is characterized by moderate to high TOC (<3%) and HI (100–400 mg HC/g). The other is well-preserved marine facies in continental slope to abyssal sea, with high TOC (>3%) and high HI (max 900 mg HC/g TOC). Molecular fossils originating from aryl carotene are the indicator of the existence of euphotic zone in the ancient ocean. The compounds of aryl isoprenes and sulfurous aryl isoprenes are detected in the black shale samples of well DSDP 367. They rooted in photosynthetic green sulfur bacteria and the carbon isotope value of these compounds is higher 10‰–15‰ than those of fossil molecules of algae and cyanobacteria. Two packages of oil-prone source rocks separately occur in the Aptian–Albian of Lower Cretaceous and Cenomanian–Turonian of Upper Cretaceous. High-graded marine source rocks of the Senegal Basin may occur in a sulfurous, anoxic deep-water environment with sufficient carbon sequestration.

Key words: Marine source rocks, Organic facies, Oil–source correlation, Anoxic environment, Oxygen minimum zone (OMZ), Carbon-storage efficiency

1. Introduction

The Senegal Basin is located in the middle of the northwest coast of Africa (Figure 1) and is the part of the Mauritania-Senegal-Guinea-Bissau (MSGB) super basin, belongs to a huge passive continental margin basin. The Senegal Basin extends southward from Mauritania to Guinea. Most of the basin, about 95 000 km², occurs within Senegal. Its evolution experienced three episodes, i.e. pre-rifting, rifting, and drifting (Figure 2).

Formations between Precambrian and Devonian are mainly composed of continental clastic rocks, and deposited in the pre-rifting episode (Figure 2), their formation thickness exceeds 5 000 m through interpreted seismic data. Gypsiferous salt rocks were deposited in the rifting episode and their

maximum thickness exceeds 2 000 m (Figure 2). The drifting episode witnessed the deposition of marine carbonate rocks as well as some shale and marl. Shale mainly during Cenomanian and Turonian in the Late Cretaceous is the major source rock in the basin due to its high organic matter content.

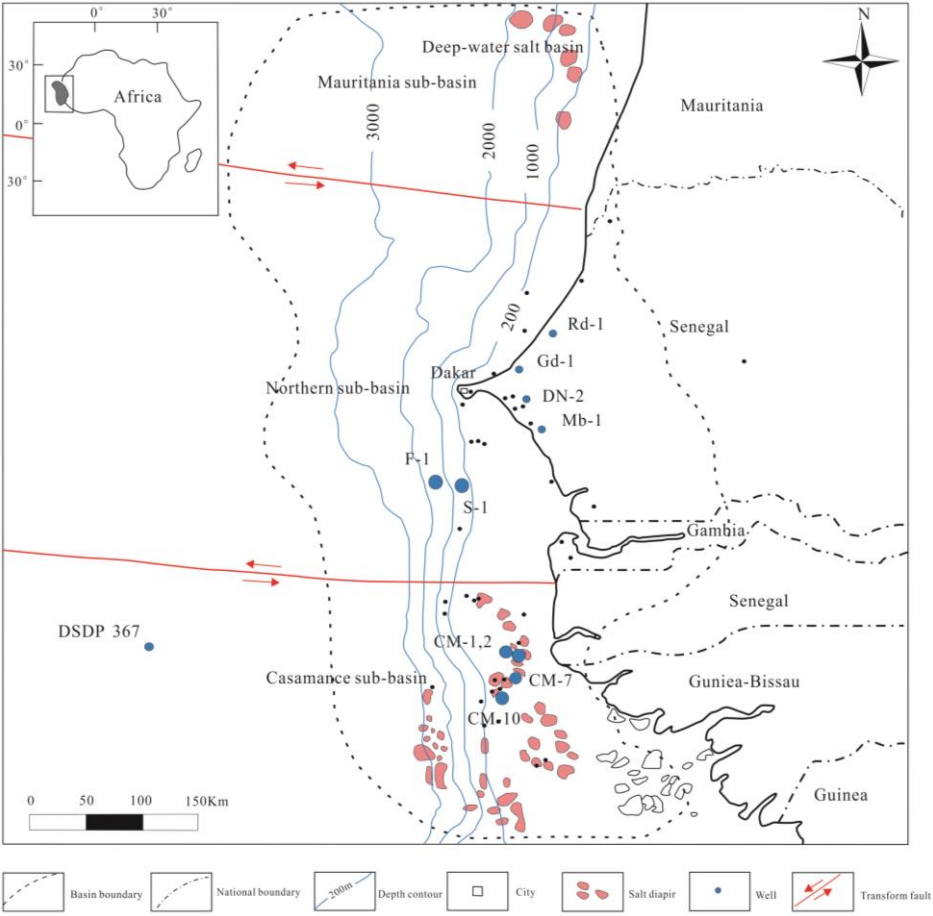


Fig.1 Geographical location and sampling well distribution of Senegal basin, West Africa

Petroleum exploration in the Senegal Basin began in the 1950s. Some small fields were discovered, but they have not been put into production due to small volume of reserves [1]. After low tide exploration for many years, some fields with commercial value were discovered in the deep-water plays in the past three years. Typically, the F and S oilfields were reported to have reserves up to 2.5 108 and 3.3 108 bbl respectively. Thus, petroleum exploration in the Senegal Basin may become promising. As per oil–source correlation, source rocks are high-graded and organic-enriched marine shale in the Cenomanian and Turonian; its TOC may reach 40% at most. A common view is that the enrichment of organic matter is dependent on anoxic preservation conditions and productivity, but which factor is dominant is under dispute. Schlanger and Jenkins (1976) proposed an idea of oceanic anoxic event (OAE), which indicates that the oxygen minimum zone (OMZ) expansion, induced by ocean current stagnation and insufficient oxygen supply at the ocean bottom, may give birth to an anoxic environment which is favorable for organic carbon preservation in the deep ocean [2]. This is the view point of preservation dominance caused by OAEs, but there were controversies about OAE origin and its progress. Later research findings on carbon isotope stratigraphy and paleontology indicated that the occurrence of black shale may be related to the positive anomalies of carbon isotopes in marine carbonate rocks [3], marine benthos extinction, and mass plankton replacement [4]. This implies that OAE corresponds to carbon pool transfer in the ocean and increased

productivity [5]. Black shale may be the product of improved productivity during a short period. This is the view point of productivity dominance.

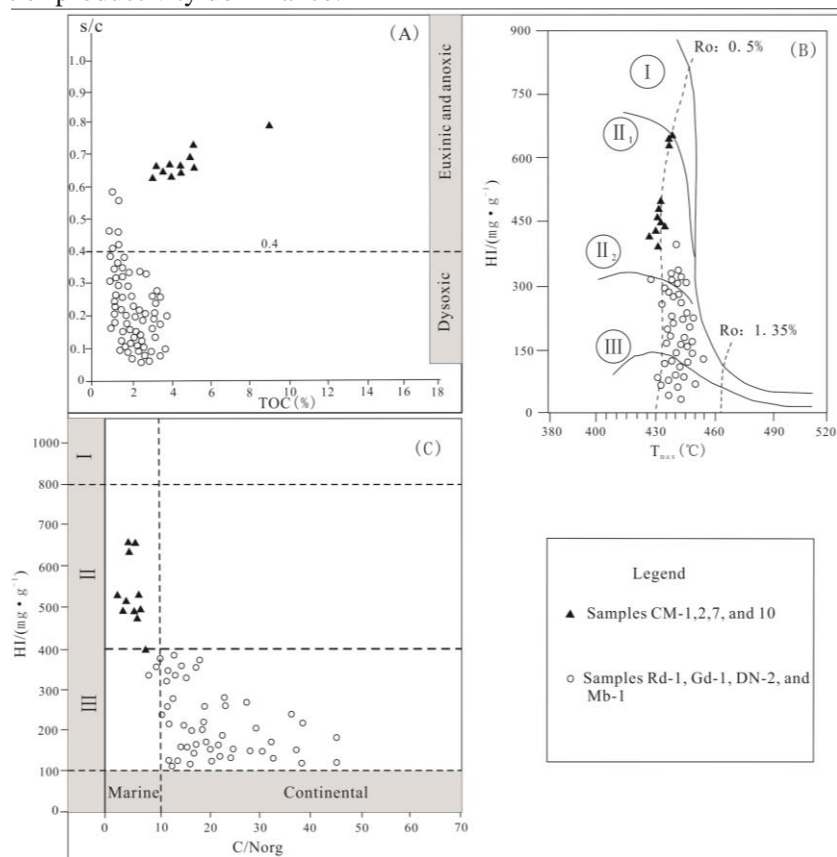


Fig. 2 Geochemical features of samples

The difference between these two points of view lies in that preservation dominance needs a nearly stagnant marine environment, while productivity dominance needs accelerated ocean current circulation, so that nutritive elements at the ocean bottom could be transported to the surface of the ocean to improve the productivity.

In spite of some breakthroughs in deep-water exploration in 2014, there is limited understanding of hydrocarbon origin and genetic mechanism. In this paper, gas chromatography, mass spectroscopy, and basin simulation were combined to investigate the oceanic productivity and preservation conditions in the Late Cretaceous Cenomanian to Turonian, from the perspective of organic geochemistry. The objective is to establish the controls of high-graded marine source rocks.

2. Materials

The study involves 11 wells, including Mb-1, DN-2, Rd-1, Gd-1, CM-1, CM-2, CM-7, CM-10, F-1, S-1, and DSDP 367 (Figure 1). The TOC and pyrolysis chromatography data of core samples were analyzed to examine the source features of organic matter.

Previous studies showed that the Cenomanian–Turonian formations were deposited in a shelf environment around Wells Mb-1, DN-2, Gd-1, and Rd-1 and in a bathyal environment around Wells CM-7 and CM-10 [12]. The absence of turbidite, existence of laminae, and low carbonate content in core samples from Well DSDP 367 indicate a typical abyssal sedimentary environment [13]. According to the analysis of source-rock properties in different geologic periods, it is concluded that source rocks in this basin may mainly occur in the Cretaceous; there are two packages of oil-prone

source rocks: one is the Lower Cretaceous Aptian–Albian shale and the other is in the Upper Cretaceous Cenomanian–Turonian shale.

With respect to C-T shelf samples (Mb-1, DN-2, Gd-1, and Rd-1) from the Senegal Basin, TOC is usually less than 3% and hydrogen index (HI) less than 300 mg HC/gTOC; the HI/OI curve [14] exhibits organic matter of type II2–III (Figure 2B); this implies terrestrial dominance [15]. As for C-T bathyal samples (CM-7 and CM-10), TOC is usually above 3% or even exceeds 8.7% (Figure 2A), and HI is over 300 mg HC/g or even up to 660 mg HC/g (Table 1); kerogen type is mainly type II (Figure 2B); this indicates hydrobiont dominance. As for abyssal samples (DSDP 367), TOC may reach 40% and HI ranges 300–900 mg HC/g TOC; kerogen type is mainly of type II (Table 1).

Table 1. Geochemical information of the Cenomanian–Turonian samples

Sample	Shelf environment	Sea area (CM-7) and bathyal (CM-10)	Abyssal (DSDP367)
Thickness /m	500–2050	300	150
Sedimentation rate /(cm/1000 a.)	10–22	3.3	0.1
TOC /%	<3	1.27–8.72	5–40
HI (mg/g)	<400	150–660	300–900
Kerogen type	II and III	II and some III	II
C/N	>10	<10	
S/C	<0.4	>0.4	
Tmax /°C	435–445	434–438	396–431
Ro /%	0.3–0.9	0.5–0.6	0.3

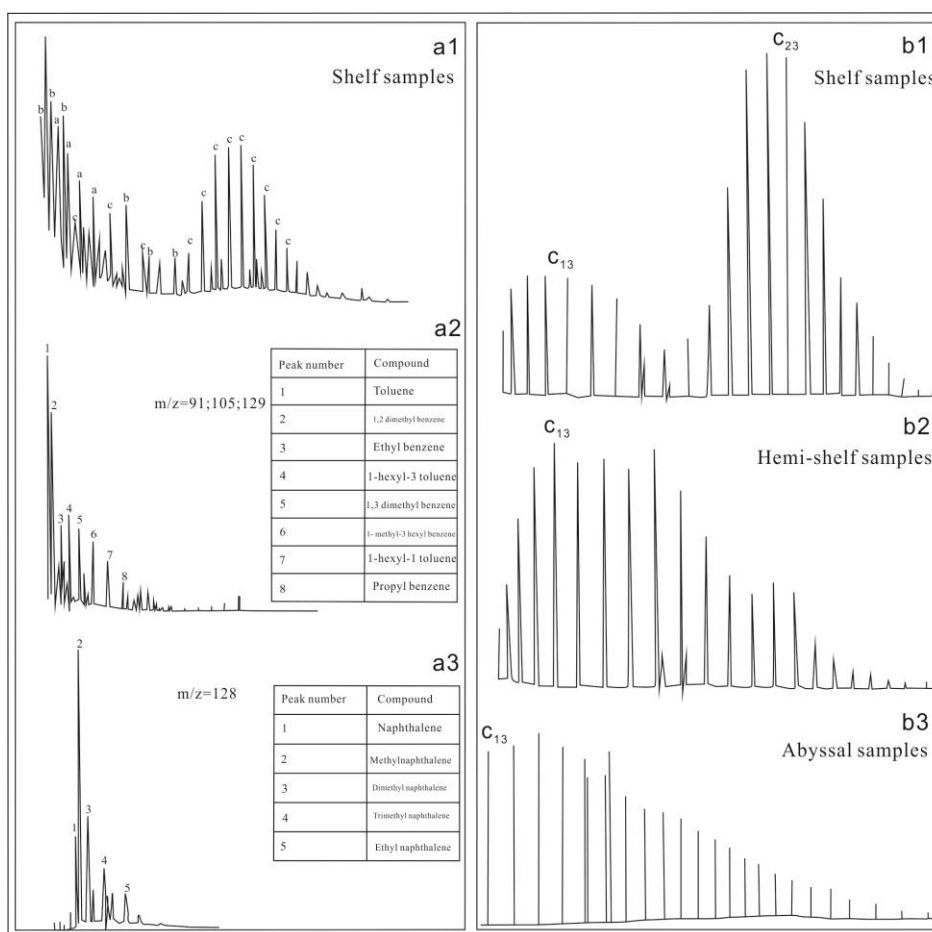
3. Methodology and Application

Pyrolysis chromatography is applied for compound analysis. As well basin simulation offers methods and means in order to solve sourcerock maturity distribution and oil–source correlation.

3.2. Pyrolysis chromatography

The main compounds of pyrolysis chromatography include alkyl benzene, normal alkanes and alkyl naphthalene, among them alkyl benzene is slightly dominant. Ethylbenzene is the dominant alkyl benzene compound, and is the result of the cyclization and further aromatization of the major chain liposomes (such as fatty acids and fatty alcohols).

C/N ratio of organic matter is also controlled by sedimentary environment. The ratio is usually larger than 10 for the samples from a shelf environment and smaller than 10 for the samples from a bathyal environment (Figure 2C). High C/N ratio indicates the origin of terrestrial organic matter; thus, it is inferred that the samples from a shelf environment witness high content of terrestrial organic matter. S/C ratio of organic matter indicates the oxidation reduction condition at deposition. The S/C ratio below 0.4 for shelf samples (Figure 3A) indicates moderate oxidation [16], and S/C above 0.4 for bathyal samples (Figure 3A) may imply an anoxic reducing environment. Shelf samples are mature enough to generate oil and bathyal samples are of low maturity (Figure 3B). In general, samples being investigated are of low to moderate maturity, which has a limited impact on organic matter. High to extremely high maturity has a large impact on the maturing degree, abundance and type of organic matter.



a) Arene gas chromatograms; b) N-alkane gas chromatograms

Figure 3. Pyrolysis gas chromatograms

The distribution of the normal alkanes is more regular in the Shelf and bathyal environment sediments samples. Namely deposition samples in the shelf environment present the bimodal distribution style, the former peak nC_{13} , the later peak nC_{23} , C_{23} - C_{29} and no obvious advantage of parity, reflects the mixing characteristics of terrestrial and Marine organic matter, and the results of the organic matter in the C/n value is consistent. On the contrary, the samples of the deep sea and the deep sea environment show a unimodal distribution, with the carbon number concentrated in C_{1-7} , it indicates that organic matter is mainly the source of Marine aquatic organisms.

In addition to alkylbenzenes, aromatic fractions also contain alkyl naphthalenes and some alkyl phenanthrenes. The occurrence of these compounds in shelf samples is also the evidence of terrestrial organic matter. Hopanoid compounds (C_{27} - C_{31}) detected in bathyal samples may denote the appearance of anaerobic bacteria in the sedimentary environment [17].

3.1. Basin Simulation

Basin simulation technology is applied to predict the maturity distribution of hydrocarbon source rocks, which provides a basis of oil and source rock correlation. Taken the measured temperature and vitrinite reflectance (R_o) of 7 actual Wells in the basin as constraint conditions, the lithospheric structure and the thermal evolution history of the present well point was simulated.

Based on thermal evolution history of 7 actual Wells and 19 virtual Wells, the correlation is established between the thermal evolution results and their depth maps of Turonian, Albian and Aptian strata, and the thermal history results were extrapolated to the entire basin.

The basin simulation results show that, as a whole the maturity of hydrocarbon source rocks on the central shelf of the basin is relatively low. However maturity varies greatly. The value in the northeast, southeast and deep water area is higher than others. The maturity of hydrocarbon source rock of Turonian top (Fig.4a) in the west deep-water area is in the immature - low mature stage, as well the maturity remains in the immature - low and high mature stage in the northeast and southwest area, even postmature for some areas. The hydrocarbon source rock of Albian top in the northern and southeastern parts enters mostly into mature and high mature stage (Fig. 4b), some areas into the postmature stage; Aptian source rock mostly in mature stage (Fig.4c), and the northeast and southwest rock is in the post-mature stage and mature area is further expanding.

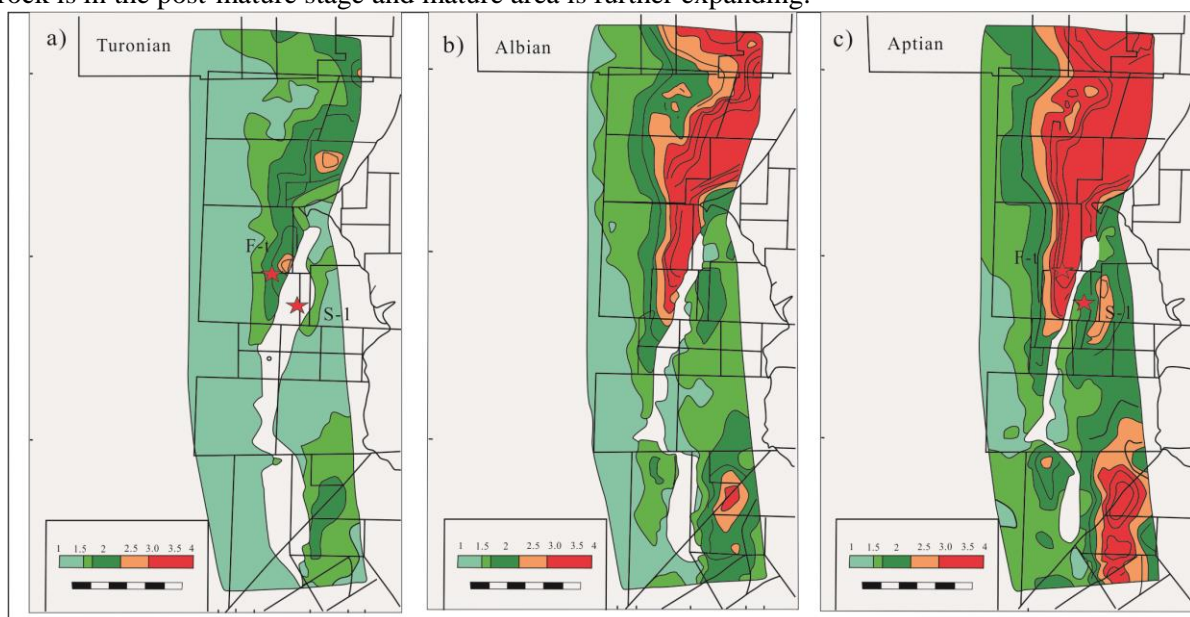


Fig. 4 Source rock maturity at the top of Turonian and Albian–Aptian in the deep-water area, the Senegal Basin

4. Discussion

Based on the above analysis, there are two issues to be discussed, including ancient productivity and organic matter preservation in the Late Cretaceous Cenomanian–Turonian. The source of nutrient should first be considered in productivity restoration. In general, the nutrient in the euphotic zone at the ocean surface originates from river import or upwelling. The former could be calculated using sedimentation rate [18]. The average sedimentation rate is 0.1 cm/1000a (Table 1) for C-T black shale deposited in the abyssal environment (DSDP 367) and 10-22 cm/ky (Table 1) in the shelf environment. Abyssal sedimentation presents small sedimentation rate and large organic matter richness, while shelf sedimentation shows large sedimentation rate and small organic matter richness. Thus, this mechanism could not be used to explain the genetic relationship of high-graded source rocks with large organic matter richness in the deep-water area, the Senegal Basin. Upwelling may also contribute to improved productivity of marine organisms. As per the simulation made by Kruijs and Barron (1990) [19], the upwelling rate at coastal Senegal was 20 cm/day (Figure 5) in the Late Cretaceous Cenomanian–Turonian. For a preservation factor of 2%, the primary productivity of the North Atlantic Ocean during this period is estimated to be 50 g C/(m²•a), which is higher than the value (20 g C/(m²•a)) in

the Kimmeridgian at the end of the Jurassic, but it is far less than the value of 200–360 g C/(m²•a) [20] in the regions with upwelling nowadays. It is thus inferred that the ancient productivity in the Late Cretaceous Cenomanian–Turonian may be insufficient to generate bathyal-abyssal organic-enriched shale.

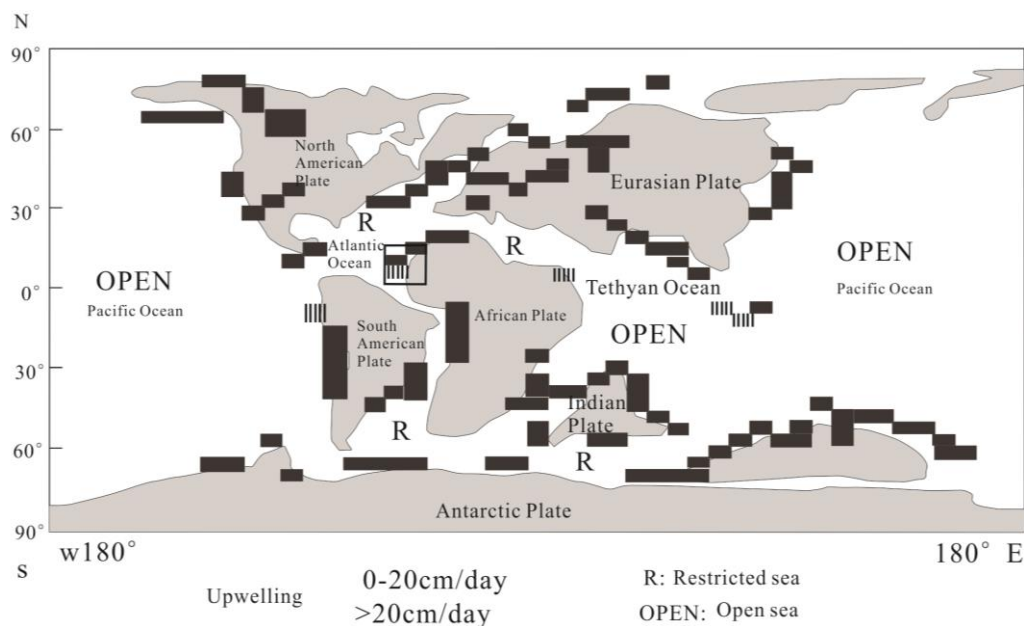


Fig. 5 Cenomanian–Turonian upwelling simulation [19]

Molecular fossils originated from aryl carotene and are the indicator of the existence of euphotic zone in the ancient ocean. Aryl isoprenes are the diagenetic product of photosynthetic green sulfur bacteria, which rely on light and sulfide to survive; thus, these compounds indicate an upper euphotic zone and lower anoxic environment in a still-water basin. Green sulfur bacteria absorbs CO² through reverse tricarboxylic acid cycle and their carotene content is slightly short of ¹³C in contrast to absorbed CO². Hence, molecular fossils of green sulfur bacteria are rich in ¹³C. Compared with organic matter of algae origin, their carbon isotopic value exhibits normal anomalies of 10-15‰ [24]. It is inferred that aryl isoprenes and sulfurous aryl isoprenes, which were detected in black shale samples from DSDP 367 (Figure 6) [25], may originate in photosynthetic green sulfur bacteria because of their positive carbon isotopic anomalies of 10–15‰ (Figure 6) compared with the molecular fossils of algae and cyanophyte. The existence of aryl isoprenes is the evidence of an anoxic still-water environment in the Senegal Basin in the Late Cretaceous Cenomanian–Turonian. Such an environment is favorable for organic matter preservation and carbon sequestration; this is the genetic basis of high-graded organic-enriched source rocks.

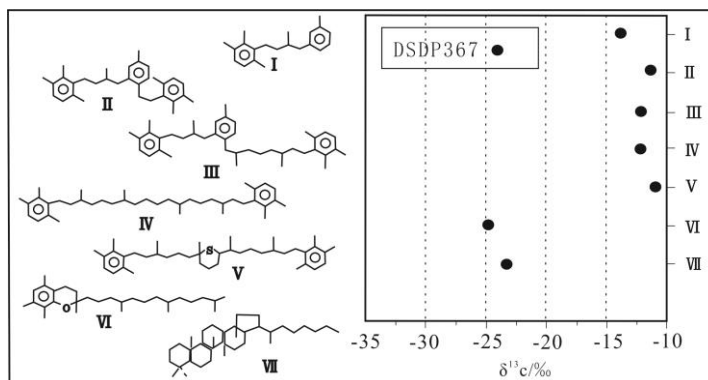


Fig. 6 Structures and stable carbon isotopes of aryl isoprenes in black shale samples from DSDP367

5. Results

There are two packages of oil-prone source rocks separately occurring in the Aptian–Albian of Lower Cretaceous and Cenomanian–Turonian of Upper Cretaceous; the latter is high-graded marine source rocks. Hybrid organic facies, with moderate to high TOC (<3%) and moderate to high HI (100–400 mg HC/gTOC), occur in shallow carbonate platforms in the shelf area. Well preserved marine organic facies, with high TOC (>3%) and high HI (of 900 mg HC/g at most), occurs from continental slope to abyssal sea. Molecular fossils originating from aryl carotene indicate the existence of euphotic zone in the ancient ocean. Aryl isoprenes and sulfurous aryl isoprenes were detected in black shale samples from DSDP 367. These compounds may come from photosynthetic green sulfur bacteria, and their carbon isotopes exhibit positive anomalies of 10-15‰ compared with the molecular fossils of algae and cyanophyte.

In accordance with above discussion about geochemical features, biomarkers, ancient productivity, and anoxic environment, a the model of ancient oceanogenic sedimentation and organic facies in the Cenomanian–Turonian is established (Fig. 7), and the genetic mechanism of high-graded source rocks was clarified. The model involves the controls and distribution of organic-enriched shale in the Senegal Basin. In the Late Cretaceous Cenomanian–Turonian, the shelf area lacked organic facies due to high sedimentation rate and high oxygen content in water; this made it hard for organic matter preservation and carbon sequestration. In contrast, abyssal and bathyal regions with low sedimentation rate had a better environment for organic matter preservation and carbon sequestration in OMZs. In conclusion, an anoxic environment is the major controlling factor of high-graded marine source rock.

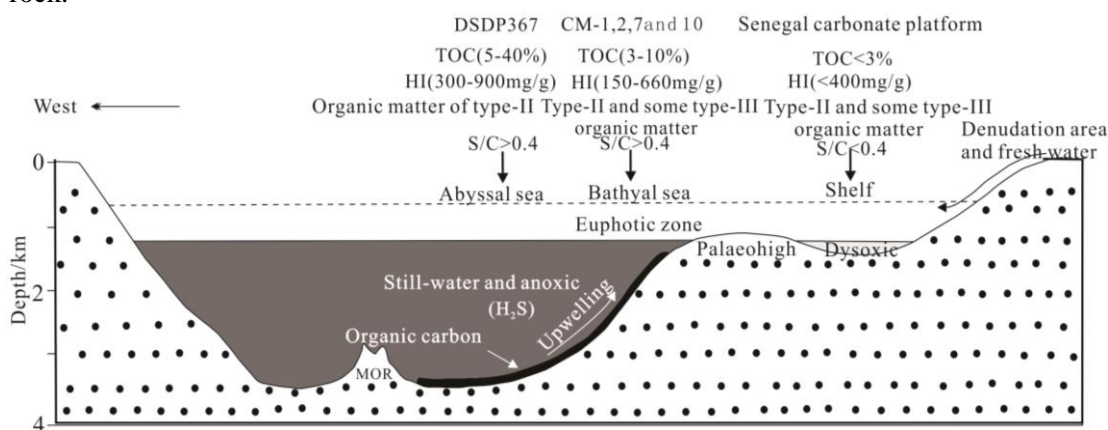


Fig. 7 Schematic model showing ancient oceanogenic sedimentation and organic facies in the Late Cretaceous Cenomanian–Turonian, the Senegal Basin

6. Conclusions

(1) There are two types of sedimentation and organic facies in the Senegal Basin. One is hybrid organic facies, with high richness and moderate to high TOC, in shallow carbonate platforms in the shelf area; organic matter may originate from aquatic organisms and terrestrial higher plants. The other is marine organic facies, with high richness and high HI, distributing from continental slope to abyssal sea, where high-graded marine source rocks may occur.

(2) In the deep-water area, crude oil accumulating in Albian and Turonian reservoirs may originate in the Aptian-Albian and Cenomanian–Turonian respectively.

(3) High-graded marine source rocks in the Senegal Basin may occur in a sulfurous, anoxic deep-water environment with sufficient carbon sequestration. An anoxic environment is the major control of high-graded marine source rocks in the Late Cretaceous Cenomanian–Turonian; this was validated by the pyrolytic chromatograms of molecular markers and stable carbon isotopes of aryl isoprenes. Compared with the Late Jurassic, the productivity also improved. In conclusion, the Cenomanian–Turonian formations have the advantages for organic matter enrichment.

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