

## Geochemical features and genetic mechanism of deep-water source rocks in the Senegal Basin, West Africa

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### Summary

The Senegal Basin is a passive margin salt-bearing basin with potentially large volume of petroleum resources on the west coast of Africa. Some deep-water fields with commercial value have been discovered since 2014, but hydrocarbon sources and genetic mechanism are still unclear. This paper discussed the maturity of source rocks of the 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 source of organic matter was analyzed, 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), suggesting moderate preservation condition. 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 were 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. There are two packages of oil-prone source rocks separately occurring 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.

### Theory / Method / Workflow

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. Source-rock maturity was simulated for oil–source correlation. Moreover, the model of ancient oceanogenic sedimentation and organic facies in the Cenomanian–Turonian was built, and the genetic mechanism of high-graded source rocks was clarified.

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.

Basin simulation technology is applied to predict the maturity distribution of hydrocarbon source rocks, which provides a basis of oil and source rock correlation. 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.

### Organic matter

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 II<sub>2</sub>–III (Figure 3B); 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 3A), 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 3B); 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).

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 3C). 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.

### Pyrolysis chromatography

The chromatograms of major pyrolytic products, including alkylbenzenes, N-alkanes, and alkylnaphthalenes, are shown in Figure 3a. Among alkylbenzenes which slightly dominate over the diagram, ethyl benzene is the major compound generated by the cyclization and aromatization of chain liposomes (e.g. fatty acid and fatty alcohol).

Figure 4b shows the chromatograms of N-alkanes from shelf and bathyal samples. These samples exhibit regular patterns. Shelf samples have a dual-peak pattern, i.e. a prepeak nC<sub>13</sub> and a postpeak nC<sub>23</sub>. There is no distinctive odd-even predominance within C<sub>23</sub>–C<sub>29</sub>; this indicates the hybrid origin of terrestrial and marine organic matter (Figure 4 b1). This result agrees with the conclusion based on C/N ratio. Bathyal and abyssal samples have a single-peak pattern, and carbon number concentrates within C<sub>12</sub>–C<sub>17</sub> (Figures 4 b2 and b3); this indicates the origin of marine organic matter.

## Results, Observations, Conclusions

Here, two issues are discussed, i.e. 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/(m<sup>2</sup>•a), which is higher than the value (20 g C/(m<sup>2</sup>•a)) in the Kimmeridgian at the end of the Jurassic, but it is far less than the value of 200–360 g C/(m<sup>2</sup>•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.

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 absorb CO<sub>2</sub> through reverse tricarboxylic acid cycle and their carotene content is slightly short of <sup>13</sup>C in contrast to absorbed CO<sub>2</sub>. Hence, molecular fossils of green sulfur bacteria are rich in <sup>13</sup>C. 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.

## Results

The Cretaceous is the major source formation in this basin. 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 model was established to delineate sedimentation and organic facies in the Late Cretaceous Cenomanian–Turonian (Figure 7). This 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.

## 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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