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Origin Of Bitumen Seeps InThe Sedimentary Basin Of Côte D'ivoire – The Onshore Case

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ABSTRACT: The Ivorian onshore sedimentary basin, which has several areas of bitumen seepage in Samo, Kodjoboué, and Eboinda, has yet to yield any discoveries of liquid or gaseous petroleum The study aims to understand the sources of bitumen observed on the surface or deep within the sediments. Scientific work by various authors, based on bitumen discoveries and technical studies by oil companies, has led to the discovery and production of oil in Cretaceous formations in the offshore part of the Ivorian Basin. The study reveals that mapping these seepages shows bitumen outcrops in Adiaké, Kodjoboué, Samo, and Eboinda within the sandy-clayey complex, as well as bitumen traces in oil wells at Port-Bouet-1, Bérou-1, and Eboinda-1. The satellite faults of the Lagunes fault are believed to be the migratory sources of oil from the reservoir depocenters of wells D1-1X and IVCO-3 offshore, toward the onshore sediments. These observations strengthen the geological and petroleum interest of the onshore area of the Ivorian basin and pave the way for further studies of its active petroleum system.

Keywords: Seepage, bitumen, onshore basin, Côte d'Ivoire

INTRODUCTION

The discovery of oil represents a significant turning point in a country's development, both economically and geopolitically, by fostering industrialization and generating significant revenue through its exploitation. Many countries have experienced a radical transformation of their economies after discovering significant oil deposits. Oil exploration in Côte d'Ivoire truly began in the 1950s with the first discoveries of bitumen deposits at Eboinda. The scientific work stemming from these discoveries contributed to a better understanding of the geological history of the Ivorian sedimentary basin, as demonstrated by various authors, including Martin (1973), Mascle (1976), Digbehi (1987), Aka (1991), Sombo (2002), and Kouame (2012). The bitumen observed in the basin's formations is primarily associated with secondary hydrocarbon migration. Subsequently, technical studies by oil companies led to the discovery and production of hydrocarbons in the offshore zone. Despite these offshore discoveries, the geological processes responsible for the presence of bitumen in the basin's onshore zone remain to be proven. This study aims to understand the sources of the bitumen observed in the sediments of the onshore basin at Eboinda. This work will provide information on the characterization of sedimentary deposits, the mapping of bitumen seeps, and finally the deduction on the geological factors of bitumen seeps in the onshore basin.

PRESENTATION OF THE STUDY AREA

Located in southern Côte d'Ivoire, the study area covers the terrestrial portion of the Ivorian sedimentary basin. This area is approximately 360 km long, stretching from Sassandra in the west to the Ivorian-Ghanaian border in the east, and 35 km wide. Its geographic coordinates are 5°40' to 2°44' west longitude and 5°00' to 5°30' east latitude (Figure 1), with an area of 8,500 km². The onshore basin is an extension of the sedimentary deposits of the Côte d'Ivoire margin. This margin formed during the opening of the equatorial Atlantic, which, starting in the Early Cretaceous, separated the African and South American continents on either side of the Gulf of Guinea (Blarez, 1986; Blarez&Mascle, 1988).

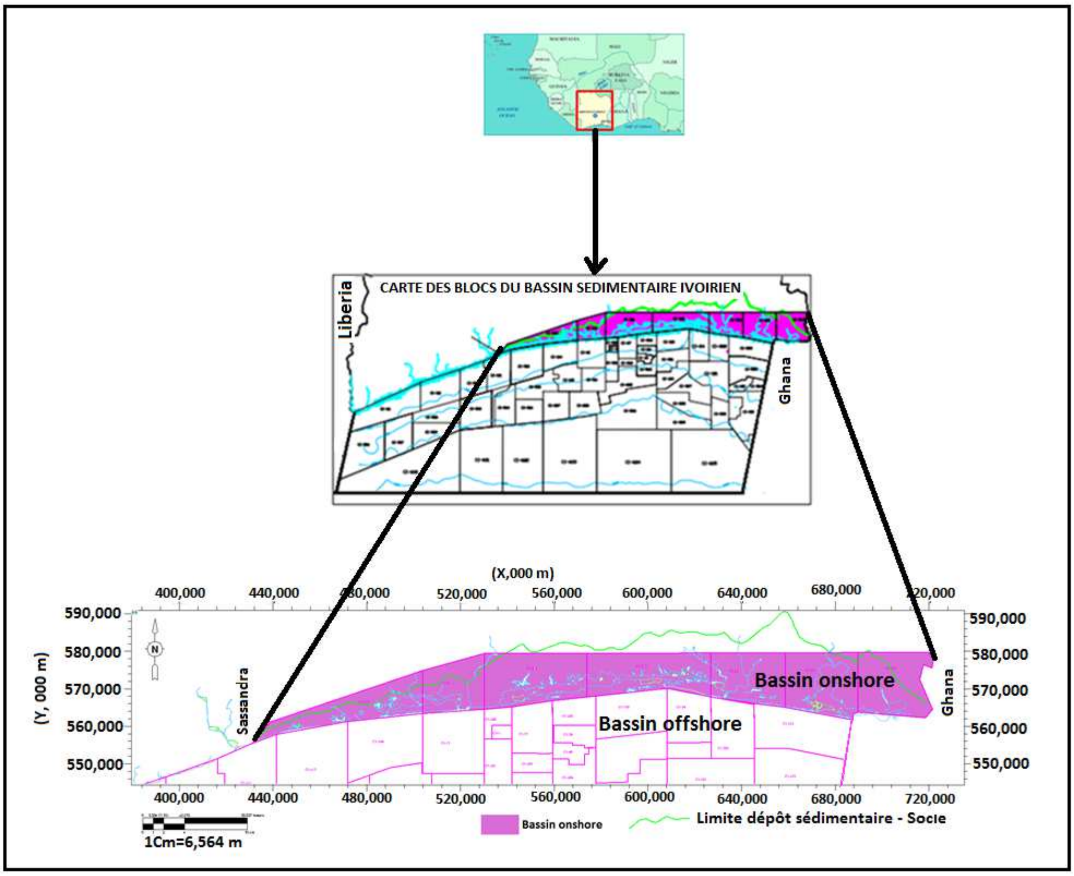

Figure 1: Location of the study area

MATERIALS AND METHODS

Materials

The materials used in the study consist of 2D seismic lines from 4,533 km of the ICS97, ICE97, JQ77, JQ78 and TCI81 campaigns (**Table 1**); a position plan containing the seismic mesh for the creation of the different maps (**Figure 2**) and geological reports of some of the boreholes that were the subject of geological study (**Table 2**).

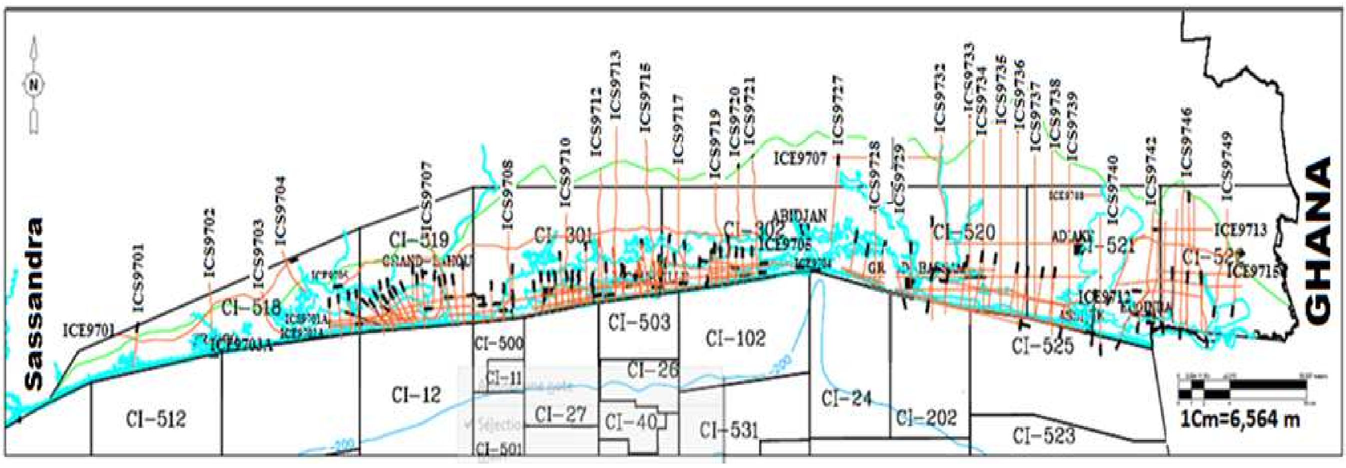

Figure 2: Position plan of the 2D linesused

Table 1: Some seismiclinesused (ABBEY, 2022)

Line name	Year of production	Orientation	Operator	Contractor	Distance (Km)
ICE9701	1997	E - W	PETROCI	CNSPC	56,60
ICE9701A	1997	E - W	PETROCI	CNSPC	25,56
ICE9702	1997	E - W	PETROCI	CNSPC	32,13
ICE9702A	1997	E - W	PETROCI	CNSPC	22,23
ICE9703A	1997	E - W	PETROCI	CNSPC	46,05
ICE9703B	1997	E - W	PETROCI	CNSPC	105,84
ICE9703C	1997	E - W	PETROCI	CNSPC	81,47
ICE9705	1997	E - W	PETROCI	CNSPC	126,93
ICS9701	1997	N -S	PETROCI	CNSPC	7,60
ICS9702	1997	N -S	PETROCI	CNSPC	10,57
ICS9703	1997	N -S	PETROCI	CNSPC	13,63
ICS9707	1997	N -S	PETROCI	CNSPC	20,25
ICS9708A	1997	N -S	PETROCI	CNSPC	2,07
ICS9733	1997	N -S	PETROCI	CNSPC	46,08
JQ77-01	1977	E - W	PETROCI	CGG	137,98
JQ77-28	1977	N - S	PETROCI	CGG	9,77
JQ78 -102	1978	N - S	PETROCI	CGG	5,07
TCI81-09	1981	N- S	TOTAL	CGG	16,20
TCI81-101	1981	N- S	TOTAL	CGG	10,15
TCI81-109	1981	N- S	TOTAL	CGG	8,47

Table 2: Geological drilling report of the different wells (ABBEY, 2022)

Well	Block	Year	KB/Rt (m)	TD (m)	Formation au TD	Status
Adiadon–1		1958	4,88	800,10	Antécambrienne	Sec
Gd Lahou–1	CI - 519	1958	4,88	1057,96	Maastrichtienne	Sec
Gd Lahou Pci–1		1979	34,14	2300,00	Albienne	Sec
Groguida–1		1961	7,92	2609,09	Albo-aptienne	Sec
Attoutou–1		1979	10,97	3500,02	Albo-aptienne	Sec
Tiémé–1	CI - 301	1979	14,02	2699,92	Albienne	Sec
Tabot–1		1958	17,98	1115,87	Campanienne	Sec
Port-Bouet–1	CI - 302	1959	11,89	3938,02	Albo-aptienne	Gaz
Vitré–1		1957	9,14	230,12	Sable à éléments de diorite	Sec
Vitré–2	CI – 520	1957	7,92	1078,08	Crétacé inférieure	Sec
Bérou–1		1960	7,92	4098,95	Albo-aptienne	Sec
Eboinda–1	CI – 521	1958	18,90	1061,01	Albienne	Sec
Eboinda–2	CI - 522	1958	19,20	587,96	Turonienne	Sec

Methodological approach

The methodology developed includes the following steps and phases: data collection, structural interpretation of seismic data and stratigraphic interpretation

a) **Data collection**

Data collection began with the printing of 171 North-South and West-East seismic sections and the onshore area location plan using an HP DesignJet 800ps printer in the LANDMARK workstation of Seisworks software. Quality control of the seismic sections led to the use of ICS97 and ICE97 series 2D seismic lines due to their processing scale and high quality.Subsequently, geological data from wells (Adiadon-1, Petroci Gd Lahou, Gd Lahou-1, Groguida-1, Attoutou-1, Tiémié-1, Tabot-1, Port Bouet-1, Vitré-2, and Eboinda-1 & 2) were used to calibrate the seismic data.

b) **Manual creation of maps**

To produce the isobath maps, manual and digital steps and operations were carried out :

- ✓ calibration of the seismic sections to the well data by manually identifying on the seismic section the markers corresponding to the geological roofs determined during drilling;
- ✓ recognition on the seismic sections of a depositional sequence by the geometric relationships of the strata based on the terminations and geometries of reflectors describing the different lower boundaries (onlap - termination of horizontal strata on an inclined base surface and downlap - termination of more inclined strata on a less inclined base surface) and upper boundaries (toplap - apex bevel showing inclined strata, truncation - ablation by erosion) by MITCHUM et al. (1977) ;
- ✓ Manual pointing of reflectors was performed by laterally tracking the various markers identified on the seismic section using well data. Simultaneously, faults were traced by observing the horizontal throws of the reflectors;
- ✓ timing of the pointed reflectors, consisting of plotting the round-trip time values (Two Way Time) corresponding to each shot point of the tracked contours and traced faults onto the position plane;
- ✓ manual plotting of isovalue curves on the position plane by manually drawing curves of equal travel time from the plotted values;
- ✓ digitization of manual data using Neuramap software, converting paper data to digital data;
- ✓ creation of maps where the digitized contours and polygons are transferred to the Openwork software of Decision Space on the Landmark work platform in Haliburton;
- ✓ lithostratigraphic correlation consisting of tracking lithostratigraphic data from the Lower Cretaceous, Upper Cretaceous, Tertiary, and Quaternary periods from geological reports of wells drilled in the terrestrial basin.
- ✓

III – RESULTS

III - 1) Characterization of the sedimentary deposits of the onshore basin

The onshore basin is part of the Ivorian sedimentary basin in the Gulf of Guinea province, which corresponds to a passive transform-margin basin. The Gulf of Guinea province is affected by three main distinct phases: a pre-rift phase, a syn-rift phase, and a post-rift phase, separated by unconformities.

Examination of the seismic profiles and borehole data from the study area revealed that two geodynamic phases characterize the onshore basin. The syn-rift phase corresponds to the Early Cretaceous, during which sediments record the presence of faulted blocks and infillings of graben. This sequence characterizes the initial phase of the Ivory Coast Basin and is marked by extensional faults in the Gulf of Guinea. The lower part of the syn-rift is associated with continental deposits, while the upper part of the Albian is marked by sediments under marine influence (Petroci&Beicip, 2010). The sedimentary zone connected to Ghana shares the same geological history associated with the opening of the South Atlantic, with syn-rift, sag, and post-rift phases observed in multichannel seismic surveys (Blarez et al., 1986).

From the Late Cretaceous to the Quaternary (Cenomanian to the present), the post-rift phase records the continental drift and continued crustal extension, leading to the formation of oceanic crust. With less influential tectonics, this phase experienced a succession of transgressions and regressions resulting in the formation of several unconformities from the Late Cretaceous to the present (Sombo, 2002). The first stage of sedimentation in the basin began in the Early Cretaceous, specifically in the Albo-Aptian (the oldest sediments reached by drilling). This stage is a phase of lining, or even clogging, the depressions induced by the preliminary episode of basin fracturing. These depressions were thus filled with detrital, terrigenous sediments of primarily continental origin, coming from neighboring lands undergoing erosion (Sombo, 2002). They were transported by various agents of erosion, particularly surface water. During this period, sedimentation occurred in a continental, fluvio-lacustrine environment, with the deposition of reddish, azoic detrital sediments resulting from the erosion of surrounding landforms. The oil wells known in the emerged portion have reached metamorphic rocks of magmatic origin, as confirmed by the oil exploration work of Petroci&Beicip (2010).

On the seismic profiles, the thickness of the sedimentary deposit is generally constant, except at the extremities of the study area where it is narrowed (Figure 3). To the west, the entire sequence of reflectors is unconformable, characterized by breast-like, semi-transparent, and discontinuous facies resulting from alternating transgression and regression. At the top of the sequence, discontinuous reflectors are characterized by low amplitude and high frequency. To the east of the study area, the Upper Cretaceous exhibits continuous, medium-frequency reflectors, indicative of a calm hydrodynamic environment.

Analysis of 2D seismic profiles highlighted the main structural features identified in the study area. On the seismic sections, an unconformity indicates the separation between the syn-rift phase (Lower Cretaceous) and the post-rift phase (Upper Cretaceous, Tertiary, and Quaternary).
The syn-rift phase is characterized by the presence of large tilted blocks, horsts, and grabens (Figure 4). This phase contains normal faults located at the base of the Lower Cretaceous. The faults are primarily planar with a seaward dip. A thick sequence of Lower Cretaceous clastic rocks was deposited during the syn-rifting phase. The normal faults conform to the most common structural style throughout the Ivorian sedimentary basin, as confirmed by the work of Petroci&Beicip (2010).The post-rift phase comprises fewer fractured sedimentary intervals. This phase is represented by well-stratified reflectors and is characterized by gravity tectonics, with numerous growth faults, known as listric faults, located in distinct superimposed stratigraphic intervals from the Late Cretaceous to the Tertiary (Figure 4). Post-rift sedimentation consists of successive wedges identifiable on seismic profiles. All the maps show an architecture composed of remarkable structural features:

A major normal fault called the "Lagoon Fault" crosses the onshore zone from west to east. This fault is parallel to the coast and was revealed by the gravimetric survey carried out from 1952 to 1953 by CGG (PETROCI & BEICIP, 1990) and confirmed by the interpretation of 2D seismic profiles (Figure 4). It divides the onshore basin into two distinct zones:
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The northern part of the Lagunes Fault belongs to the West African Craton, an area covered by 200 to 300 m of recent Miocene-Pliocene sediments; the southern part of the Lagunes Fault belongs to the continental margin, with an intense basement, ranging from 3000 to 6000 m in depth.

The second important feature is the Adiadon horst, called "upper Adiadon," in the vicinity of Fresco, i.e., to the west of the study area. This structure is due to the vertical movement of a given surface where the metamorphic rocks of the basement were encountered at 700 ms (798.9 m depth of the Adiadon borehole) on the seismic sections.During the various phases of rifting, large areas under extensional stress gave rise to complex graben systems in the basin. South of the "Lagoon Fault" and west of the "Adiadon Heights," the Adiadon Depression records sedimentary deposits at a depth of approximately 1500 m. East of the "Adiadon Heights" and towards the center of the study area, the large Jacqueville Depression records sediments extending to depths of over 6000 m (Figure 5).The interpretation of seismic and well data from the onshore basin reveals a structural legacy, expressed by faults, tilted blocks, and variations in sedimentary deposit thickness from the Early Cretaceous to the Quaternary.

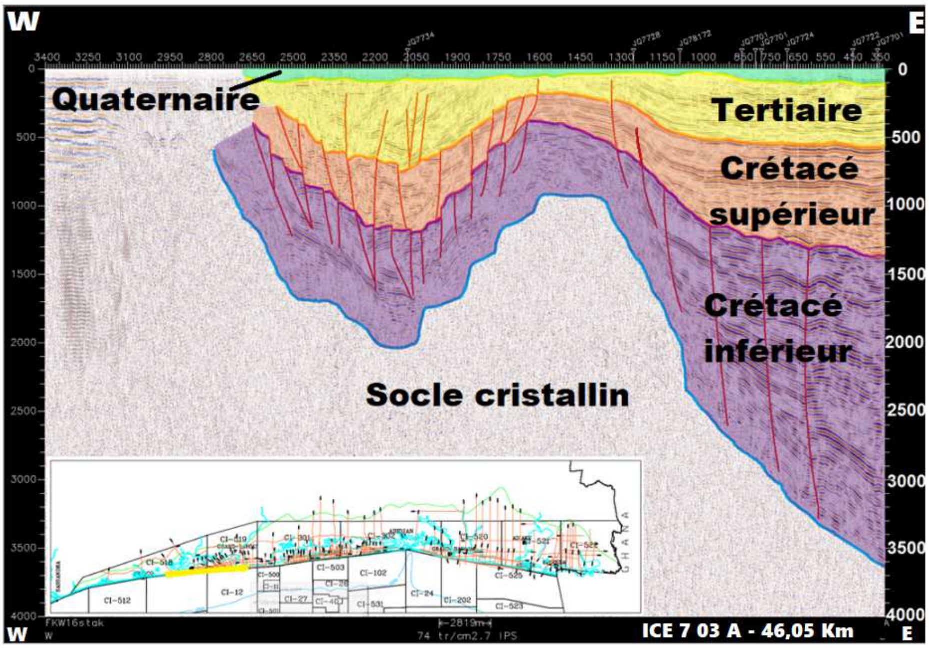

Figure 3: Profile map showing the behavior of reflectors west of the onshore

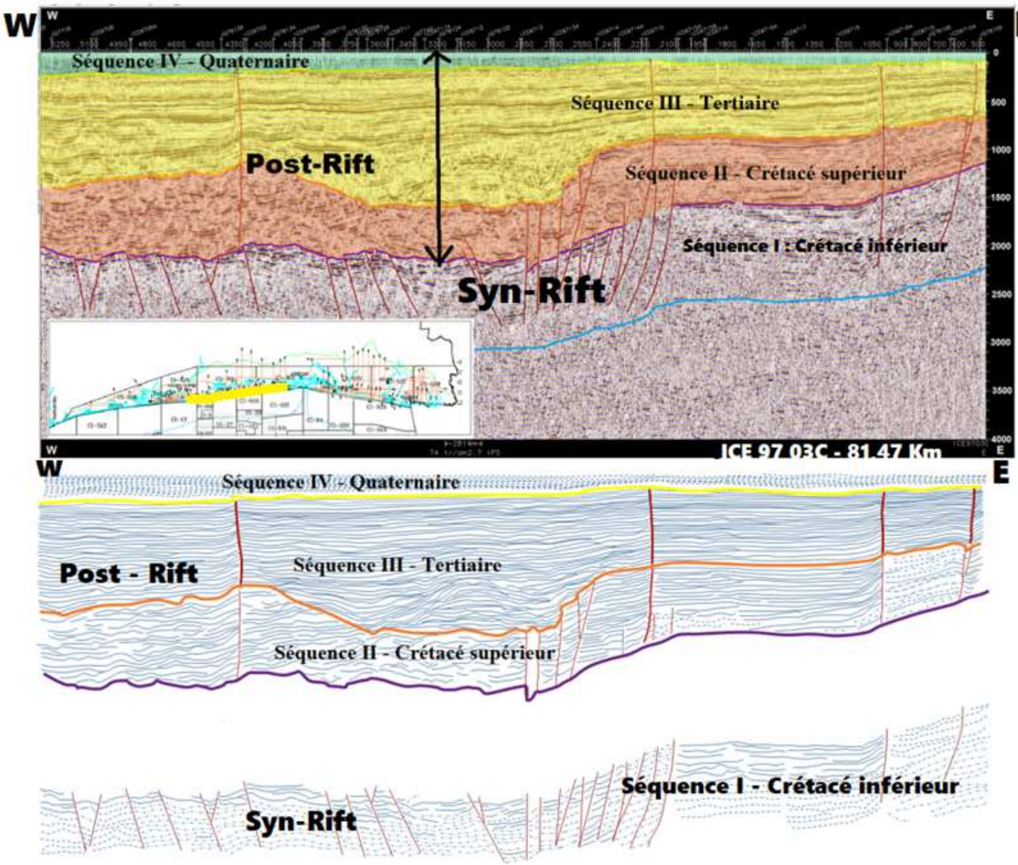

Figure 4 : Map showing sediment infilling during syn-rift and post-rift phases

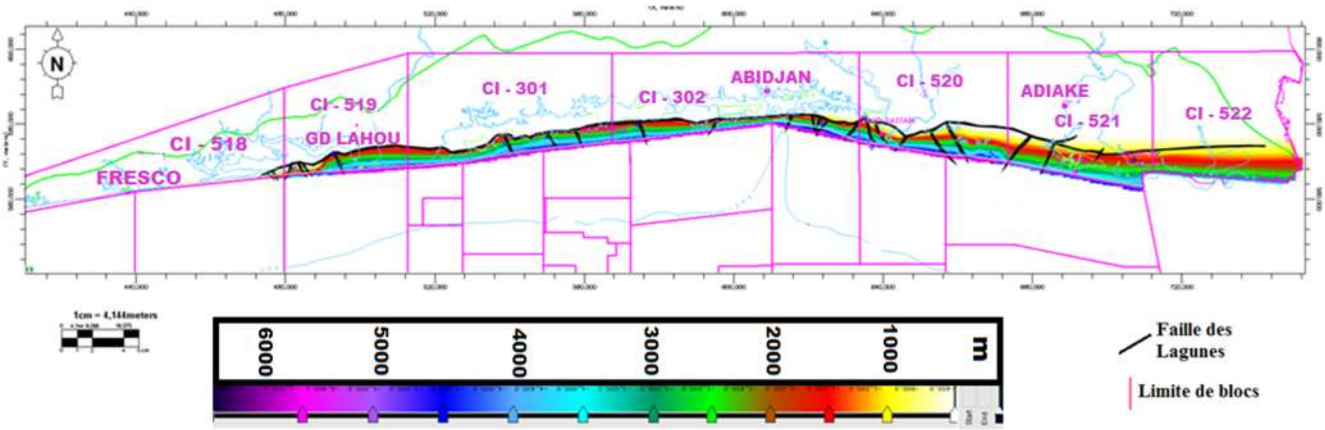

Figure 5: Isobath map at the top of the crystalline basement

Mapping of Onshore Bitumen Seeps

Bitumen seeps observed in a basin are manifestations of heavy hydrocarbons that have migrated from a deep source to the surface, where they have partially degraded. Bitumen seeps are the visible product of an inactive petroleum system. In the onshore basin, seeps have been identified in wells and in outcropping sediments.

Outcropping of seeps in the sediments

Several outcrops of bitumen have been observed in Adiaké, Kodjoboué, Samo, and Eboïnda in silty and sandy clays (Figure 6). The first indications of bitumen in Côte d'Ivoire were discovered in the Eboïnda region in 1895 by the Western African Oil and

Fuel Company Limited. Exploration in 1941 led to the discovery of a reserve of 100,000 tons of pure bitumen and the opening of a bitumen quarry. The French Petroleum Company (SFP) also extracted 250 tons of bitumen at Eboïnda between 1941 and 1943. As for the outcrops at Adiaké, the deposits are lenticular, with abundant bituminous horizons (7.5 m thick) in thesouthwest and in the Gnampon clays to the northwest. Superficial bitumen deposits and a small, deep lens were observed at Djédoukro.

The formations range in age from the Upper Cretaceous to the Quaternary. At Adiaké, the white sands, which contain the majority of the bitumen lenses, have been identified as identical to the Eboïnda sands (Guede, 2022).The Kodjoboué area, located at the end of an arm of the Kodjoboué Lagoon, southeast of Bonoua in Samo, is rich in bituminous deposits under the dead leaves and in the humus more than a hundred meters from the lagoon. A brief study of the Kodjoboué area revealed a very thin layer of bituminous clay with a total potential reserve of 14,096,625 tons of bitumen. Geochemical studies conducted by Total showed that the bitumen from Kodjoboué is malty.

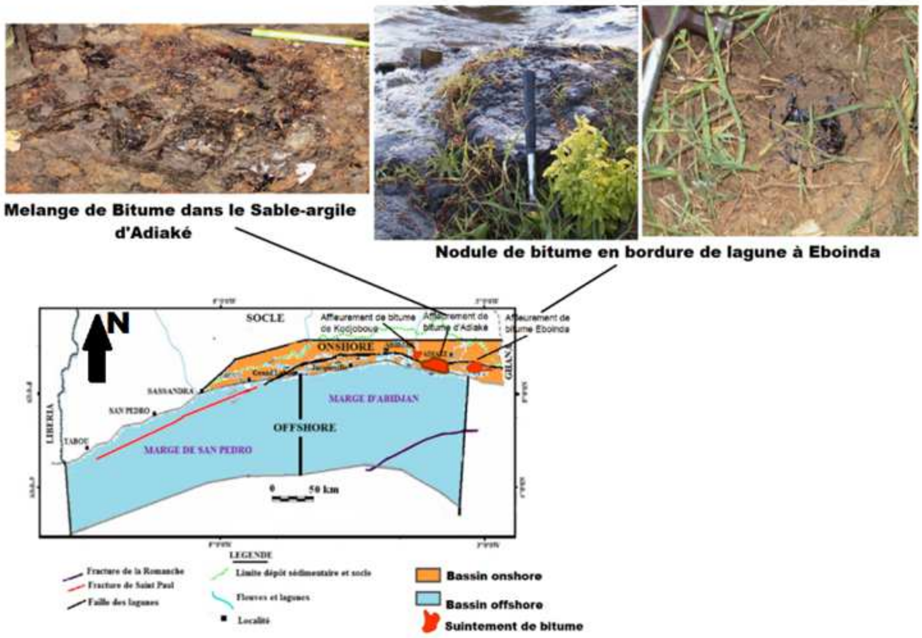

Figure 6: Bitumen outcrop map

Bitumen Presence Index in Onshore Wells

In oil wells, only 3 onshore wells showed bitumen evidence from East to West: Eboinda-1, Berou-1, and Port-Bouet-1:

- Port-Bouet – 1 well

Located in the middle zone of the basin southeast of Abidjan, the Port-Bouet-1 1 well in block CI 302 (Figure 7) was drilled in the highest point of a faulted compartment. The objective of this well is to explore the sedimentary sequence of the Côte d'Ivoire Basin down to the basement, and in particular the Lower Cretaceous reservoirs beneath the Miocene cover, as well as the Continental Pre-Albian reservoirs encountered in the Gulf boreholes in Ghana. The Port-Bouet – 1 well penetrated the sedimentary sequences to a maximum depth of 3938 m (Table V), with diffuse bitumen impregnation from 2697 m to 3938 m.

- Bérou-1 Well

With a maximum depth of 4099.60 m, the Bérou-1 well was drilled by the African Petroleum Company (Société Africaine des Pétroles) from November 1959 to May 1960. This well is located on the edge of the Assinie Canal and is 48 km east of the Port-Bouet-1 well in block CI 520. Drilled on a "nose"-shaped structure, its purpose was to conduct petroleum potential studies of the Lower Cretaceous on a "plunging nose" structure where stratigraphic traps may exist (PETROCI & BEICIP, 2010). The sedimentary sequences encountered range from the Quaternary to the Albian-Aptian, with bitumen observed between 1781 m and 1957 m, and an intermittent bitumen showing down to 2265 m.

- Eboinda-1 Well

Drilled from April 22 to July 9, 1958, the Eboinda-1 well is located in the eastern part of the basin near the Ghanaian border, within permit CI-521. This well was drilled to conduct a geological survey at the eastern end of the basin and to locate the top of the Lower Cretaceous continental series. Situated on the axis of a shallow transverse bulge, the Eboinda well penetrated a Quaternary to Albian sedimentary series to a maximum depth of 1060.90 m, with a bitumen intercalation from 0 to 100 m. A deepening of the bitumen impregnations is observed from east to west of the study area.

The work of Jekayinfa et al. (2023) and Abu et al. (2021) confirms studies showing that the Voltaian Basin (Ghana) contains sediment deposits up to 5–7 km thick in its center, and that viscous bitumen is observed in core samples taken from the Oti/Pendjari and Panabako formations at depths of 450 to 764 m. In the eastern part of the Dahomey Basin (Nigeria), the work of

Abu et al. (2019) and Akinmosin (2019) also confirms the presence of bitumen seeps (tarsand) that outcrop for more than 6 km from Okitipupa to Ijebu Ode.

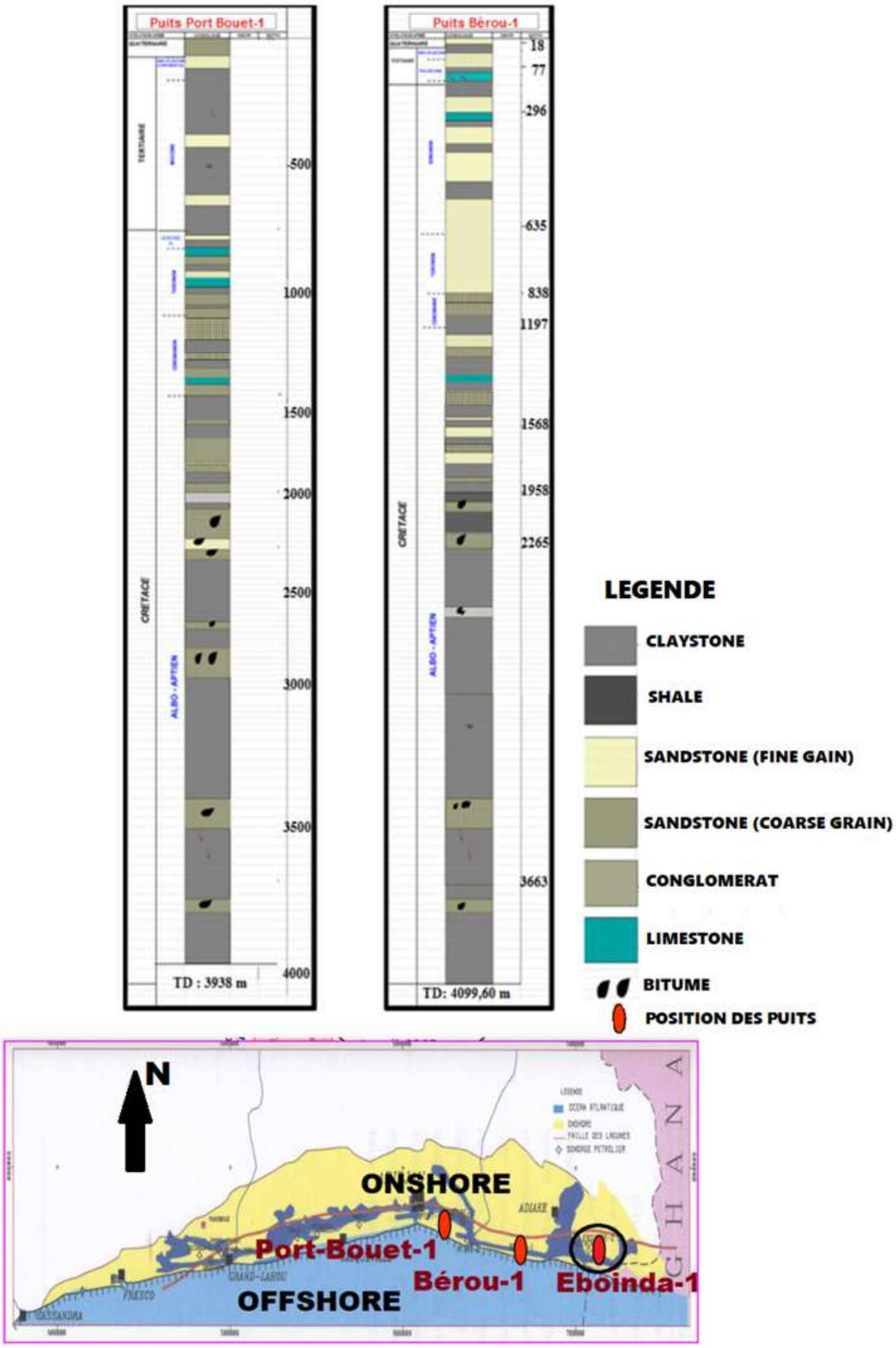

Figure 7 : Bitumen impregnation map in the Port-Bouet-1 and Bérou-1 boreholes

Deduction on the Sources of Bitumen Seeps

The interpretation of seismic and well data from the onshore basin reveals a structural legacy characterized by faults, tilted blocks, and variations in sedimentary thickness from the Lower Cretaceous to the Quaternary. In Côte d'Ivoire, the various hydrocarbon discoveries have been made in two main tectono-sedimentary domains: the syn-rift and post-rift domains.The syn-rift section, which contains most of the hydrocarbons, is composed of Albian-age sediments. According to Petroci&Beicip (2010), the traps identified in the syn-rift stage are primarily structural, while in the post-rift section, the sediments are Cenomanian to recent, with tectonic influence less pronounced. These post-rift structures are therefore more subtle, with sandstone and sandy bodies trapped stratigraphically within units that are generally more clayey in the Ivorian terrestrial basin. With the exploitation of nearly 10 tons of bitumen per day between 1904 and 1950 by the French oil company SAP, the Ivorian onshore area could thus be a geological environment favorable to the discovery of liquid or gaseous hydrocarbons.

The present studies of isobath maps and well data from the study area show the presence of petroleum systems comprising structural and stratigraphic traps, clay caps, and source rocks composed of continental sandstones, clayey limestones, and clayey sands, as well as hydrocarbon migration pathways (Figure 8). In the Dahomey Basin, which extends from eastern Ghana to southwestern Nigeria (also called the Benin Basin), studies by Mahamuda et al. (2018) and Jekayinfa et al. (2023) confirm that the geological structures responsible for seeps are similar to those of the Ivorian Basin, and in the Upper Cretaceous formations of Afowo(Maastrichtian), major bitumen reservoirs have been identified due to the absence of cap rock and the presence of faults that facilitate their emergence at the surface.

Several hypotheses support the discovery of bitumen at both the surface and deep within the Ivorian onshore basin :

✓ These heavy oils originate from kerogen degraded by heat and migrating from a source rock to a more porous reservoir rock. The observation of impregnation at different levels (Port Bouet-1, Bérou-1, and Eboinda-1) could be explained by multiple hydrocarbon inflows, likely linked to fault activity. Other migration pathways for the oil that gave rise to the bitumen could exist, notably from offshore blocks to onshore blocks, where reservoirs from wells D1-1X and IVCO-3 could supply the Port Bouet-1 and Bérou-1 depots, respectively.

✓

✓ The oil that formed the basis of the bitumen was likely generated in a deep basin and migrated along satellite faults north of the Lagoon Fault with a thin layer of sediment (200 m). Upon reaching the surface, the oil altered and transformed into bitumen, which is observed primarily north of the Lagoon Fault, eastward into the sands of Eboïnda, Adiaké, Kodjoboué, and Samo. It is also probable that some of this oil formed was destroyed during the various periods of emergence and erosion that marked the sedimentary history from the Albian to the Miocene. It is almost certain, as evidenced by surface evidence, that another portion of this oil underwent dismigration along the system of satellite faults in the onshore basin.

✓

✓ The studies by Petroci&Beicip (2010) confirm potential source rocks (Albian-Cenomanian) in the offshore part, with the existence of numerous deposits (Espoir, Bélier, Foxtrot, Baobab) which could be possible sources by percolation from these deep levels to the surface, becoming bituminous indications in the onshore.

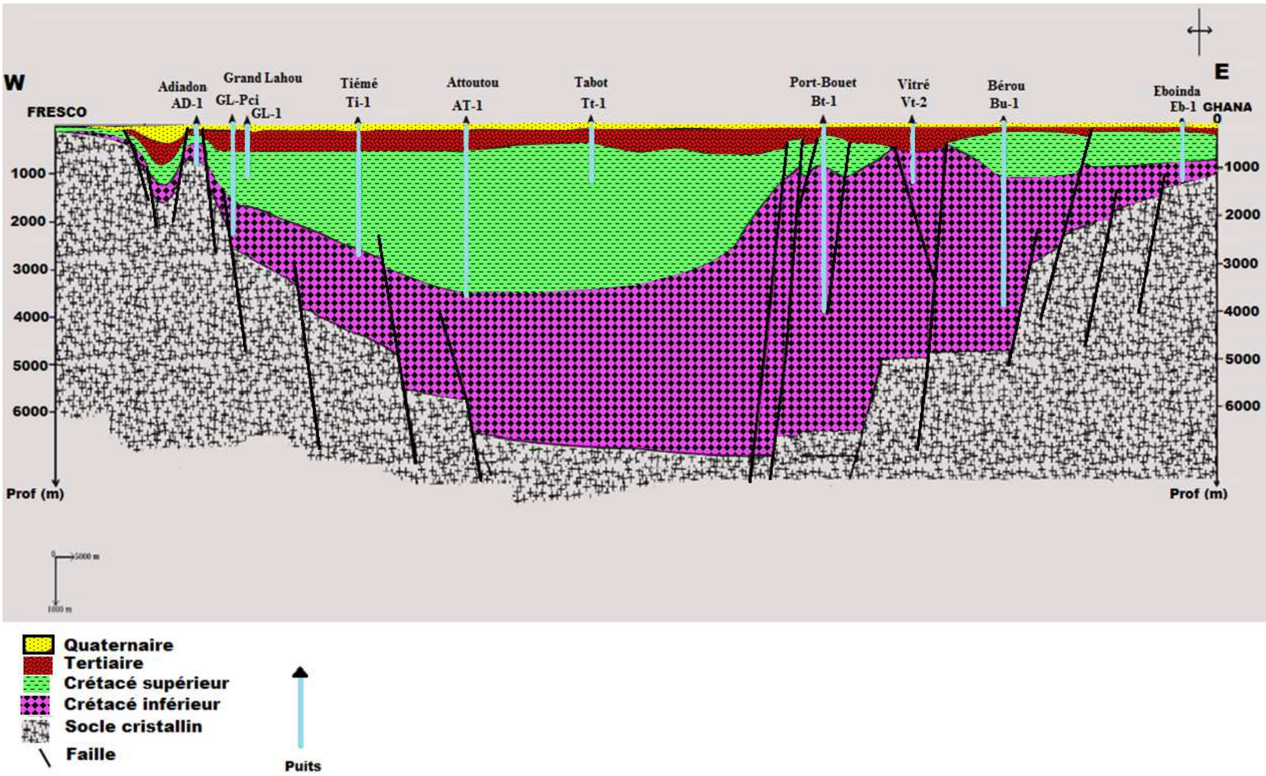

Figure 8: Geological crust map showing the sedimentary configuration of the onshore basin

✓ The observation of bitumen seepage in the different geological levels of the boreholes (Eboinda-1, Bérou-1, Port-Bouet-1) could be explained by several hydrocarbon inflows, probably linked to the activity of satellite faults of the lagoon fault. Based on seismic and borehole data modeling of the intermediate onshore-offshore zone, the bitumen seepages would likely originate from the depocenters Port Bouet-1 and D1-1X (offshore borehole) and BEROU-1 and IVCO-3 (offshore borehole), of Upper Albian age (Figure 9). The oil that formed the basis of bitumen was likely generated offshore and migrated along satellite faults. The thin layer of sediment north of the Lagunes Fault also likely explains the dysmigration of bitumen east of the onshore basin. This mechanism is similar to that of Mahamuda et al. (2018) in the Benin Basin, where surface oil migration occurred through fractures and tectonic faults, or due to the absence of an impermeable cover and a favorable dip.

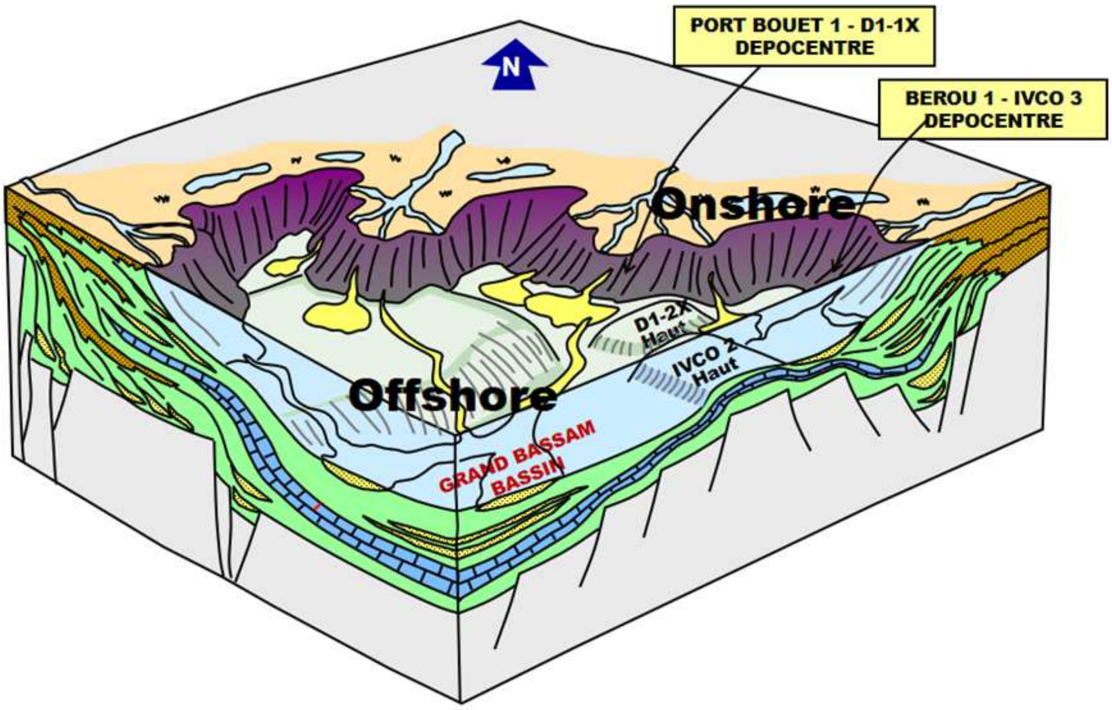

Figure 9: Modeling map of the depocenters of the intermediate onshore-offshore zone

Conclusion

The study on the origin of bitumen seeps, using an integrated approach to seismic and geological data, revealed the absence of liquid or gaseous oil discoveries despite the presence of bitumen in the sandy sediments of the onshore sedimentary basin. Characterization of the sedimentary deposits revealed two episodes of sediment deposition: the synrift (Lower Cretaceous), characterized by large tilted blocks, horsts, and grabens; and the post-rift (Upper Cretaceous, Tertiary, Quaternary), featuring less fractured sedimentary intervals. Mapping of onshore bitumen seeps revealed various bitumen outcrops observed at Adiaké, Kodjoboué, Samo, and Eboïnda in silty and sandy clays, as well as bitumen occurrences in oil wells at Eboinda-1, Berou-1, and Port-Bouet-1. Satellite faults of the Lagunes Fault are thought to be the migration pathways for oil originating from the depocenter reservoirs of wells D1-1X and IVCO-3 offshore and flowing into onshore sediments. Analysis of seismic data and well geological reports contributed to understanding the links between onshore bitumen seeps, satellite faults of the Lagunes Fault, and offshore depocenters. Further petro-geochemical studies will determine the origin and maturity of the hydrocarbons responsible for the onshore bitumen seeps.

Conflict of Interest

The authors declare no conflict of interest.

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