HYDROCARBON SYSTEMS OF THE ABIDJAN MARGIN, COTE D'IVOIRE

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ABSTRACT

The Abidjan Margin, Côte d'Ivoire, has been the subject of exploration activity for forty years and has generated reasonable hydrocarbon success. From 1974-1992 the Espoir and Belier fields were produced with 31 mmbo and 20 mmbo of cumulative production respectively. More recently, several independent oil companies have come to the area to develop existing discoveries (Lion, Panthere, Gazelle, and Foxtrot), re-develop old fields (Espoir with 93 mmbo and 190 bcf of remaining recoverable reserves) and explore for new hydrocarbon traps.

This study has analysed source rock, maturity data and oil geochemistry from regional wells, to build a basin model and predict the hydrocarbon systems present in the Abidjan Margin. Analysis of source rock data from sixteen regional wells has allowed the identification of three potential hydrocarbon systems: Middle Albian gas prone source rocks; Upper Albian oil-prone source rocks; and Cenomanian / Turonian oil-prone source rocks. Maturity data (vitrinite reflectance and spore colouration) from nine regional wells have been used to calibrate 1-D burial history models and help constrain regional paleo-heatflows. Based on the results of the calibrated 1-D models, pseudo-wells were created in the basinal settings for the Jacqueville Trough (five pseudo-wells) and the Grand Bassam Sub-basin (eight pseudo-wells) using Platt River's 1D software package. This work allowed the oil-prone source kitchens to be defined in the shallow water and deep water off the Abidjan Margin. Oil geochemistry was performed (by Geomark) on seventeen oils from the Abidjan Margin. This oil geochemical data was re-interpreted by the authors and has been integrated into the present study.

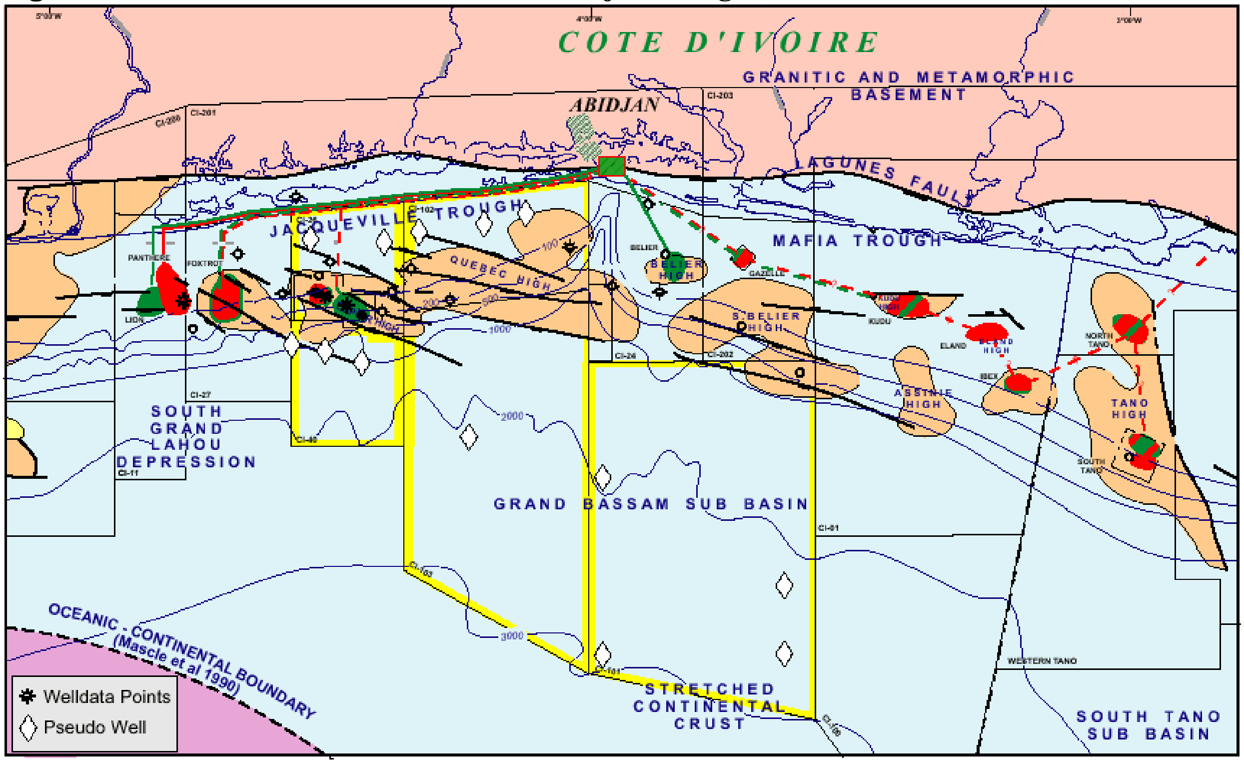
The work has indicated that there are likely to be three active hydrocarbon systems in the Côte D'Ivoire. Firstly, gas has been generated from disseminated carbonaceous material in the Middle Albian. Secondly, oil-prone claystones in the Upper Albian have generated oil in the Jacqueville Trough and Grand Bassam Sub-basin which have migrated along conduits above or below the break-up unconformity (Intra-Upper Albian 98Ma sequence boundary). Lastly, the Cenomanian / Turonian claystones have good source potential and are likely to have contributed hydrocarbons from the Grand Bassam Sub-basin but are immature in the Jacqueville Trough.

Oil and gas generated in the Jacqueville Trough and Grand Bassam Sub-basin will have migrated towards the inverted Top Albian highs, which characterise the Abidjan Margin (Grillot *et al.* 1991). A series of these inverted Albian highs are located in the Central Abidjan Margin (Lion, Foxtrot, Espoir and Quebec highs). The majority of the hydrocarbons discovered to date in the Abidjan Margin are trapped in Albian reservoirs within these Albian highs. Minor amounts of oil and gas have also been discovered in Upper Cenomanian sub-marine channels. These are partially stratigraphic traps but are often over pre-existing Albian highs and have probably benefited from migration up the break-up unconformity.

TECTONIC ELEMENTS AND GENERALISED STRATIGRAPHY

The Abidjan Margin shown in Figure 1 is predominantly an offshore basin running from the Côte d'Ivoire into Ghana. It is bounded to the east and west by major strike slip faults, the Romanche and St Paul's Fracture Zones respectively. To the north the basin is bounded by the Lagunes fault system made up of a series of east –west normal faults down-thrown to the south. To the south the basin is bounded by the continental-oceanic crustal boundary recognised by Mascle *et al* (1996).

Figure 1: Tectonic Elements of the Abidjan Margin, Côte d'Ivoire.

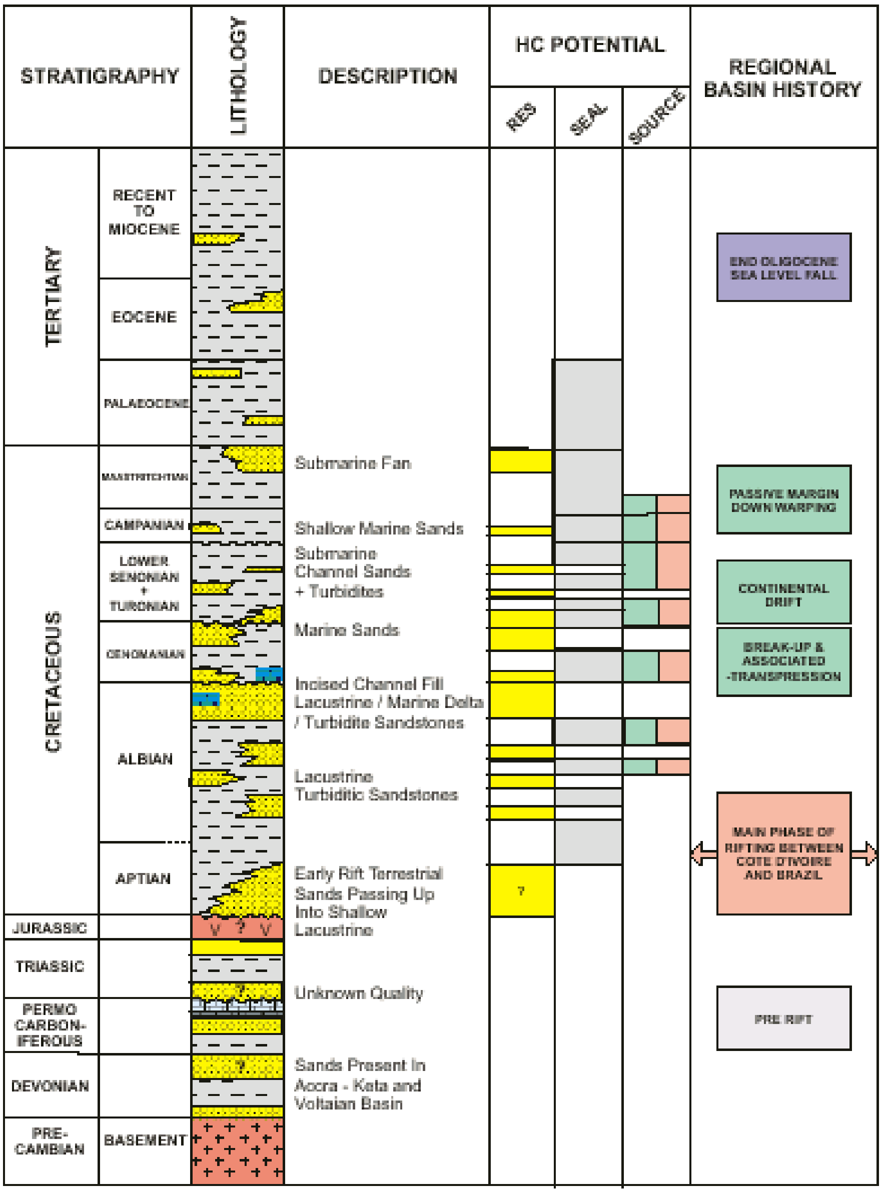


The basin is believed to have begun rifting in the early Aptian (or Barremian) times. Although the oldest rocks that penetrated offshore Côte d'Ivoire are of Lower Albian age, wells offshore Ghana have penetrated syn-rift Aptian stratigraphy as well as pre-rift Permian, Carboniferous and Devonian rocks. Continental break-up occurred at the end of the Albian, when a series of Albian highs were created which include the Foxtrot, Espoir and Quebec Highs. These highs are made up of numerous tilted fault blocks cut by faults trending westnorthwest-eastsoutheast. The highs are often bounded to the north by a series of en-echelon normal faults down-throwing into the Jacqueville Trough to the north. The highs are also bounded on their southern flank by a series of en-echelon faults down-throwing to the south into the Grand Bassam Sub-Basin.

The en-echelon nature of the Top Albian Highs, their faults and the potential offsets seen on the Lagunes Fault, implies that transfer zones may be present trending northeast-southwest and related to the major strike slip faults bounding the basin to the east and west (Romanche and St Paul's Fault Zones).

The generalised stratigraphy of the Abidjan Margin is shown in Figure 2 and includes the main hydrocarbon plays in the Albian and Upper Cretaceous identified offshore Côte d'Ivoire (Morrison *et al.* 1999, Chierici 1996 and Tucker 1992). Further speculative hydrocarbon plays exist in the Tertiary, lower syn-rift Early Albian-Aptian and pre-rift section. Pre-rift stratigraphy may include Devonian sandstones productive in the Saltpond Basin, as well as Permian and Carboniferous sands penetrated on the Tano High offshore Ghana. Rifting was initiated in the early Aptian and sands of this age are preserved on the Tano High offshore Ghana (Tucker 1992).

Figure 2: Generalised Stratigraphy of the Abidjan Margin, Côte d'Ivoire



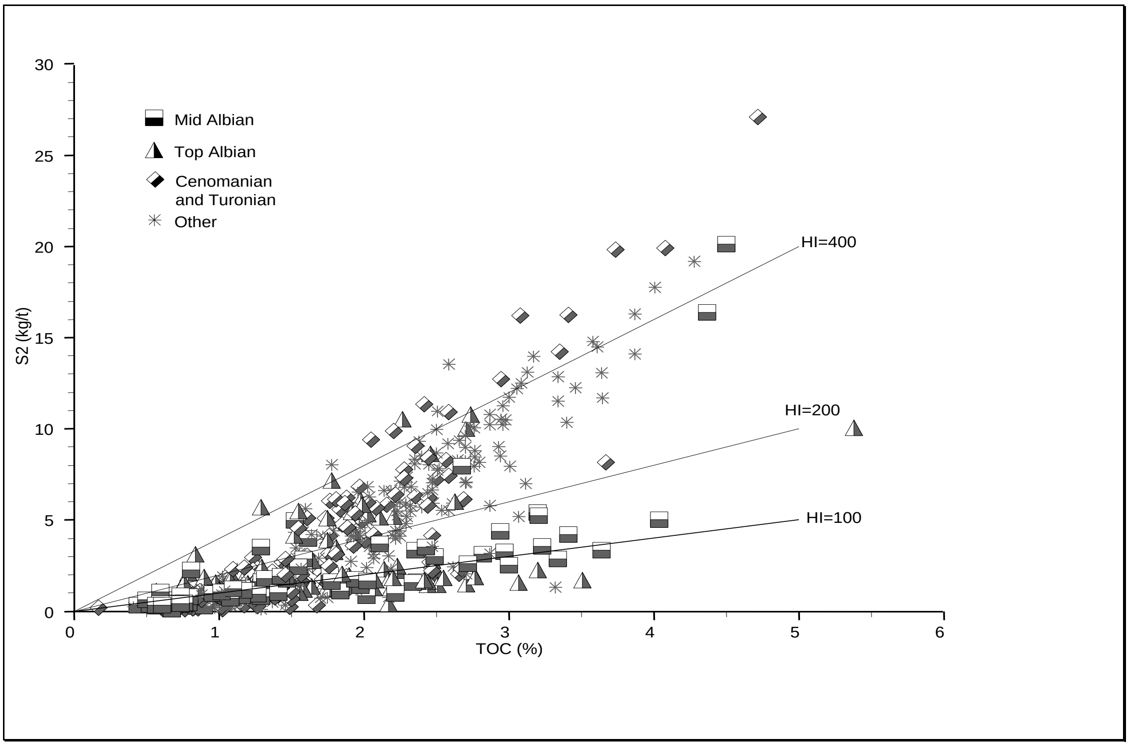
The oldest stratigraphy penetrated offshore Côte d'Ivoire are Lower Albian syn-rift sediments. During the Apto-Albian times the basin was enclosed resulting in the deposition of lacustrine claystones as well as turbidite and delta sandstone reservoirs. The Middle Albian turbidites comprise the reservoir in the Foxtrot gas field and Upper Albian turbidite/delta sandstones form the reservoir in the Espoir and Lion oil fields. After continental break-up at the end of the Albian, a series of delta and submarine fan systems deposited Upper Cretaceous sands across the Abidjan Margin. These include Cenomanian reservoirs (Panthere gas field), Lower Senonian reservoirs (Belier oil field), Campanian sands (B-3X gas/condensate discovery), and the Maastrichtian reservoirs (the Ibex and Lion fields).

Source rocks have been identified in the syn-rift Albian lacustrine shales and within multiple Upper Cretaceous marine claystones.

SOURCE ROCK POTENTIAL

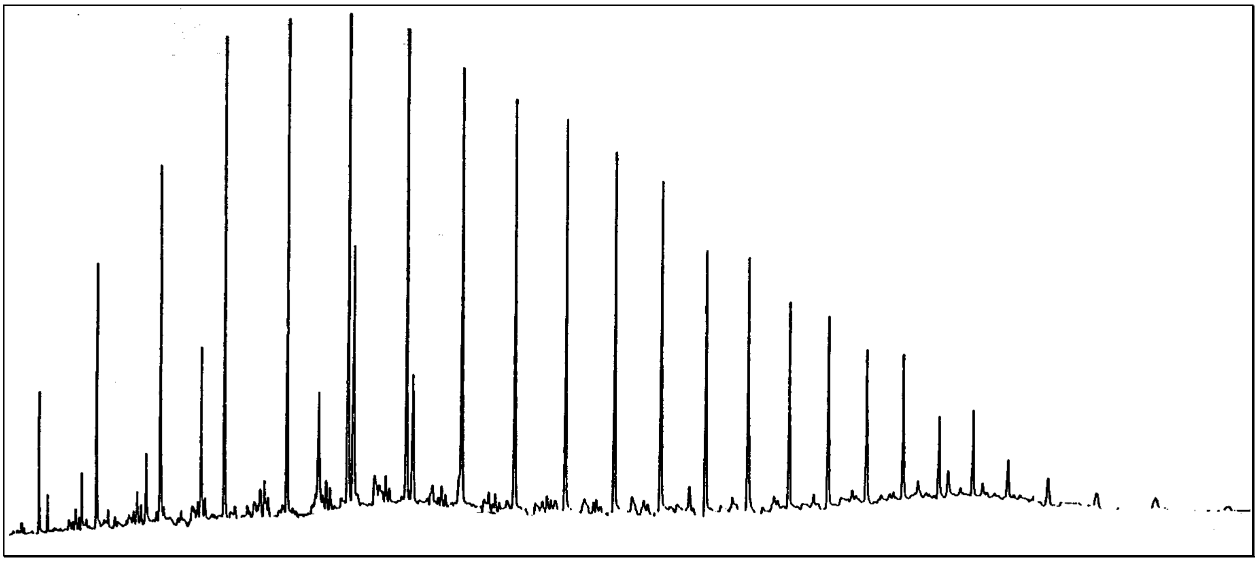
The identification of potential source rocks has been made primarily on the basis of Total Organic Carbon (TOC) content and Rock-Eval pyrolysis data, complemented with visual kerogen descriptions and some molecular geochemical data (gas chromatography). Emphasis is given to Albian to Turonian source rocks, as younger sediments are generally immature with respect to hydrocarbon generation, even within basinal depocentres. A summary of the total sample set is shown below in Figure 3.

Figure 3 Screening data (Total Organic Carbon content and Rock-Eval pyrolysate yield) for source rocks offshore Côte D'Ivoire



Middle Albian source rocks consist of thin oil prone beds interbedded with other poorer quality, gas prone shales, siltstones and sandstones. Much of the data are available for bulked composite cuttings that generally fail to identify these rich thin horizons. Selected picked lithologies, however, show good source rock potential with Hydrogen indices up to 450 mg HC/g TOC and generative potentials of up to 20 kg/tonne rock. The saturated hydrocarbon gas chromatogram of an extracted Middle Albian source rock is shown in Figure 4 and is characterised by a full suite of n-alkanes showing some odd carbon presence between nC25 and nC31 suggesting some terrestrial input. The pristane/phytane ratio of 1.99 would suggest deposition in a dysoxic environment.

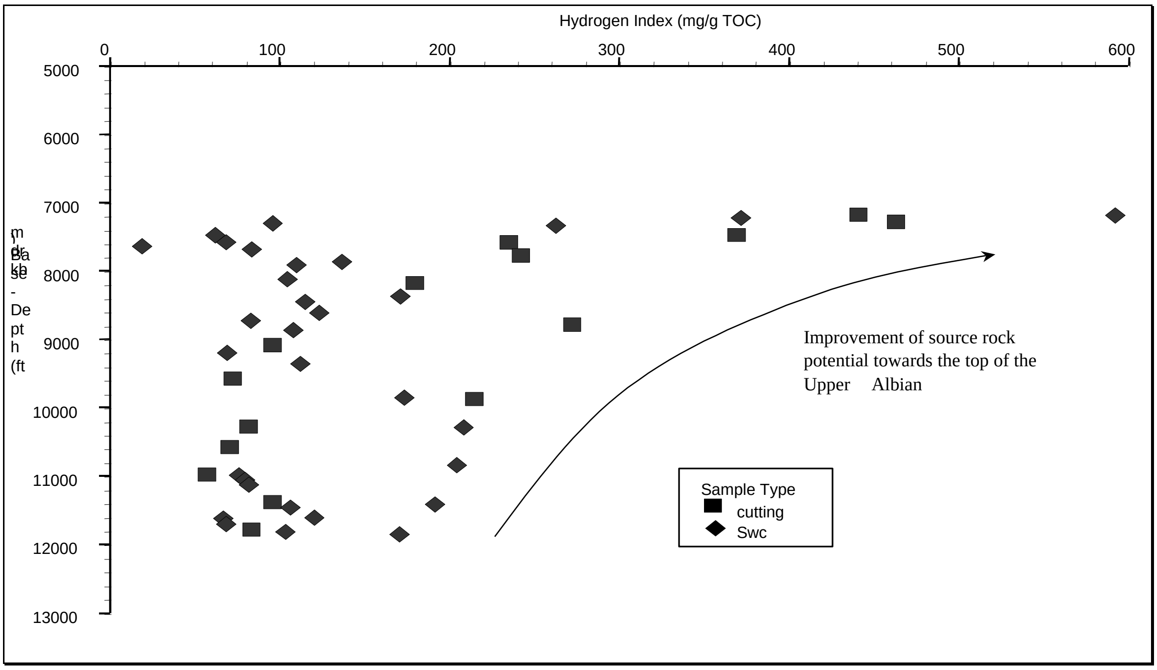
Figure 4 Saturated hydrocarbon gas chromatogram for Mid Albian source rock extract



Upper Albian samples show variable source rock quality ranging from inert to excellent oil prone facies. In many of the wells analysed there appears to be an increase in source potential towards the top of the Upper Albian, coincident with the 97 Ma maximum flooding surface (Haq *et al.* 1987 &1988) and can be seen in Figure 5. The best source rock identified displays a Hydrogen Index of 591 mg HC/g TOC and a generative potential of 49.4 kg Py/tonne rock. Integration with palynological studies suggests that this increase in source potential towards the top of the Upper Albian is related to marine transgression over the area and the development of anoxic bottom waters, favouring the preservation of oil-prone source rocks.

Cenomanian and Turonian source rocks display geographically variable source rock characteristics with TOC contents and oil generating potentials increasing away from the present day (and paleo) coastline. Proximal wells display the leanest TOC contents and are dominated by inert organic matter. More distal wells display richer, more oil-prone, source rocks with hydrogen Indices of up to 574 mg HC/g TOC and generative potentials of 27 kg Py/tonne rock.

Figure 5 Cross plot of Hydrogen Index versus depth highlighting the improvement in source rock potential towards the top of the Upper Albian (97 Ma maximum flooding surface)



BURIAL HISTORY MODELLING

Burial history modelling has been performed on a number of drilled wells and seismically defined pseudowells from within the Jacqueville Trough and the Grand Bassam Sub-Basin using Platte Rivers BasinMod® 1-D software. The primary objective has been to build and calibrate models based on data from drilled locations (stratigraphy, temperature and measured maturity). The calibration concepts are then applied to the pseudowell locations in order to understand the present day and paleo-maturity (and hence hydrocarbon generation) of key source horizons at basinal settings.

Initial investigation of bottom hole temperature data suggested that there is no significant variation in the geothermal gradient across the study area with much of the scatter being attributable to poorly or uncorrected raw temperatures. Models were built using recent biostratigraphical studies to help constrain chronostratigraphical input. Lithological inputs were taken from well composite logs. Sensitivity analysis was performed on a number of unconformities.

Drilled locations were initially modelled with a constant heat flow through time that honoured the present day bottom hole temperature. Although generally good calibration of measured and predicted maturity was achieved for Upper Cretaceous and younger sediments, deviation was commonly observed in Mid Albian sediments (Figure 6). A number of possible solutions were investigated, including increasing the present day heat flow, and varying the intensity of erosion at a number of unconformities (most importantly the post-rift Top Albian unconformity). The most satisfactory and plausible explanation for the divergence in measured maturity is to invoke a higher paleo-heatflow associated with the Albian rifting (Figure 7).

Figure 6 Calibration plot showing the disparity of measured and predicted maturity versus depth when using a constant heat flow through time for an Espoir well

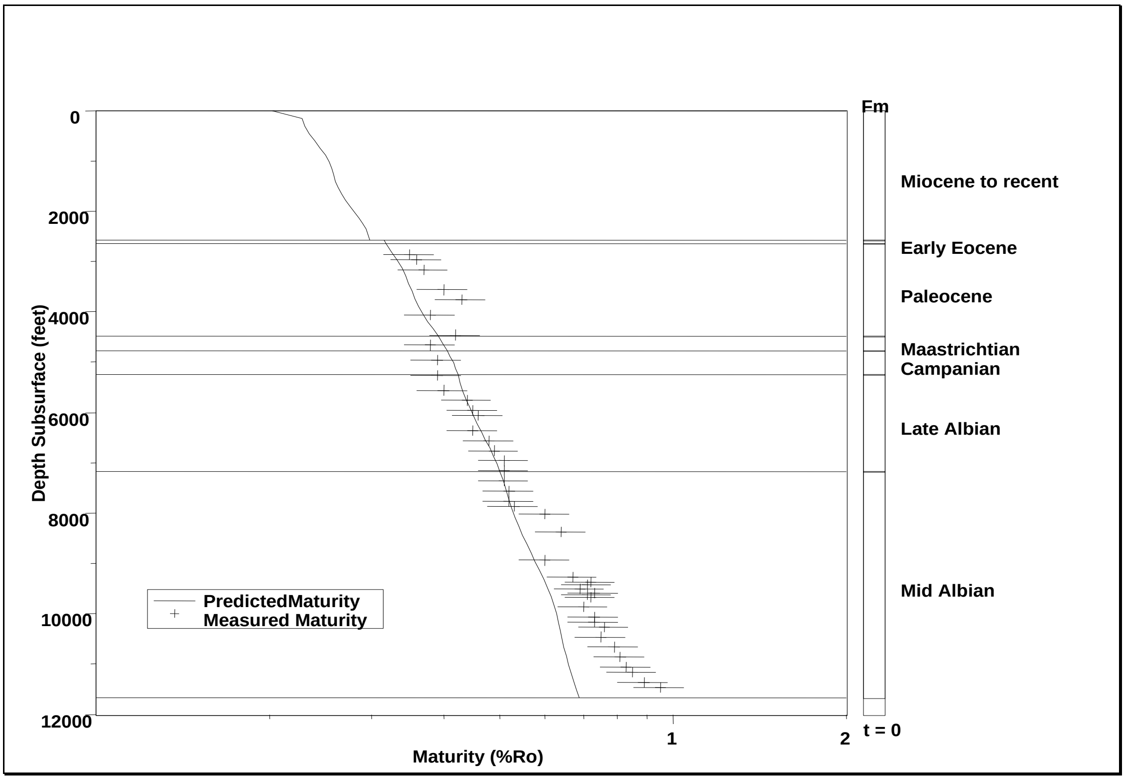
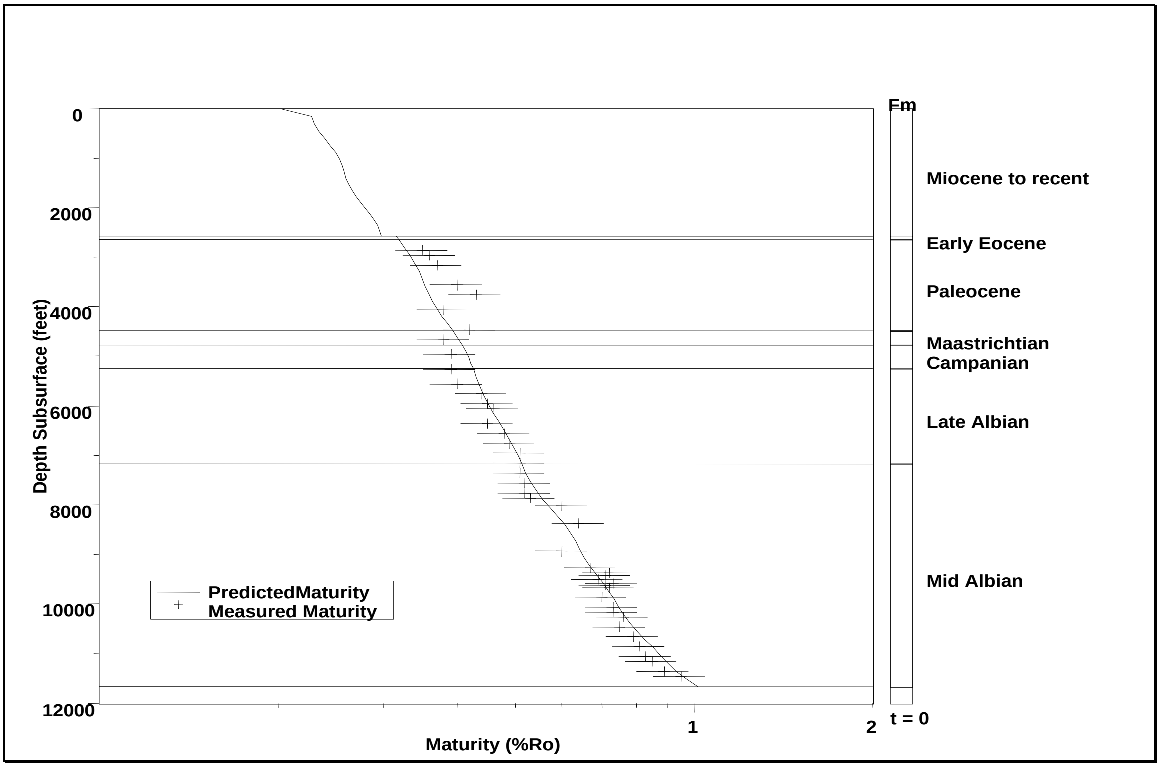


Figure 7 Maturity versus depth plot showing good calibration of measured and predicted vitrinite reflectance when using an increased syn rift heat flow for an Espoir well

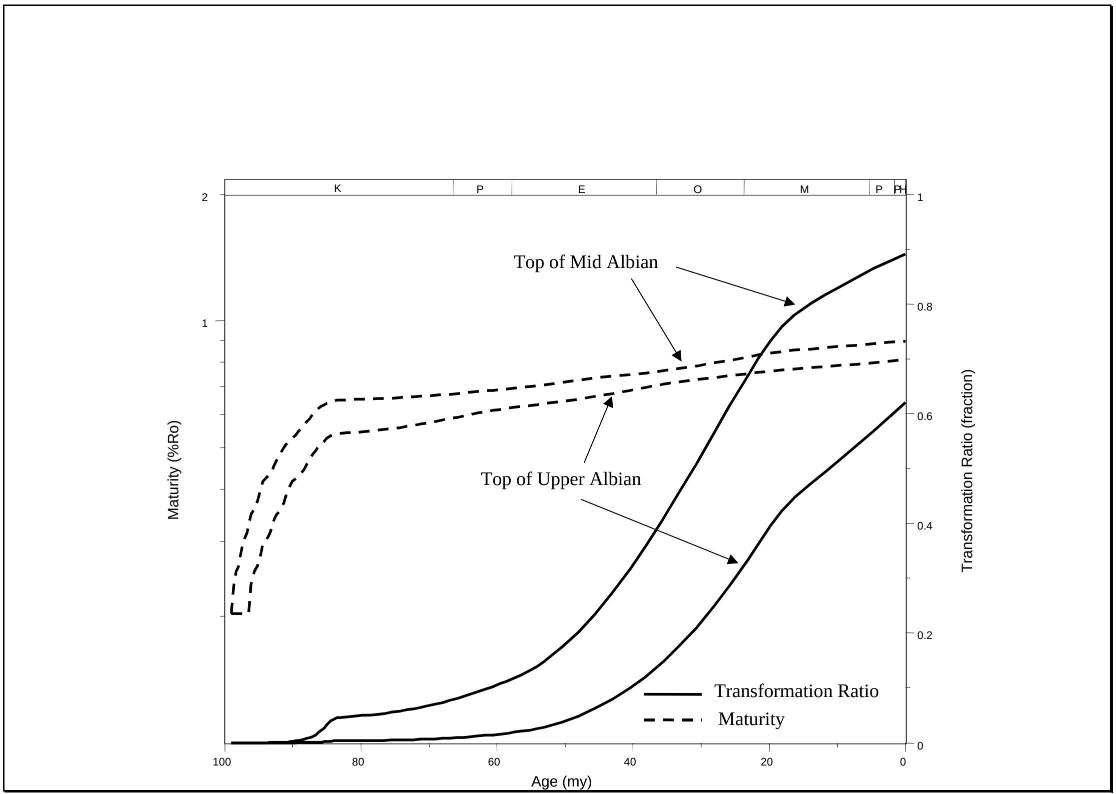


All wells have been successfully calibrated using a regionally consistent set of criteria. Present day heat flows (heat flow = thermal conductivity x geothermal gradient) honoured both the lithological and thermal (bottom hole temperatures) inputs. The paleo-heat flow has been modelled to increase to values of between 95 and 125 mW/m2 at 100 Ma and then to exponentially die away over a 30 my period. Two main unconformities have been considered and modelled. The post-rift Upper Albian unconformity shows variable extents of erosion ranging from 500 to 3000 ft. The other main unconformity occurs in the Miocene and eroded sections of between 600 and 3000 ft have been modelled. The extent of both unconformities have been constrained both by calibration of measured and predicted maturity and also by considering regional seismic lines and the location of individual wells with respect to their tectonic settings (especially important for Albian rotated fault blocks).

PSEUDOWELL MODELLING

Because of the complex tectonic history and thermal evolution of the study area a number of scenarios have been considered. When using a present day heat flow of 45 mW/m^2 (and a higher paleo heat flow) significant generation of hydrocarbons is predicted from a Type II kerogen within the Cenomanian to base Upper Albian section within the deepest depocentres of the shallow water Jacqueville Trough (Figure 8). Stratigraphically lower units are seen to have matured rapidly during the syn-rift period with no further generation from an oil prone Type II kerogen being predicted. Moderate recent gas generation from the Mid Albian is predicted.

Figure 8 Cross plot of Transformation Ratio (Type II kerogen) and maturity versus time for seismically defined pseudowell within the shallow water Jacqueville Trough



For structurally shallower pseudowells within the Jacqueville Trough, the predicted extent of hydrocarbon generation from a Type II kerogen is less, with Transformation Ratios of approximately 30% being predicted towards the east of the Jacqueville Trough.

Geochemical data suggest the gas present offshore Côte D'Ivoire has been generated from a humic Type III kerogen and is not associated with late mature oil-prone source rocks. Modelling of shallower pseudowells towards the east of the study area predicts no recent gas generation from the Mid Albian, with generation only occurring during the syn rift period when higher heat flows prevailed. Deeper pseudowells to the west of the Jacqueville Trough have, however, been subjected to enough Tertiary burial to reinitiate gas generation. The findings are to some extent corroborated by the absence of gas discoveries towards the eastern extent of the Jacqueville Trough.

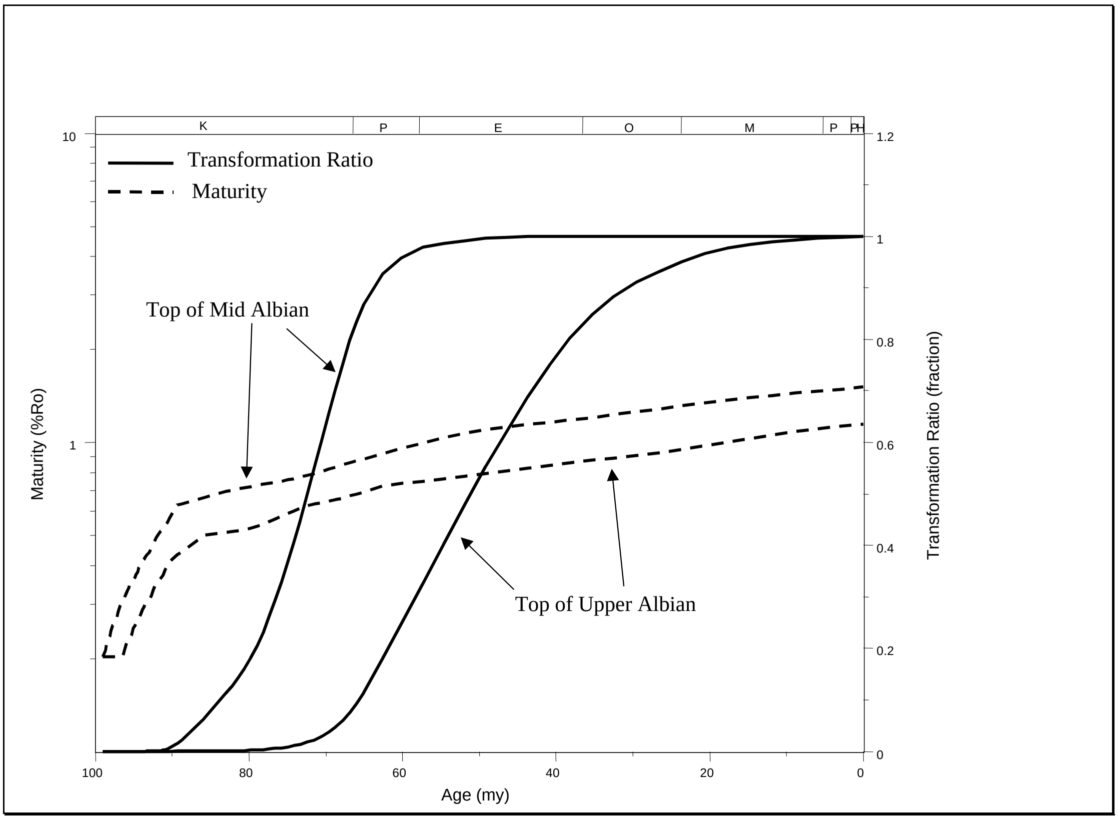
Eight pseudowell locations have also been modelled further south within the deep-water Grand Bassam Sub-Basin. Gravity magnetic studies indicate a significant thinning of the crust as the continental/oceanic boundary is approached. As such, somewhat higher present day heat flows would be expected. Progressively higher heat flows of 50 and 60 mW/m^2 have therefore been used during the burial history modelling of deeper water pseudowells.

When using a present day heat flow of 50 mW/m^2, significant generation of oil is predicted from source rocks buried below 8600 ft ssf (sub-sea floor) in the deep-water Grand Bassam Sub-Basin. More specifically a number of key source kitchens potentially charging several deep water structures and the inverted Albian highs between the Jacqueville Trough and the Grand Bassam Sub-Basin have been modelled.

Modelling of a source kitchen in the Jacqueville Trough and the Grand Bassam Sub-Basin, indicates that both are likely to charge the inverted Albian highs. It predicts that the Cenomanian/Upper Albian boundary has reached a maturity of approximately 0.8% Ro and would have started to generate significant amounts of oils. Interestingly, molecular geochemical data suggest that the structure being tested by this pseudowell contains oil generated from a source rock lying at approximately 0.75% Ro. Modelling also predicts up to 70% transformation of an Early to Mid Albian gas prone kerogen.

An optimal deep water pseudowell was also tested to predict the extent and timing of oil and gas generation from the deepest source kitchen within the study area. Here the Cenomanian/Albian lies at approximately 11250 ft ssf and when using a present day heat flow of 55mW/m^2 a thermal maturity of approximately 1.1 to 1.2% Ro is predicted (Figure 9). As such, significant generation of oil and wet gas is predicted during the Tertiary from potential Cenomanian and Albian source rocks.

Figure 9 Cross plot of Transformation Ratio (Type II kerogen) and maturity versus time for seismically defined pseudowell within the Grand Bassam Sub-Basin

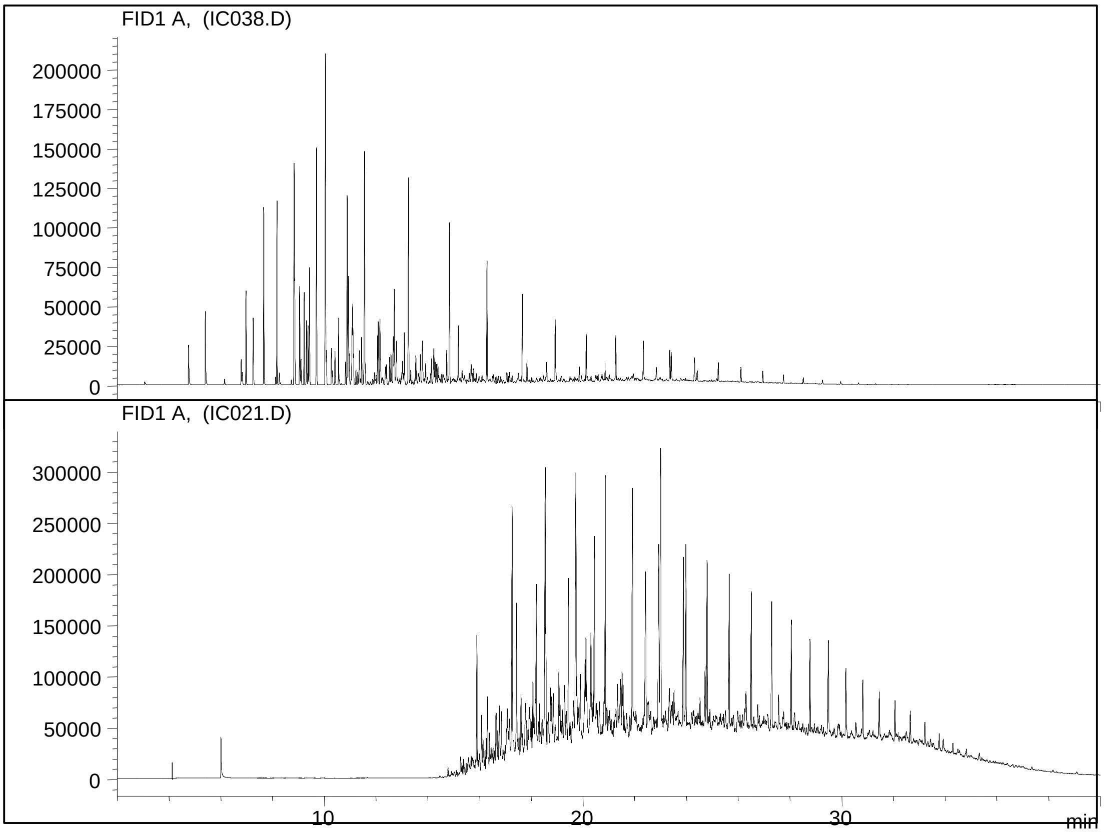


OILS GEOCHEMISTRY

Bulk, molecular and isotopic data were available for 17 oils from offshore Côte D'Ivoire. The analyses were performed by Geomark Research Inc. (Houston, USA) in 1998 and the data re-interpreted during this study. The oils are trapped in a number of different stratigraphic units ranging from the Albian reservoirs of the Espoir field to Maastrichtian shows in other wells.

Significant variation is seen in the physical properties of the oils across the study area with API gravities ranging from 20.5^o to 47^o. Whole gas chromatography suggests that these variations are in part controlled by the maturity of the sample set (with API gravity increasing with increasing maturity) and also in part by secondary alteration processes (biodegradation and water washing) that lower the API gravity of the oil. Figure 10 shows two representative whole oil gas chromatograms. The top sample has an API gravity of 43.4^o and is characterised by a full suite of n-alkanes. The lower sample has an API gravity of 21.2^o and displays a suite of heavier n-alkanes that are superimposed onto an unresolved hump indicating some degree of biodegradation. In addition to biodegradation, this sample has been effected by severe water washing, as highlighted by the total lack of light hydrocarbons in the gasoline range (nC_4-nC_{10}).

Figure 10 Whole oil gas chromatographs from offshore Côte D'Ivoire



Because of the variable effects of these secondary alteration processes, the relative maturity of samples has not been assessed from whole oil gas chromatography. Instead gas chromatography – mass spectrometry (GC-MS) data for biomarker compounds (steranes and triterpanes) has been used. Much of the biomarker data suggests there is a consistent variation in the maturity of reservoired hydrocarbons with expulsion maturities of between 0.65% and 0.85% Ro being predicted.

With the exception of two of the oils from the vicinity of the South Belier High/ Mafia Trough, all samples show consistent biomarker distribution which, when the effects of maturation are taken into account, are thought to derive from the same source rock. Although no definitive environmental biomarkers have been identified, the integrated interpretation of all available data would suggest that the oils from the inverted Albian highs (Espoir/Lion) have been generated from a source rock deposited in a dysoxic, marginal marine environment. This is consistent with the marine transgression that effected the area towards the end of the Albian.

The two oil samples from the South Belier High/Mafia Trough display geochemical characteristics consistent with generation from a more terrestrially influenced source rock deposited in a more oxic environment. In view of source rock interpretation and burial history modelling a Middle Albian source is not unlikely.

CONCLUSIONS

With the exception of two oils from the South Belier High/Mafia Trough, all the oils studied are considered to have derived from the same source rock type. Unfortunately, the lack of detailed geochemical data (GC-MS) for identified source rocks means that direct oil-source correlation is not possible. However, based on the available source rock data and in view of the burial history modelling, the number of likely source rocks is limited. Burial history modelling indicates that there are several possible source kitchens in operation:

1. Modelling the deeper seismically defined areas of the Jacqueville Trough indicates that the Cenomanian and older sediments have reached sufficient maturity to initiate the recent generation oil from a Type II kerogen. The Upper Albian is predicted to lie at a maturity of approximately 0.75 to 0.85% Ro.

2. The Middle Albian of the Jacqueville Trough is likely to have generated some gas and may be responsible for the gas accumulations found offshore Côte D'Ivoire.

3. Modelling of seismically defined pseudowells within the Grand Bassam Sub-Basin to the south also suggests that the Cenomanian and Albian sediments have attained sufficient maturity to generate significant quantities of oil and wet gas, which are likely to migrate northwards towards the inverted Albian highs (Lion, Foxtrot, Espoir and Quebec Highs).

4. Although there is no direct evidence, if the improvement of Cenomanian/Turonian source rock potential is extrapolated to the Grand Bassam Sub-Basin then it is likely that these source rocks may form the basis of a yet unexplored deep water petroleum system.

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