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SEISMIC EXPRESSION OF STRUCTURAL AND STRATIGRAPHIC TRAPS CONTROLLING BITUMEN ACCUMULATION IN THE DAHOMEY BASIN, NIGERIA

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Abstract: The Dahomey Basin in southwestern Nigeria hosts one of Africa's largest onshore bitumen deposits, largely controlled by structural and stratigraphic traps formed during the basin's rift–drift evolution. This study applies integrated seismic refraction and Multichannel Analysis of Surface Waves (MASW) techniques to delineate and characterize bitumen-bearing horizons. Fifty-one seismic profiles were acquired along E–W traverses using a 24-geophone spread and processed with SeisImager 2D software for P- and S-wave velocity modeling. This study focuses specifically on the Makun Field, located in the southern sector of the eastern Dahomey Basin, where extensive bitumen seepages and Afowo sandstone exposures occur. The velocity models reveal three distinct lithological units, with P-wave velocities ranging from 300–2800 m/s and S-wave velocities from 86–1890 m/s, enabling discrimination of topsoil, saturated sands, and bituminous sands. Two major bitumen-bearing horizons were mapped, a shallow horizon (2–15 m depth, 6–12 m thick) and a deeper horizon (40–130 m depth, up to 45 m thick). Fault-assisted migration pathways and stratigraphic continuity of Afowo sand bodies sealed by Araromi shales strongly influenced the distribution of these horizons. These results confirm the existence of a functioning petroleum system and highlight exploration zones suitable for both surface mining and thermal in-situ recovery methods. This work improves understanding of the spatial distribution and geometry of bitumen reservoirs, offering a framework for optimized exploration and sustainable resource development.

Keywords: Bitumen accumulation, seismic refraction, hydrocarbon exploration, velocity modeling.

Introduction

Seismic exploration remains one of the most effective geophysical techniques for subsurface imaging and delineation of hydrocarbon-bearing structures, including bitumen deposits. Energy waves in seismic surveys are initiated by introducing controlled energy into the earth-typically achieved by striking a steel striker plate vertically with a sledgehammer, firing a seismic shotgun, or exploding a small explosive charge. The energy propagates as seismic waves whose quickest wave is the compression wave or P-wave. As a result of its speed, the P-wave, or more generally referred to as the primary wave, will most likely be the first to be received by geophones and therefore, easier to identify on seismic traces than other seismic phases. The use of P-waves and seismic reflected energy is particularly important in sedimentary basins like south-western Nigeria's Dahomey Basin, where there are bitumen accumulations in structurally and stratigraphically controlled traps. The Dahomey Basin is a marginal basin that developed along the West African passive margin, and is characterized by complex tectono-stratigraphic evolution, involving syn-rift and post-rift sequences that have giant hydrocarbon and bitumen accumulations. Although, previous studies have mapped surface bitumen occurrences, few have integrated seismic refraction and MASW to resolve subsurface geometry of bitumen-bearing units at basin scale. Seismic methods provide an inexpensive and non-destructive means of delineating these deposits through visual imaging of structural traps such as faults, folds and basement highs, and stratigraphic traps such as pinch-outs, unconformities and channel fills.

As there is increased need for unorthodox sources of energy and the need to know more about the distribution of the Nigeria's bitumen reserves, there has been enhanced interest in characterizing the seismic expression of the trapping system. Proper seismic data interpretation can give information concerning the geometry, connectivity, and lithological complexity of the bitumen-bearing unit, thereby helping in the formulation of improved exploration models. Through the integration of structural and stratigraphic seismic interpretation, the study aims at improving understanding on bitumen accumulation patterns in the Dahomey Basin and therefore, providing valuable inputs for future exploration and responsible exploitation of this unconventional hydrocarbon reservoir.

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Regional Geology and Tectonics

The study area is situated in Ogun State, within the eastern sector of the Dahomey Basin (Fig. 1). The Dahomey Basin — also referred to as the Benin Basin — is a marginal Atlantic basin that stretches from southeastern Ghana through Togo and Benin into southwestern Nigeria, where it is bounded to the east by the Okitipupa Ridge, a structural high that separates it from the prolific Niger Delta petroleum province (Falufosi & Osinowo, 2021; Toyin *et al*., 2024). This basin originated as part of the West African rift system associated with the breakup of Gondwana and the subsequent opening of the South Atlantic during Late Jurassic to Early Cretaceous (Akinmosin *et al*., 2020; Mosuro *et al*., 2021). The rift event generated a series of fault-bounded half-grabens that not only controlled the deposition of the syn-rift sediments, but also influenced the spatial and temporal distribution of source rocks, reservoirs, and structural closures, thereby defining the hydrocarbon prospectivity of the basin (Mosuro *et al*., 2021).

Structurally, the basin is characterized by half-grabens, and fault-assisted closures that form traps for hydrocarbon accumulation. Offshore, the structural style is dominated by rollover anticlines, growth faults, and rollover anticlines, while onshore, the fault network provides vertical and lateral migration pathways that facilitate the charging of shallow reservoirs and surface seepages, resulting in extensive bitumen and tar sand occurrences (Falufosi & Osinowo, 2021; Adekeye *et al*., 2023).

Stratigraphy and Reservoir Units

Stratigraphically, the Dahomey Basin exhibits a well-developed rift-to-drift succession critical to the development of its petroleum system. The basal Ise Formation represents the syn-rift unit and comprises coarse-grained continental sandstones and grits interbedded with lacustrine shales, Grabens. (Omatsola & Adegoke, 1981; Akinmosin *et al*., 2020). Overlying the Ise Formation is the Afowo Formation, which marks a transitional to early post-rift phase and consists of cross-bedded, medium- to coarse-grained sandstones with interbedded shales and minor conglomerates (Reijers, 2011; Toyin *et al*., 2024). The Afowo Formation serves as the principal hydrocarbon reservoirs both onshore—where they host tar sands—and offshore, where equivalent offshore reservoirs produce oil and gas through subsurface drilling. These sandstones generally possess good to excellent reservoir quality, with porosities between 15–25% and permeability is sufficient for commercial production under favorable trap conditions (Adekeye *et al*., 2023).

The Araromi Formation, which overlies the Afowo Formation, represents the Maastrichtian to Paleocene marine transgressive sequence. It consists mainly of dark grey marine shales with occasional limestones and sandstones, and is regarded as the most prolific and regionally extensive source rock in the Dahomey Basin (Falufosi & Osinowo, 2021). Total Organic Carbon (TOC) values range between 2–4 wt%, and in deeper offshore depocenters, the shales have attained sufficient maturity to generate oil and gas (Adekeye *et al*., 2023). Above the Araromi Formation occurthe Ewekoro and Akinbo formations, composed of shallow marine carbonates and sandstones that act as secondary reservoirs and regional seals in some localities (Mosuro *et al*., 2021).

The stratigraphic architecture creates a classic source reservoir seal triplet: fluvial to shallow marine sandstones (Ise and Afowo formations) overlain by thick regional shale seals (Araromi Formation). In the deeper offshore sections, this sequence is more continuous and better preserved, allowing the Araromi shales to generate hydrocarbons that migrate vertically and laterally into overlying and adjacent reservoirs (Adekeye *et al*., 2023). Onshore, hydrocarbons generated from the Araromi Formation and migrated upward along extensional faults into the Afowo sandstones, where biodegradation near the surface converted the hydrocarbons into viscous heavy oil and bitumen (Akinmosin *et al*., 2020; Toyin *et al*., 2024).

This process led to the formation of the extensive tar sand belt of southwestern Nigeria, which spans approximately 120 km in length and 4–6 km in width and contains one of Africa's largest bitumen deposits (Adekeye *et al*., 2023). The bitumen-bearing sandstones occur at shallow depths, typically less than 10 m below ground level, and consist of thick, cross bedded high porosity sand bodies that act as natural reservoirs.

Hydrocarbon Potential-Petroleum System

Hydrocarbon prospects in the Dahomey Basin include both conventional and unconventional resources. Offshore, commercial oil and gas discoveries have been made in the Aje Field (OML 113), where Cenomanian–Turonian sandstones equivalent to the Afowo reservoirs produce light oil and gas-condensate (Falufosi & Osinowo, 2021; Toyin *et al*., 2024). The success of the Aje Field confirms the presence of an active petroleum system with mature source rocks, effective migration pathways, and high-quality reservoirs. Basin modeling studies suggest peak hydrocarbon generation during the Late Cretaceous–Paleogene, indicating that the system remains active today (Adekeye *et al*., 2023).

Recent advances in geochemistry and geophysics (2023–2024) have provided stronger evidence for the genetic link between offshore oils and onshore tar sands. Biomarker studies reveal similar depositional signatures and maturity trends, suggesting derivation from a common Lower Cretaceous lacustrine source (Toyin *et al*., 2024). Additionally, high-resolution aeromagnetic, gravity, and resistivity surveys have refined the basement structure, delineated fault zones, and improved understanding of migration pathways and trap geometries (Mosuro *et al.*, 2021). These integrated datasets reinforce the view of the Dahomey Basin as an underexplored, but petroleum-prolific province with significant potential for future conventional and unconventional hydrocarbon exploration.

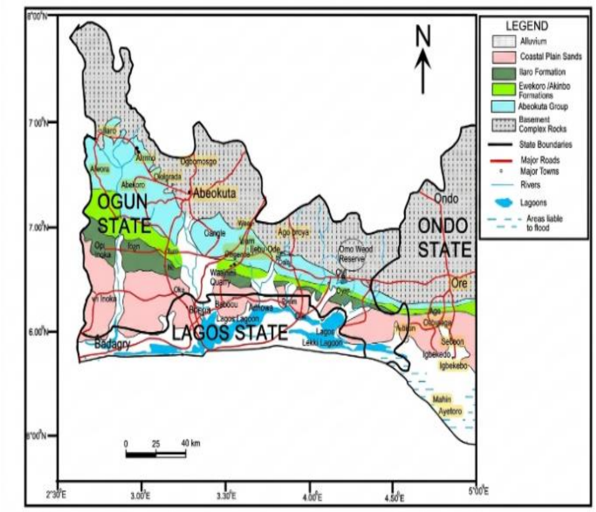

Fig. 1 Geological map of Dahomey Basin in the Nigerian sector and the states located on the basin (Olabode & Mohammed, 2016).

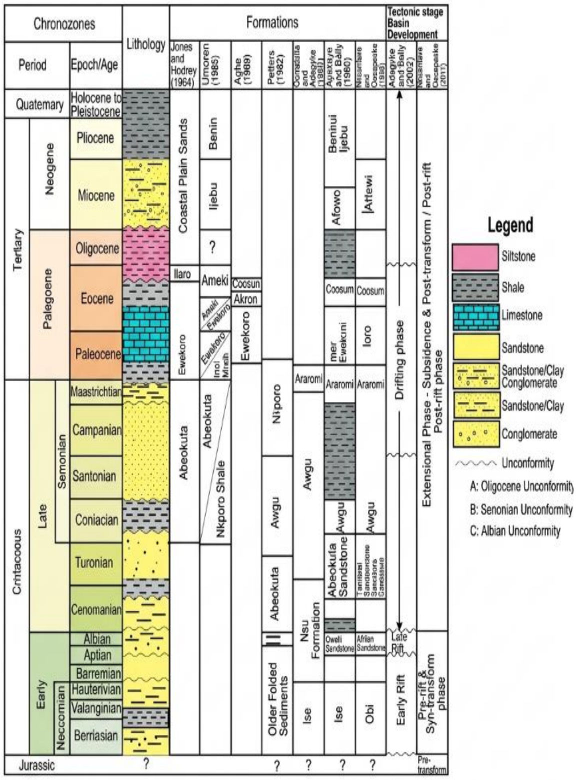

Fig. 2 Generalized stratigraphic column and tectonic stage of basin development in the Nigerian sector of the Dahomey Basin (Olabode & Mohammed, 2016).

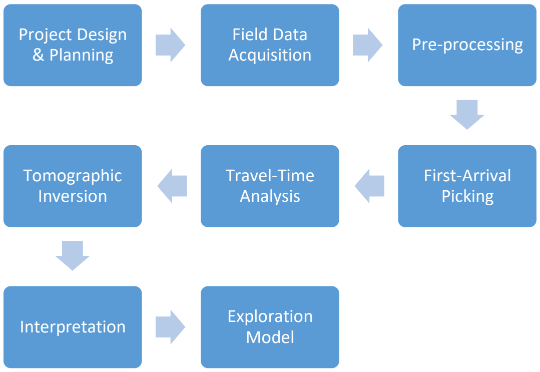

Fig. 4 Flowchart of Seismic Data Acquisition, Processing and Interpretation.

Materials and Methods

ABEM TERALOCK MARK 6 was used in the collection of data (Fig. 5a and b). The seismic refraction method was used, to find out the arrival times of the head waves and to map the depth to the refractors in which the waves travel. This method also gives information about materials properties, and what kind of material occurs in each layer.

Seismic Short Gathers

A total of fifty-one seismic refraction profile lines were run through the established traverses at an average lateral distance of about 300m in the West- East direction to generate both the P-wave and S-wave data. In - Line seismic refraction technique was carried out by placing 24 Geophones within a spacing of 5m from each other along the traverse line (Fig. 4). Geophones were driven into the ground and connected via cable to an ABEM Terraloc 6 seismograph. A 10 kg metal plate was placed 5 m offset from the first geophone, and a 15 kg sledgehammer was used to generate seismic P-waves.

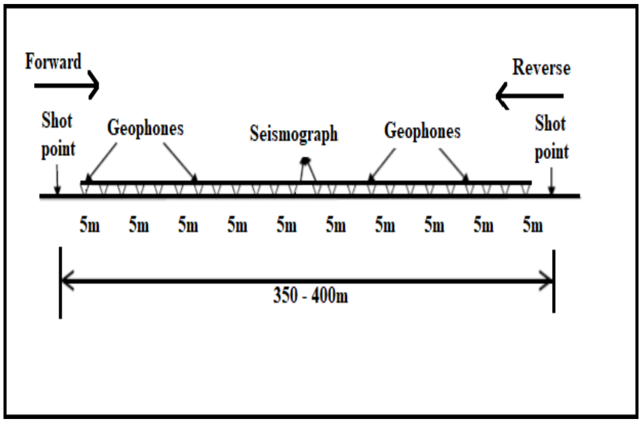

Fig. 4 Adopted data collection profile line.

Each impact shot was repeated (stacked) 2–10 times to boost the signal-to-noise ratio. During recording, the operator hit

"Record" on the seismograph as each shot was made. After each shot, the first-arrival travel times were averaged and saved in a data file labeled by geophone position. Then the geophones were moved along the line and a new shot was taken. This procedure was repeated until all offsets along a line were acquired. The Table 1 summarizes the general layout and procedure of the seismic short gathers conducted during the field survey. Each traverse consisted of a 24-geophone spread with 5 m spacing. Seismic energy was generated using a 15 kg sledgehammer striking a 10 kg metal plate, with shots fired at multiple offsets along each line to ensure full subsurface coverage.

Table 1. Summery of seismic gathers.

Traverse Line	File Range	Shot Positions	Remarks
Makun L1–L3	21502–21870	2.5 m offset (G1–G24), between G6–G7, G12–G13, G18–G19	Multiple shot gathers per line; east–west orientation
Makun L4–L6	21871–22110	Same as above	Consistent shot spacing and offset pattern

Data Processing

The acquired seismic data were processed with SeisImager 2D refraction software. This software is a fully integrated refraction modelling and interpretation software package that runs on Geometrics seismograph or PC. The first seismic refraction breaks were picked using the automatic pick function, with manual override. Figure 5a shows sample of picked data records. The picked first arrival times were plotted against the source-to-geophone distances to produce a set of travel-time-distance curves for each line.

Figure 5b shows sample of travel-time curve. All noisy signals were cleaned up with comprehensive filtering, and viewing of all prior picks were done simultaneously for shot-to-shot coherence. Both the primary (P-wave) and shear (S-wave) velocities were derived from the processed shot gathers. The P-wave velocities were obtained by using the seismic refraction tomography method, while the S-wave velocities were extracted by utilizing the multichannel analysis of surface waves technique (MASW).

Results and Discussion

Data Processing

The processed seismic refraction data revealed three distinct subsurface lithological units, characterized by their P-wave and S-wave velocity ranges. The P-wave velocities vary from 300 to over 2800 m/s, while S-wave velocities range from 86 to over 1890 m/s. These velocity contrasts allow the discrimination between unconsolidated topsoil/clay layer saturated sand horizon, and bituminous sand bodies.

Two prominent bituminous sand horizons were delineated across the survey area. The first horizon occurs at shallow depths, generally between 2 m and 15 m, with thicknesses ranging from 6 m to 12 m. The second horizon is more discontinuous but thicker, occurring at depths between 40 m and 130 m and reaching thicknesses of up to 45 m in localized depocenters. Figures 7 and 7 present representative P-wave and S-wave cross sections, respectively, showing distinct velocity layering and highlighting zones interpreted as bitumen-bearing sandstones.

The derived velocity models were consistent across multiple profiles, confirming lateral continuity of the bituminous sand horizons in several traverses. Table 5 summarizes the velocity ranges and corresponding lithological interpretations.

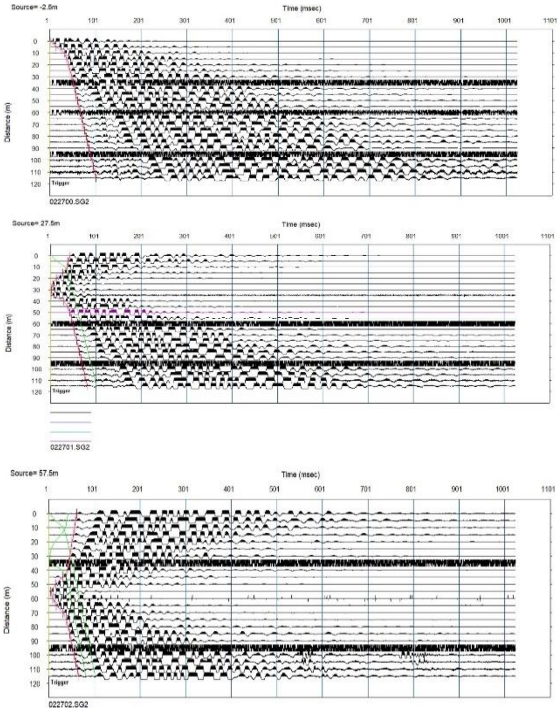

Fig. 5a Example of pick shot records from seismic refraction line.

The seismic refraction and MASW investigation conducted across Makun have provided new insights into shallow subsurface configuration of the Dahomey Basin, highlighting structural and stratigraphic controls on the bitumen occurrence. Interpretation of the P- and S-wave velocity models (Figs. 6, 7) reveals three major lithological units that broadly correspond to near-surface topsoil, the underlying lateritic or clayey sand sequence, and a deeper, more consolidated bituminous sand layer. The velocity contrasts defining these units are consistent with the known stratigraphy of Afowo Formation and its overlying younger sediments.

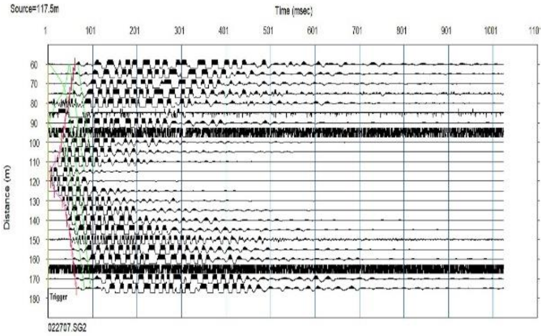

Fig. 5b Example of picked shot records from seismic refraction line.

Analysis and Interpretation

The processed seismic refraction data produced about three subsurface geo-earth materials. The P-wave velocity values obtained varied from 300 to over 2800m/s while the S-wave velocity varied from 86 to over 1890m/s. Figure 6 shows representative samples of P-wave cross section of the profile lines while Figure 7 shows representative samples of S-wave cross section of the profile lines. Table 5 shows the summary of the inferred P-wave and S-wave velocities of the entire project area with their corresponding inferred geo-earth materials.

P-Wave cross section: The P-wave (compressional wave) cross section provides a direct insight into the elastic and lithologic composition of the subsurface layers within the Makun area of the Dahomey Basin. The velocity distribution along the profiles shows three major horizons corresponding to topsoil, lateritic or clayey sand, and a deeper bituminous sand formation. The P-wave velocity varies from approximately 300 to 2,800 m/s, showing a systematic increase with depth, which reflects the progressive compaction and cementation of sediments. The first layer, characterized by velocities between 300 and 600 m/s, represents the unconsolidated topsoil comprising loose sandy-clay materials and organic matter. The low velocity is indicative of a high porosity, low density, and significant moisture content. This layer is thin, typically not exceeding 5 m, and functions as the weathered zone where energy attenuation is highest.

The second layer exhibits intermediate velocities ranging from 700 to 1,400 m/s, signifying lateritic or clayey sand that has undergone moderate consolidation. The increase in velocity compared to the topsoil suggests reduced porosity and partial cementation. The lateritic horizon is known for its heterogeneity, and this is reflected in lateral velocity fluctuations seen across the section. Such variations may be attributed to differences in moisture, clay fraction, and local lithology transitions. Gentle undulations observed along this layer's interface likely mark minor structural features such as shallow folds or erosional surfaces that influence near-surface drainage and bitumen migration.

The third and deepest layer on the P-wave cross section is marked by the highest velocities, between 1,800 and 2,800 m/s, and corresponds to the bituminous sand horizon. The distinct velocity contrast between this horizon and the overlying layers is indicative of higher stiffness and density due to bitumen impregnation and compaction. In typical hydrocarbon-bearing sediments, bitumen can sometimes reduce velocity due to its viscous nature; however, in this study, the high velocities are interpreted to result from cementation effects where bitumen acts as a binding agent, reducing pore space and enhancing the elastic moduli of the host sandstones.

The bituminous sand layer is laterally continuous across the section, but shows gentle structural undulations, suggesting the presence of shallow structural traps that control local bitumen accumulation. Areas of relatively higher velocity may correspond to more lithified or bitumen-rich zones, while lower velocity patches could represent less saturated or more porous sands. The correlation of these high-velocity zones with surface bitumen seeps provides strong evidence that this horizon represents the primary bitumen-bearing stratum in the Makun area. Overall, the P-wave cross section effectively delineates the subsurface layering and demonstrates the seismic expression of shallow structures influencing bitumen occurrence.

S-Wave cross section: The S-wave (shear wave) cross section obtained from the MASW inversion provides complementary information to the P-wave model by revealing the shear strength and rigidity of the subsurface materials. Because S-waves are not influenced by pore fluids in the same way as P-waves, they are particularly sensitive to lithologic stiffness, degree of consolidation, and cementation, thereby offering a more direct measure of mechanical properties within the bitumen-bearing sequence. The S-wave velocities across the study area range from about 150 to 1,800 m/s, following a similar three-layer structure as the P-wave model, but with more pronounced contrasts between horizons.

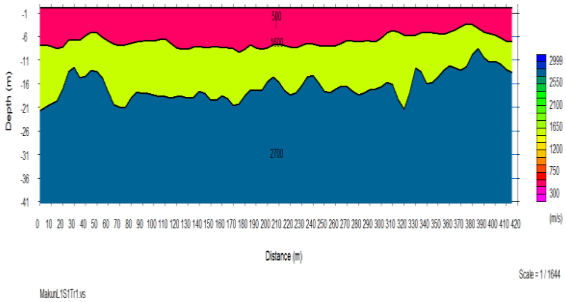

Fig. 6 Representative samples of P-wave cross section from Makun.

The uppermost layer exhibits shear-wave velocities between 150 and 300 m/s, typical of soft, unconsolidated surface soils with high moisture content and low shear strength. This horizon, generally less than 5 m thick, represents the highly weathered and compressible zone, which has little structural competence. Beneath this, the intermediate layer displays velocities between 400 and 900 m/s, corresponding to lateritic or clayey sand deposits. The increase in velocity signifies partial compaction and improved mechanical strength, consistent with the lateritic development common in tropical sedimentary terrains. Local variations in S-wave velocity within this zone may be linked to variable clay content, differential cementation, or fluctuations in the water table, which collectively control the shear response of the sediments.

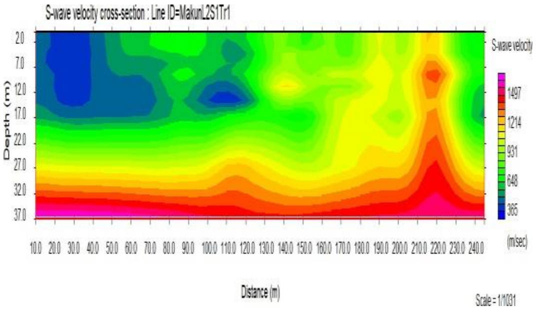

Fig. 7a S-wave cross section from Makun.

The deepest layer in the S-wave section shows velocities ranging from 900 to 1,800 m/s and corresponds to the bituminous sand horizon identified on the P-wave model. The high shear-wave velocity within this layer reflects the increased stiffness and elastic rigidity induced by bitumen saturation and compaction. Bitumen acts as a semi-solid cementing medium, filling pore spaces and strengthening the formation. The continuity of this layer across the section, along with observed lateral velocity variations, suggests a mechanically competent stratum with localized heterogeneity resulting from variable bitumen impregnation and lithologic composition.

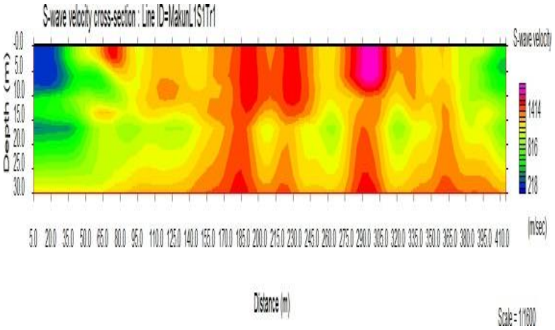

Fig. 7b S-wave cross section from Makun.

The alignment of high S-wave velocity zones with known surface seep areas supports the interpretation that the bituminous sand is both structurally and compositionally distinct from the overlying units. Additionally, the combined analysis of P- and S-wave velocities yields Poisson's ratio values of approximately 0.25-0.35, which are typical of moderately consolidated sedimentary rocks, further confirming the presence of compacted bituminous sands. In essence, the S-wave cross section reinforces the P-wave interpretation by providing a clearer view of the mechanical integrity and rigidity of the subsurface layers. It establishes that the bituminous horizon is a stiff, consolidated unit underlain and overlain by softer, less competent materials.

These mechanical contrasts not only explain the seismic velocity distribution, but also provide insights into how near-surface deformation and stratigraphic configuration control bitumen accumulation and entrapment in the Dahomey Basin. The integration of both wave types thus gives a robust understanding of the shallow subsurface framework and validates seismic refraction and MASW as reliable tools for mapping bituminous deposits in this geologic setting.

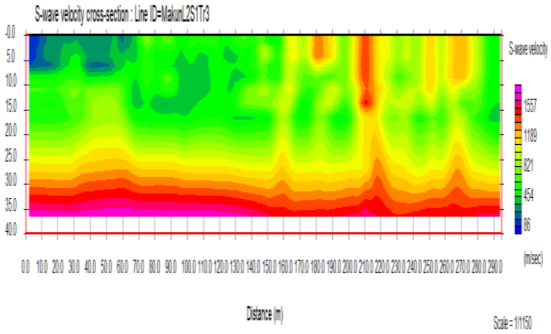

Fig. 7c S-wave cross section from Makun.

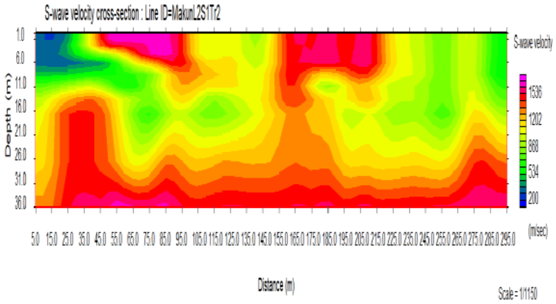

Fig. 7d S-wave cross section from Makun.

Table 2. Adopted P-wave and S-wave velocity values used for lithology delineation of the geo-earth materials within the project area (modified from Wolf, 2015).

	P-wave velocity (m/s)	S-wave velocity (m/s)	Inferred geo-earth materials
1	300 – 500	86 – 607	Top soil, clay, clayey sand,saturated sand
2	800 – 2800	178 – 1881	Bituminous sand

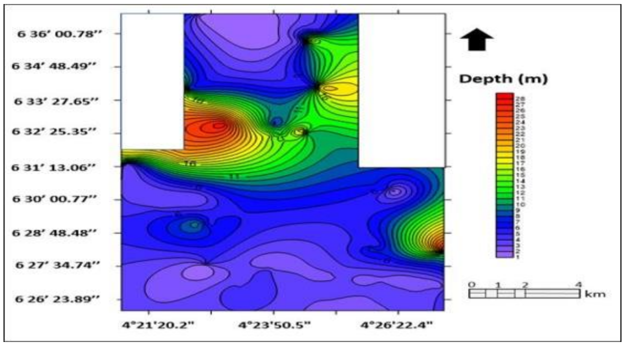

Fig. 8a Map of depth to bituminous sand layer for horizon 1.

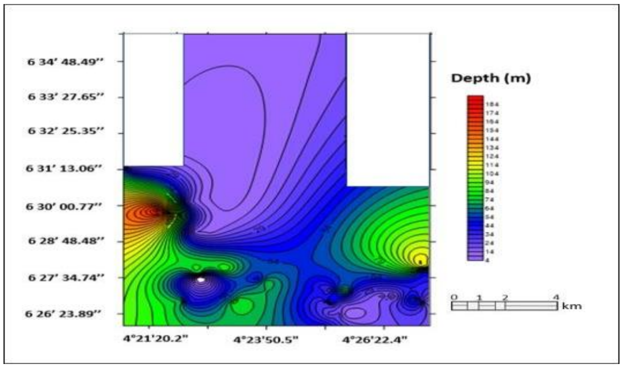

Fig. 8b Map of depth to bituminous sand layer for horizon 2.

Structures and stratigraphy: The integration of P-wave and S-wave velocities provides valuable insight into the lithological composition and geotechnical properties of the Dahomey Basin's shallow subsurface. The significantly higher velocities (P-wave: 800–2800 m/s; S-wave: 178–1881 m/s) associated with the bituminous sands reflect their degree of consolidation and hydrocarbon saturation, distinguishing them from overlying unconsolidated topsoil and clay layers. Structurally, the distribution and depth variability of the bituminous horizons suggest a control by fault-assisted migration pathways. The alignment of bitumen-rich zones with known fault trends in the basin indicates that vertical migration of hydrocarbons from deeper source rocks likely occurred along these extensional faults. This is consistent with previous studies linking the Araromi and Afowo source intervals to near-surface heavy oil occurrences (Toyin *et al*., 2024; Adekeye *et al*., 2023).

Stratigraphically, the bitumen-bearing units are interpreted as fluvial to shallow marine sand bodies of the Afowo Formation, later sealed by the overlying Araromi marine shales. This source–reservoir–seal configuration forms a classic petroleum system, where biodegradation near the surface transformed the oil into heavy bitumen. The observed lateral continuity of these sand bodies enhances their potential as targets for surface mining or thermal recovery methods such as Steam-Assisted Gravity Drainage (SAGD). From an exploration perspective, the velocity models delineate priority zones for bitumen development, particularly where thicker accumulations (>30 m) occur at shallow depths (<50 m), minimizing overburden removal costs. Additionally, the deeper horizon (>100 m) offers a potential resource for in-situ recovery operations.

Conclusion

This study successfully integrated seismic refraction and MASW techniques to map and characterize bitumen-bearing horizons in the Dahomey Basin. Three major lithological units were identified based on velocity contrasts, with P-wave and S- wave ranges clearly separating topsoil/clay, saturated sand, and bituminous sand.

Two distinct bituminous sand horizons were delineated, with thicknesses ranging from 6 m to 45 m and depths extending to over 130 m in some areas. The bitumen accumulations are controlled by fault-assisted migration pathways and stratigraphic continuity within Afowo sand bodies. The results support the presence of a working petroleum system in the Dahomey Basin, linking onshore tar sands to offshore oils.

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