Paleoecologic and Organic Geochemical Assessment of Cretaceous Hydrocarbon Source Rocks in the Gulf of Guinea: New Insights from Eastern Dahomey and Benue Rift Basins with Implications for the Cenomanian-Coniacian Petroleum System*

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Abstract

An integration of foraminifera paleoecology and organic geochemical studies of shale samples from shallow onshore boreholes and a deepwater X well in the Eastern Dahomey Basin coupled with selected exploratory wells and exposed Cretaceous sections in the Benue Basins were carried out.

Black shales of the Afowo and Eze-Aku Formation (Cenomanian- Turonian) in the Dahomey and Lower Benue Basins respectively contain a large abundance of planktonic foraminifera e.g. Rotalipora greenhornesis, Hedbergella delyioensis, Heterohelix moremani, Heterohelix cenomana, Heterohelix globulosa, Hedbergella planispira, Whiteinella inonata, Praeglobotruncana sp.(?) and no significant benthic foraminifera. This assemblage was deposited under a deepwater, euxinic environment of the neritic to upper bathyal probably not deeper than 250 m. Paleogeographic interpretations indicate a northeasterly shoaling of marine conditions characterized by the dominance of benthic foraminifera e.g. Ammobaculites sp., Ammotium sp., Lenticulina sp. and Bolivina sp. in the time equivalent shales of the Yolde Formation (Upper Benue Basin).

Fifteen shales of the Afowo Formation from the deepwater well have Total Organic Carbon (TOC) contents from 0.62 to 2.31% (mean-1.07%), S2 values from 3.27 to 11.63 (mean-5.41), Hydrogen index (HI) values from 331 - 653 (mean-525), Vitrinite reflectance (Ro) of 0.68 to 0.95% and dominated by Type II oil prone kerogen. Ten outcrop samples of the Eze-Aku shales exhibited TOC from 3.05 to 5.47% (mean-4.07), S2 values from 8.4 to 21.2 (mean-13.9), HI range from 237 -387 (mean-333), Ro of 0.43 to

0.58 with a prevalence of Type II oil and gas prone assemblage. These contrast with the time equivalent shales of the Yolde Formation where thirty four samples from an exploratory Nasara well (TD-2,100 m) in the Upper Benue Basin exhibited TOC contents from 0.1 to 1.1% (mean-0.4%), S2 from 0.16 to 1.39 (mean -.43), HI values from 38-200 (mean-94), Ro of 0.64 to 0.77% and dominated by Type III gas prone kerogen. Burial history construction suggests maturity for these sequences since the Santonian age.

We conclude that the Cenomanian - Coniacian transgressive sequences in the Eastern Dahomey and the Lower Benue Basins have good to excellent quality source rocks related to the world wide Oceanic Anoxic Event - 2 (OAE 2) thus forming an integral element of the petroleum system of the regionally extensive coastal basins in the West African Gulf of Guinea.

Introduction

The Gulf of Guinea province consists of wrench-related coastal and offshore basins extending easterly from Cote d'I Voire, Ghana, Togo and Benin into the flanks of the Niger Delta Basin. The basins evolved from tectonism involving block and transform faulting during the breakup of African and South America. Basin evolution comprises of the intracratonic (pre-drift), synrift (or rift) and post rift (drift) stages resulting in east to west structural basins with the boundaries of each basin defined by the east – west transform fault systems (Figure 1). Previous reports suggest that the principal source rock for the Cretaceous Composite Total Petroleum System (TPS) in this region are Albian, Cenomanian and Turonian marine shales with Type II and Type II – III oil prone and Type III terrigenous kerogen (Brownfield and Charpentier, 2006). These source rocks include the Cenomanian to Turonian black shales related to the worldwide anoxic oceanic conditions and are thought to be confined to the Ivory Coast and Tano Basins whereas the Dahomey and Benin Basins are supposed to contain non-marine to marginal marine gas prone Type III successions. We have carried out foraminifera paleoecology and organic geochemical studies of shale samples from shallow onshore boreholes and a deepwater X well combined with selected exploratory well and exposed Cretaceous sections in the Eastern Dahomey and Benue Basins. The new results provide evidence for the extension of the Cenomanian – Coniacian marine black shales into the Dahomey Basin and at least to the Lower Benue Basin.

Regional Stratigraphic Setting

Cretaceous sediments in the Eastern Dahomey and Benue Basins consist of the basal fluviodeltaic to lacustrine sandstones, shales and minor carbonate rocks ranging in age from the Neocomian to Albian as the synrift successions (Figure 2). The syn-rift sequences consist of the continental Ise Formation in the Dahomey Basin forming the lateral equivalent of the fluviodeltaic to marine succession of the Asu River Group of the Benue Trough. These are overlain by post-rift (drift) marine Cenomanian to Coniacian Afowo Formation in the Dahomey Basin, a latent equivalent of the Eze-Aku /Yolde /Pindiga / Fika Formations in the Benue Basins (Figure 2). A period of non-deposition in the Santonian separated these successions from the overlying Campanian – Maastrichtian Araromi

Formation in the Dahomey and the equivalent Nkporo / Mamu /Gombe Formations in the Benue Basins before the growth of the Tertiary Niger Delta.

Methods of Study

About fifty-nine samples were investigated for foraminifera constituents, age relations and paleoecologic investigations and subjected to organic geochemical studies. Selected shale samples from the Afowo Formation, Eze-Aku Formation and Yolde Formation in the Dahomey, Lower Benue and Upper Benue Basins respectively were carefully processed for foraminifera investigation following the routine laboratory procedures. About 400 g of selected samples were disintegrated completely with 10% concentrated hydrogen peroxide, washed over a 0.063-mm sieve, and finally air-dried. The residues were picked for foraminifera. We followed the taxonomic concepts of Caron (1985) and Gebhardt (2004), Gebhardt et al. (2010) for planktic foraminifera and Petters, 1982 (for benthic foraminifera). After initial screening, the shale samples were subjected to detailed geochemical studies comprising the following:

a) TOC determination,
b) Vitrinite reflectance (VRo) determination and,
c) Rock-Eval Pyrolysis.

Results

Foraminifera Studies

The identified foraminifera consist of a large abundance (population and diversity) of planktonic foraminifera species including *Rotalipora greenhornensis*, *Hedbergella delrioensis*, *H. planispira*, *Heterohelix moremani*, *H. cenomana*, *H. globulosa*, *H. reussi*, *H. pulchra*, *H. striata*, *Whiteinella inonata*, *W. archaeocretacea*, *Praeglobotruncana sp*. and very sparse benthic foraminifera species in the shale samples e.g. few broken fragments of *Orthokarstina sp*.? and *Ammobaculites sp*? (Figure 3). Generally, the original shells of the fossils are already diagenetically altered / calcified. Some of the shale samples from the Lokpanta area (Lower Benue) contain fossil coccolithophores as coatings on the foraminifera texts suggesting symbiotic relationships. This assemblage signifies an euxinic environment of the neritic to upper bathyal marine water depth probably not deeper than ca. 250 m with significant high productivity of organic matter. This corresponds to zones of marine upwelling indicative of pronounced vertical mixing where vital minerals e.g. organic nutrients are most readily available. Paleogeographic interpretations along the depositional trend indicate a northeasterly shoaling of the marine conditions characterized with the dominance of benthic foraminifera e.g. *Ammobaculites coprolithiformis*, *Ammotium borunm*?, *Lenticulina olokuni* and *Bolivina sp*. in the time equivalent shales of the Yolde Formation of the Upper Benue Basin (Figure 3).

Rock-Eval Pyrolysis

TOC of fifteen shales of the Afowo Formation (Dahomey Basin) range from 0.62 to 2.31% averaging 1.07wt%; S1 yields range from 0.36 to1.48 mgHC/grock and S2 yields range from 3.27 to 11.63 averaging 5.41 mgHC/grock. Hydrogen Index (HI) values all exceed 300 ranging from 331 to 667 mgHC/gTOC averaging 525 mgHC/gTOC with a predominance of Type II oil prone kerogen (Figure 4). Vitrinite reflectance of the Afowo shales range from 0.68 to 0.95%.

Ten outcrop samples of the Eze-Aku Formation (Lower Benue) exhibited TOC values ranging from 3.05 to 5.47 wt% averaging 4.07wt%. S1 yields range from 0.36 to 5.31 mgHC/grock and S2 yields range from 8.37 to 21.15 averaging 13.89 mgHC/g rock. HI values all exceed 200 ranging from 237 to 387 mgHC/gTOC averaging 333 mgHC/g TOC indicative of Type II oil prone kerogen (Figure 4). A vitrinite reflectance range of 0.43 to 0.55% suggests marginal maturity for the Lokpanta shales at the outcrop level of sampling.

TOC values for thirty four shales of the Yolde Formation range from 0.1 to 1.1wt% averaging 0.4wt%, S1 yields range from 0.01 to 0.1 mgHC/g rock and S2 yields range from 0.16 to 1.39 mgHC/g rock averaging 0.43 mgHC/g rock. HI values of generally less than 200 ranging from 38 to 200 mgHC/g rock averaging 94 mgHC/g rock suggests the prevalence of Type III gas prone kerogen (Figure 4). Vitrinite reflectance (Ro) values range from 0.64 to 0.77% suggests marginal maturity to mature status for these shales with respect to hydrocarbon generation.

Discussion and Conclusions

Previous reports on hydrocarbon source rocks in the Gulf of Guinea have emphasized the middle Cretaceous worldwide anoxic oceanic conditions, which deposited black shale source rocks principally within the Ivory Coast and Tano Basins of this region (Brownfield and Charpentier, 2006). The Dahomey Embayment and Benin Basin are thought to contain nonmarine to marginal marine sediments in view of the structural partitioning of these basins from the thicker and larger Ivory Coast and Tano Basin (Chierici, 1996). Our current paleoecology and organic geochemical assessments of the Cenomanian to Coniacian sections in the Dahomey and Lower Benue Basins suggest that the shales of Afowo and Eze-Aku Formation are marine and characterized by the prevalence of Type II oil prone kerogen and are here considered as good to excellent quality source rocks related to the worldwide Oceanic Anoxic Event-2 (OAE 2).

The extension of the mid Cretaceous black shale deposition in the Gulf of Guinea (see Tissot et al., 1980) into the Benue Basin is revealed by the nature of the Lokpanta member of the Eze-Aku Formation previously considered as an “oil shale” with proven TOC

content above 7wt% at shallow depths (Ekweozor and Unomah, 1990). The time equivalent Yolde Formation in the Upper Benue Basin is organically lean and contain only moderate amount of Type III gas prone kerogen. The high diversity of the planktonic forms of foraminifera, coupled with extremely high P/B ratios of >90% for the Afowo and Lokpanta shales contrast with the dominance of benthic foraminifera in the time equivalent shales of the Yolde Formation. The Yolde Formation consists of interbeds of shales siltstones and calcareous mudstones and was interpreted as deposits of a nearshore marine environment (Akande et al., 1998). Paleogeographic interpretations of the current study indicate a northeasterly shoaling of marine conditions of the Oceanic Anoxic Event OAE-2 in the Benue Basin. The current study confirms that the Cenomanian – Coniacian transgressive sequences consisting of open marine oil-prone source rocks extends through the Eastern Dahomey Basin into the Lower Benue Basin thus enhancing the chances of hydrocarbon discoveries in Cretaceous targets of these Basins with the likely possibility of charging the adjacent Niger Delta Basin reservoir in the outboard areas. Associations of oil seeps and tar sand accumulations along Upper Cretaceous outcrops in the onshore Dahomey Basin correlates with similar occurrences in the Ivory Coast and Tano Basins and perhaps represent a part of the Cenomanian – Coniacian petroleum system.

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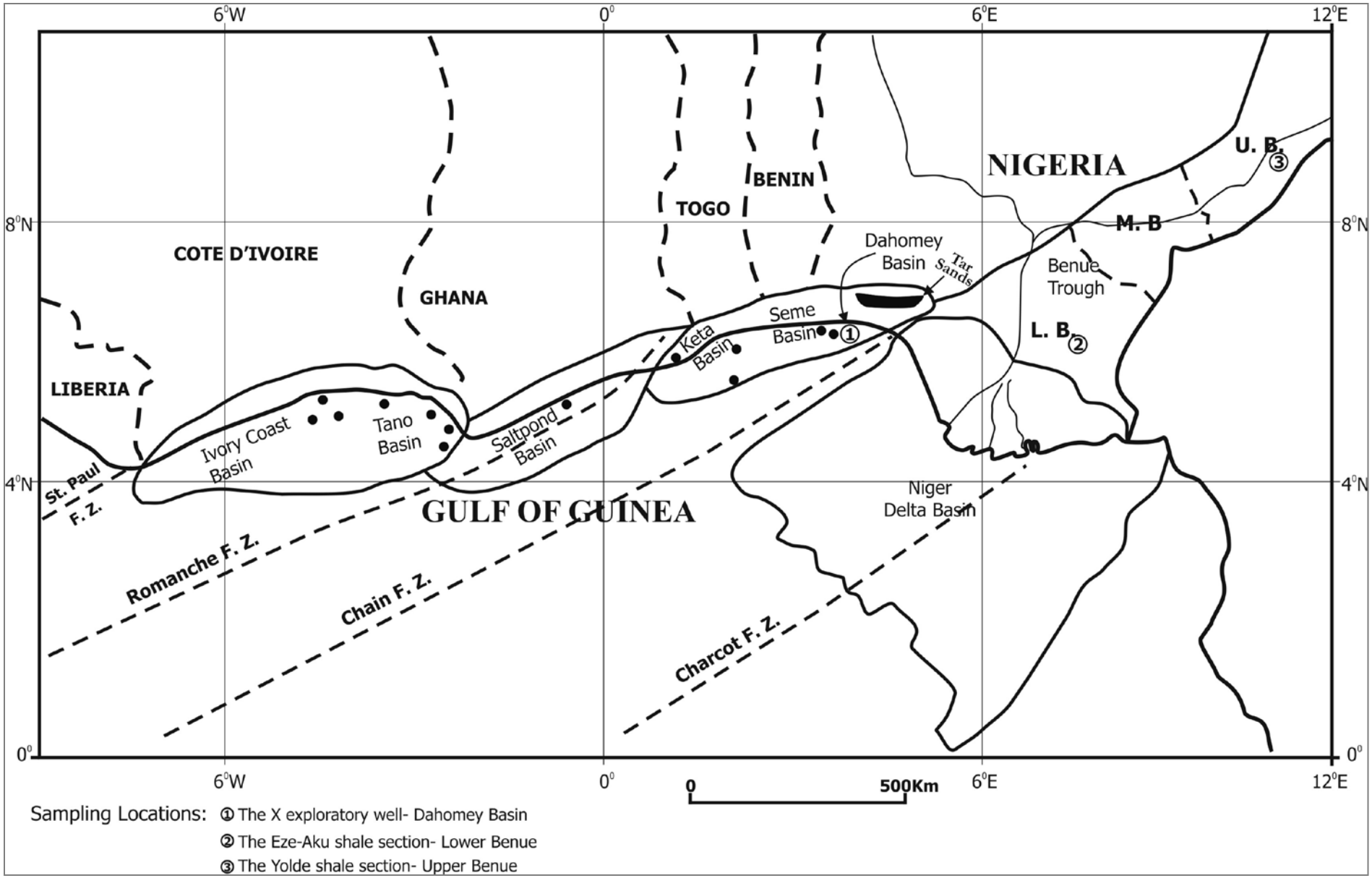

Figure 1. Major features of the Gulf of Guinea Basins showing the major fracture systems, basins outline and oil and gas discoveries. The tar sand belt of the Dahomey Basin is highlighted. Note the position of the Niger Delta maximum petroleum system and the Benue Trough L.B. - Lower Benue; M. B. - Middle Benue; U. B. - Upper Benue (modified after Kjemperud et al. 1992; and Persit et al. 2002).

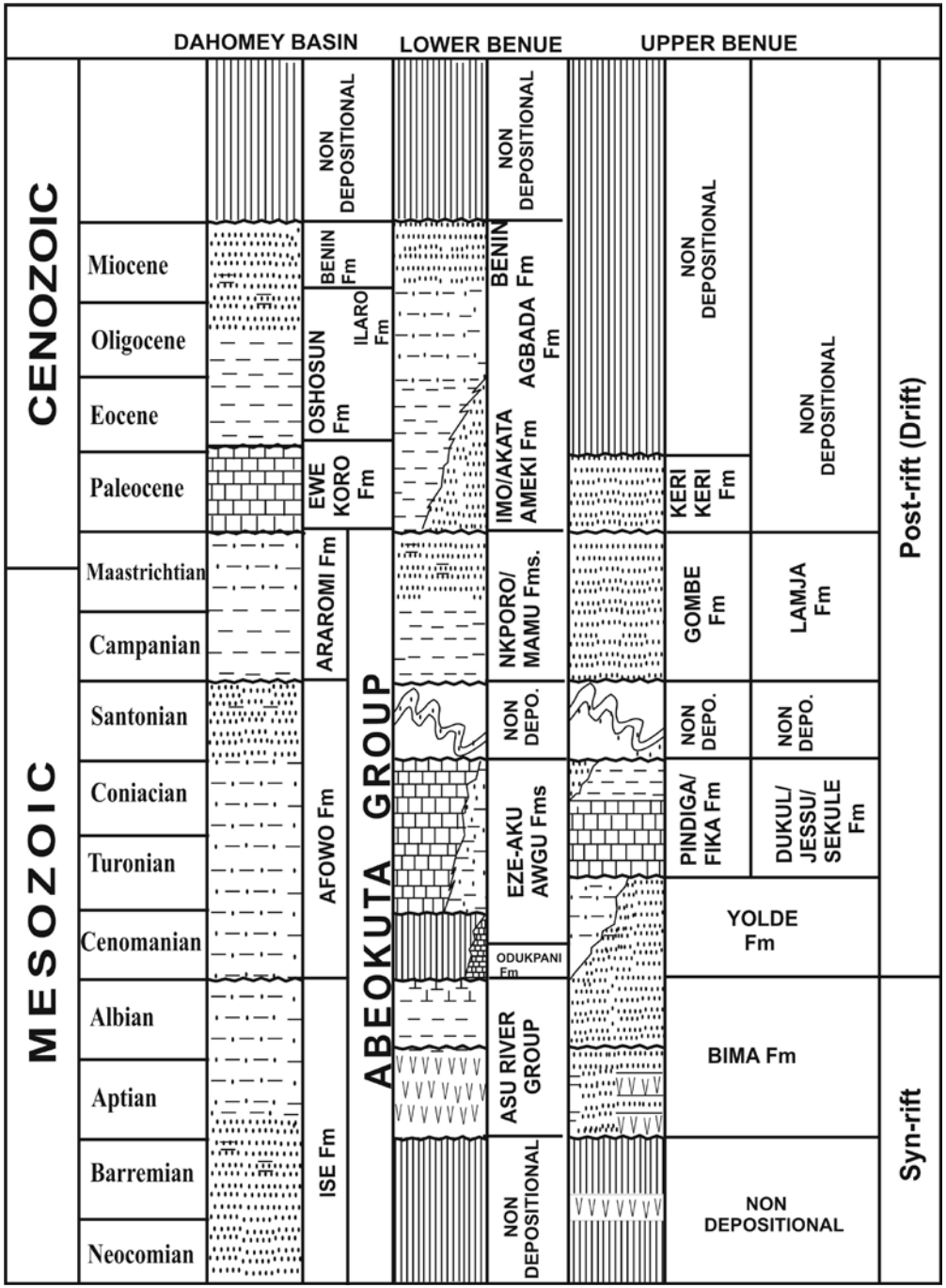

Figure 2. Generalized Stratigraphic Chart of the Eastern Dahomey, Benue Basins. (Modified after Akande et al., 2004).

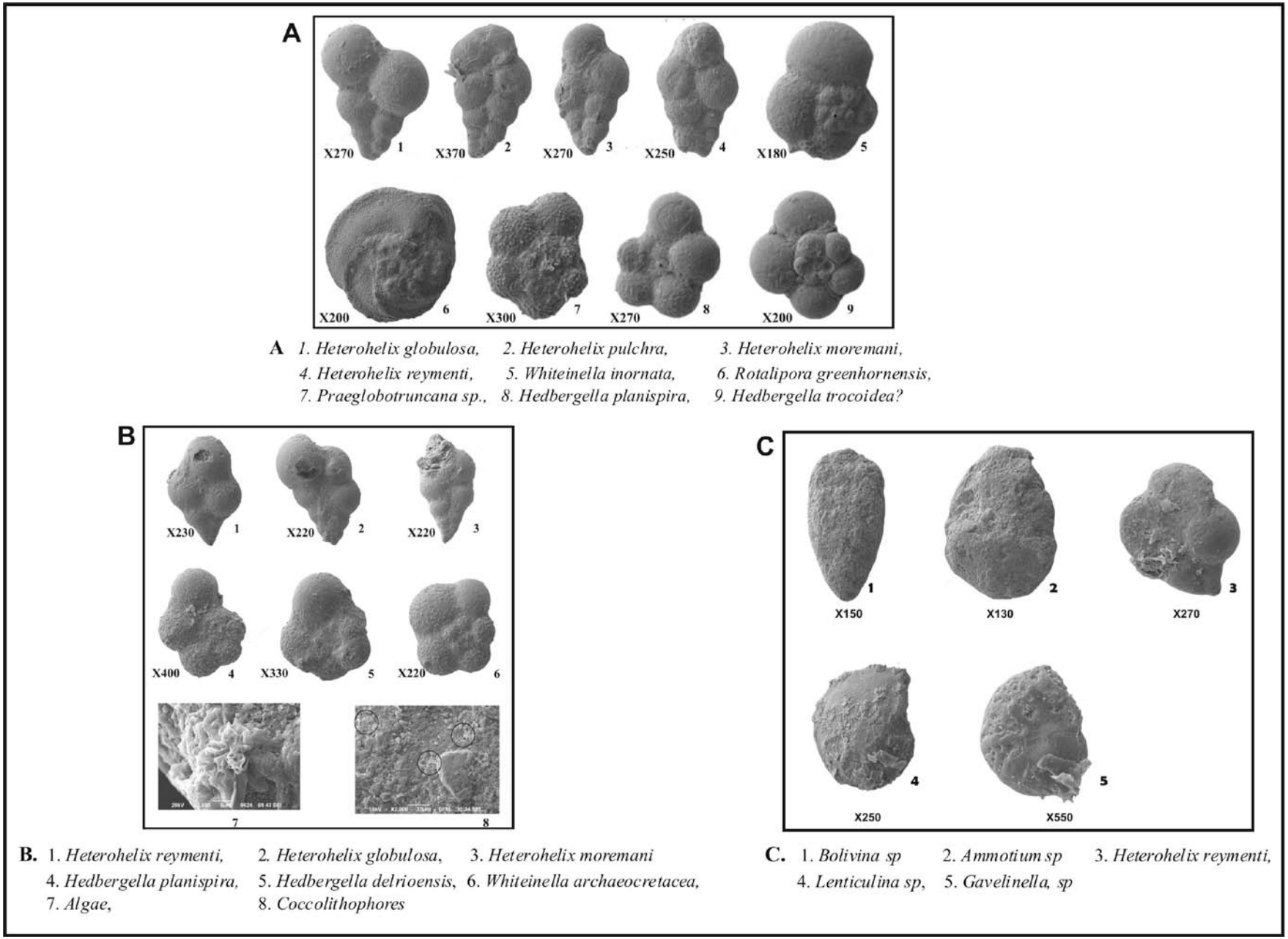

Figure 3. Photograph of Planktonic and Benthic foraminifera identified in (A) the Afowo Formation, Dahomey Basin (B) Eze-Aku Formation, Lower Benue Basin and (C) Yolde Formation, Upper Benue Basin.

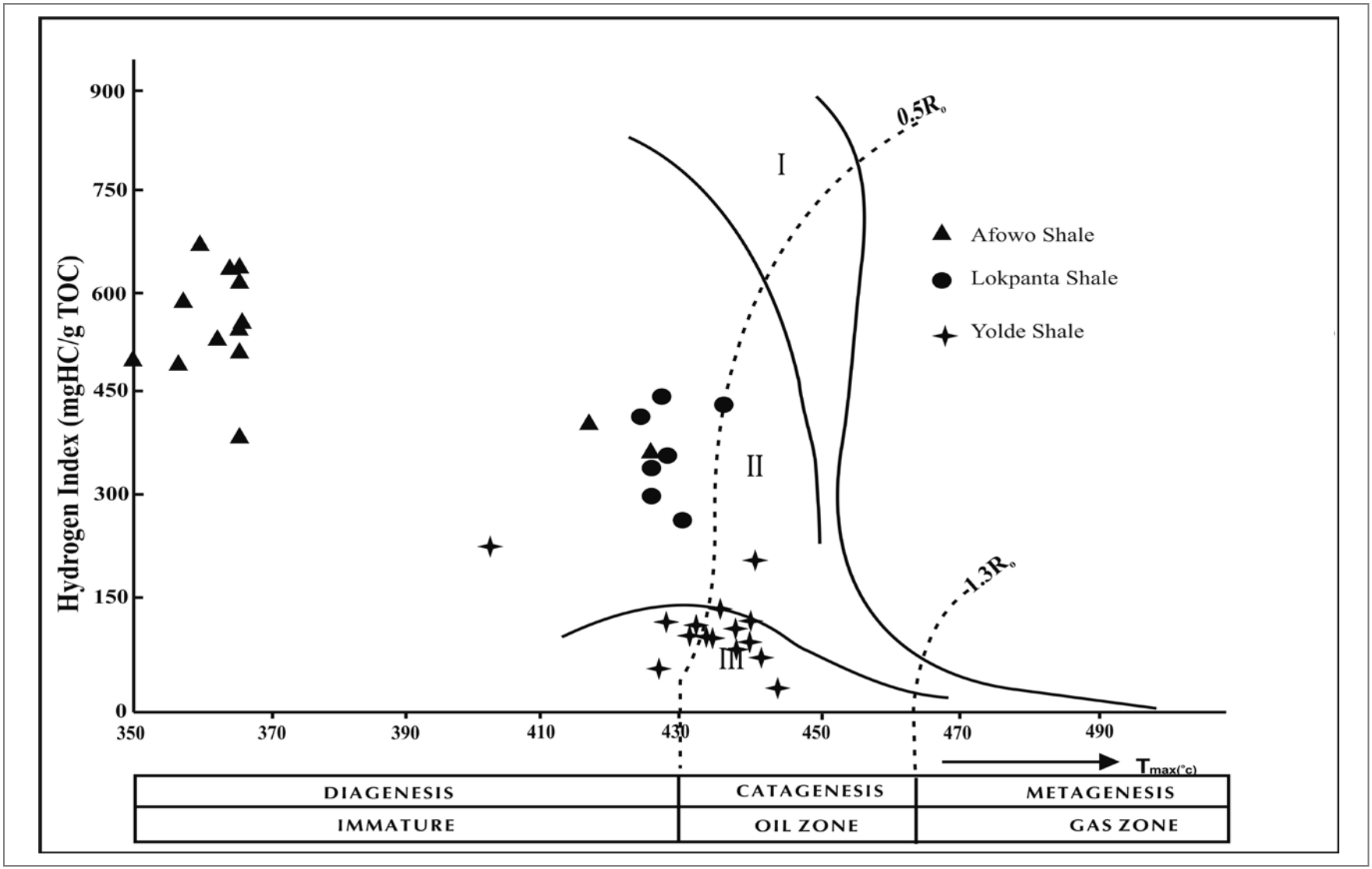

Figure 4. HI against Tmax (°C) diagram for the interpretation of kerogen types and maturity of the Afowo, Eze-Aku (Lokpanta) and Yolde shales. Lower Tmax values of the batch of Afowo shales reflect possible hydrocarbon entrapment.