Combined regional multibeam and seafloor sampling to derisk hydrocarbon exploration

Paolo Esestime[1*] and Felicia Winter[1] describe an integrated method to assess marine hydrocarbon seepage and de-risk the key elements of a petroleum system at both regional and prospect scale.

Introduction

The successful discovery of commercial volumes of hydrocarbons is strongly dependent on the correct assessment of the subsurface information such as the presence of a source rock, its depositional nature, distribution, and maturity. Understanding how these elements correlate with migration, charge and trapping mechanisms is the second most critical factor to increase confidence in the subsurface model.

State of the art technologies, especially seismic, provide advanced images of the subsurface for more reliable geological models. However hard data is crucial throughout the entire exploration lifecycle as calibrations may remain affected by several assumptions even in mature basins. Well data may be sparse or not representative especially if used in advanced seismic inversion and in the amplitude modelling of direct hydrocarbon indicators (DHIs).

Hydrocarbon seepages have driven historical exploration successes, particularly where the macro-seeps of liquid hydrocarbons are present. In the marine environment the sampling of hydrocarbon seepage is sometimes overlooked as an exploration tool, mainly due to difficulties in collecting sediment cores for full geochemical analysis (Abram, 2020).

In this article we present a two-step method to sample and interpret marine seepage through a systematic seafloor sampling campaign (Figure 1). The most suitable core locations are identified with the help of geophysical data, especially seismic, complemented by a multibeam survey that provides the acoustic properties at the seafloor and in the water column. The objective is to maximize the number of cores with viable presence of hydrocarbons, so called *positive cores*, which are then analysed for the much-desired geochemical information.

The multibeam seafloor sampling can be adjusted to match the requirements of the exploration challenges and based on the existing subsurface model to characterize the hydrocarbon families and their correlation with the source rocks. Positive cores, and those without hydrocarbons, are integrated into the subsurface model to refine the understanding of key factors like migration patterns, trapping mechanisms and charging scenarios (Figure 1). Lithologies and subsurface temperatures from the cores give additional constraints for the shallow geothermal gradient.

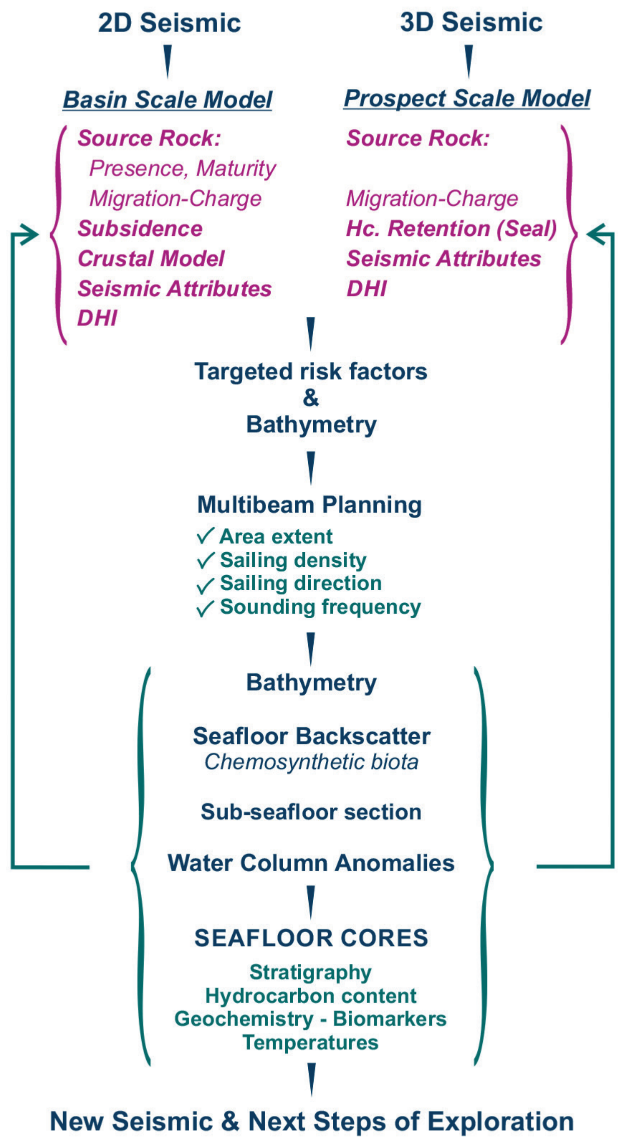

Figure 1 Schematic workflow for integration of the multibeam and seafloor sampling in the seismic and exploration life cycle.

Two case studies are presented in the following, where multibeam and seafloor sampling campaigns (MB&SS) were

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successfully integrated into the exploration cycle offshore West Africa: offshore MSGBC (Mauritania, Senegal, The Gambia, Guinea Bissau, and Republic of Guinea), and in deepwater Nigeria (Figures 2a and 2b).

Multibeam echosounder for seafloor core sampling of hydrocarbon seeps

TGS has combined multibeam and seafloor sampling surveys (MB&SS) to address several challenges of frontier and under-explored basins, from offshore Mexico to the western margins of Africa. These were based on a multiclient business model, to de-risk new and existing plays and to enable the identification of new prospects. The exploration challenges were properly defined with the existing seismic data, both 2D and 3D, to focus the multibeam and coring campaigns (Figure 2).

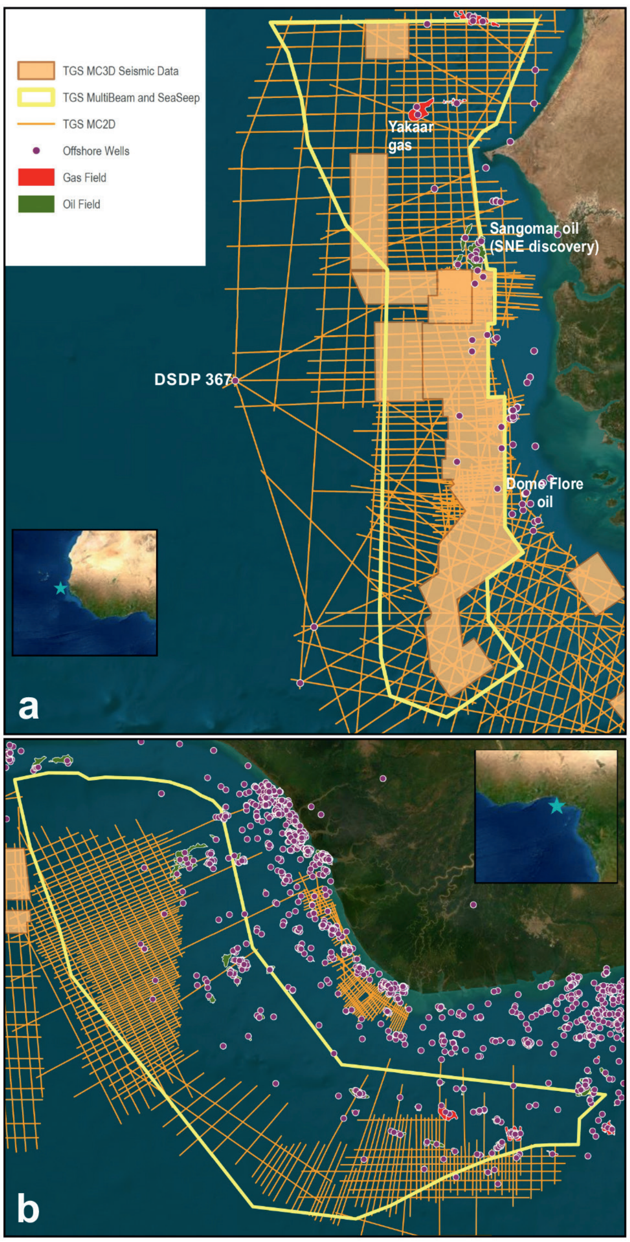

Figure 2 Area of the multibeam and seafloor sampling campaigns conducted by TGS in West Africa. a) MSGBC, offshore Mauritania, Senegal, The Gambia, Guinea-Bissau, and Republic of Guinea Conakry. b) Deepwater Nigeria.

Marine multibeam echosounder measurements are routinely used for geotechnical and environmental studies, as they provide bathymetrical reliefs up to a metre in resolution, at less than 30 m water depth. Basin-wide multibeam surveys can be scoped as part of the exploration strategy, as a complementary dataset to existing seismic, to help define the next seismic campaign (Figure 1). When compared to 3D seismic, multibeam techniques investigate the acoustic properties of both the water column and the near-surface seabed with higher resolution and at a fraction of its cost.

For regional MB&SS campaigns the overlap between the swaths of each sailing line can be reduced when compared to geotechnical hazard application allowing the vessel to efficiently cover basin-wide areas. The number of sailing lines per unit of area is the most critical factor when considering acquisition schedules and survey layout. This specification must be optimized for the water-depth to preserve a minimum overlap of never less than ~10-20%; however, 50% overlap is recommended in a wide range of marine environments. Multiple coverages are required if the seafloor morphology reduces the illumination at the swath boundaries' *grazing angle*'.

The complete survey for seafloor imaging combines the multibeam echosounder with the shallow seafloor profiler (sub-bottom profiler) for high-definition seismic data. The operational specs for both devices will depend on target-depths, lateral resolution and vertical penetration required. Common operating frequencies extend from 12 kHz to 30 kHz for a multibeam and from 3 kHz to 8 kHz for a sub seafloor profiler (Mitchel et al., 2018).

The water-column reflectivity is a by-product of the backscattering processing (Wenger and lsaksen, 2002; Urban et al., 2017; Zhao et al., 2017; Mitchell et al., 2018). This computation requires a correction for the different propagation angles within each swath. The residual deviation is modelled as different wave-paths, related to anomalies in the acoustic properties of the water column. The result is a 3D image of the waterbodies appearing as strings of bubbles rising from the seafloor as plumes characteristic of gaseous emissions. The location of the gas escape is then combined with the backscattering anomalies at the seafloor, to confirm the presence of a seepage, which makes the core sample more likely to be hydrocarbon-bearing (Orange et al., 2009).

Once MB&SS data is fully processed their joint analysis with the existing seismic data will open to aid new geophysical and geological interpretation, at the near seafloor depths (Figures 3a, 3b and 3c). More sophisticated modelling may be required for extrapolation at deeper levels of the results obtained from the MB&SS. However, even simple structural interpretation allows us to unravel hydrocarbon migration pathways and retention risks, providing those cores have been strategically located when planning the MB&SS campaigns.

The MSGBC MB&SS study

The MSGBC are the basins of the West African Margin that comprise offshore Mauritania Senegal, The Gambia, Guinea-Bissau, and the Republic of Guinea Conakry. The region hosts recent world-class oil and gas discoveries (e.g., Sangomar oilfield, Tortue and Yakaar gas discoveries). Modern broadband 2D and 3D seismic allowed structural and stratigraphic interpretation at both

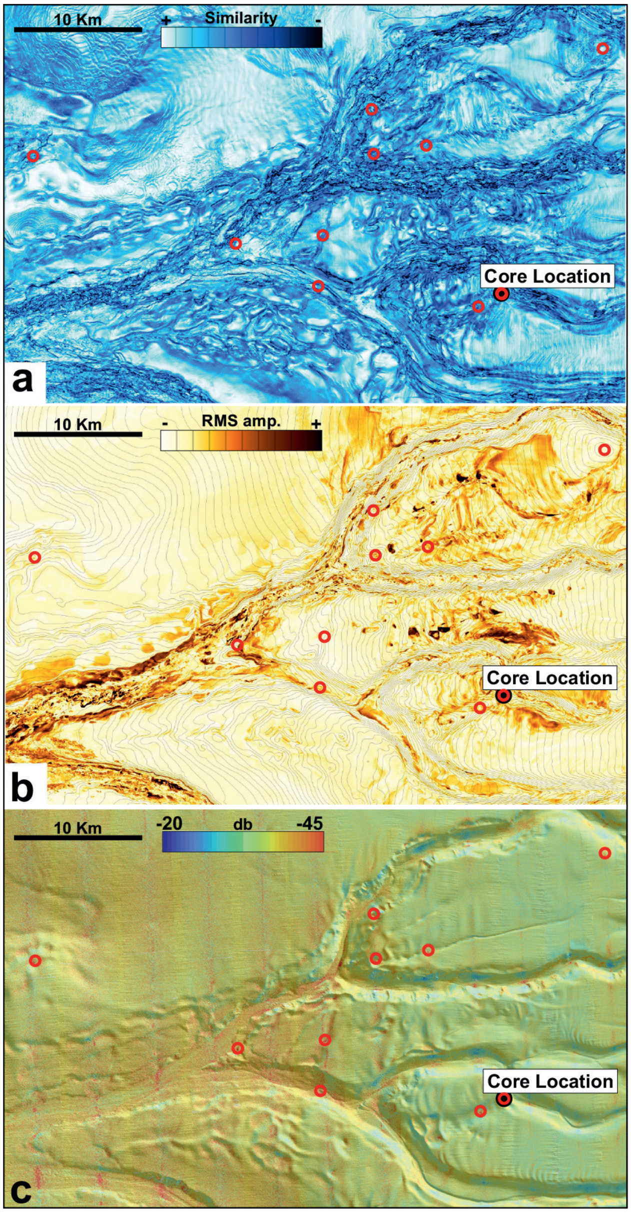

Figure 3 Joint analysis between seismic and multibeam data in the MSGBC Basin. The 3D seismic attributes are extracted in the first 60 m underneath the seafloor. Water column anomalies are indicated as red circles; a) similarity, attribute (structural discontinuities); b) RMS amplitude attribute; c) multibeam bathymetry with backscatter overlay. Data was produced in partnership with TGS, PGS and Geopartners.

basin and prospect scale (Figure 2a). The MSGBC MB&SS study was planned to de-risk the source rock presence in the shelf, the hydrocarbon maturity in deepwater, and to confirm the migration paths from the deepwater kitchen (Figure 4a and 4b).

In the Early Tertiary, marine transgressions led to the deposition of mixed carbonates and shales, a regionally viable seal for potential carbonate and clastic targets. The MB&SS data have confirmed the presence of mature source rocks in the shelf and deepwater domains, where several untested prospects and leads have been identified from modern broadband seismic data. However limited seismic evidence of hydrocarbon escapes exists, even from the known discoveries, which suggests an effective sealing capacity for the Late Cretaceous and Tertiary shales. The macro-seepages are concentrated on structures breaching from reservoir level to the seafloor, but not directly related to specific prospects or known accumulations (Figures 4a and 4b). This further suggests the presence of effective seals capable of retaining hydrocarbons despite the presence of shallow faults and other structural complexities.

A carbonate platform is regionally present, up to 6000 m thick, developed since the Jurassic period and mainly during the Cretaceous period (Figure 4a). The platform extends over continental crust stretched by several phases of rifting in the Palaeozoic-Triassic and the Lower Cretaceous, when the Atlantic Ocean opened (Soto et al, 2017; Esestime et al. 2020). The carbonates provide a thermally cold environment compared to clastic sediments. However, the heat generated from the continental crust may have increased the maturity of potential source rocks in the lower sediment section. The established basin temperatures over the shelf area are modelled by the oil-window of the oil type found at the Dome Flore prospect/discovery (Figure 2a), which is related to a lacustrine source rock, deeply buried within the inboard salt-basin of the Guinea platform. The platform has several clastic intercalations one of which is known as the reservoir of the Sangomar oilfield. Outboard carbonate build-ups and karstification may have resulted from various phases of uplift in the Late Cretaceous period providing additional traps at the palaeo-shelf edge trend. An oil-generative marine carbonate source rock has been confirmed on the platform by the MB&SS campaign which is not related to the source previously described for the Dome Flore discovery. These hydrocarbons have likely migrated through 4000-5000 m of shallow water carbonates where only a few faults and fractures are present. This insight opens a new play concept, with hydrocarbon migration independent from the enigmatic oil source at the Dome Flore (Figure 2a).

A steep slope marks the abrupt transition from the carbonate platform into the deepwater clastics, also interpreted as one of the main migration pathways. The outboard deepwater petroleum system is established by the Sangomar oilfield and the FAN-1 south discovery. The presence of oil-prone Aptian pelagic source rock gives evidence for medium-to-long-distance migration further confirmed by the MB&SS data. The migration paths concentrate along the carbonate slope and connect the deepwater kitchen to a variety of structural and stratigraphic prospects at the shelf edge. This kitchen has a thermal regime favourable for oil as well as gas (e.g., Tortue and Yakaar and Great Tortue Ahmeyim (GTA)). Additional source rocks have been identified in the Turonian-Cenomanian shales from the DSDP borehole 367 (Figure 2a). The MB&SS campaign confirmed different oil and gas provinces, predominantly oil-generative, despite the presence of gas fields in northern Senegal.

Deepwater Nigeria MB&SS study

Nigeria's prolific basin at the eastern end of the Gulf of Guinea is dominated by a broad shelf hosting the Niger Delta. This world-class delta extends from the onshore areas as far out as into deepwater offshore Nigeria, partially over the oceanic crust. The deltaic progradation can be subdivided into two main lobes, northwest and southeast, with a similar structural evolution. The lobes are controlled by gravity-driven systems, detached on regional shales, which led to the formation of extensional faults inboard, and the famous fold and thrust belts in deepwater.

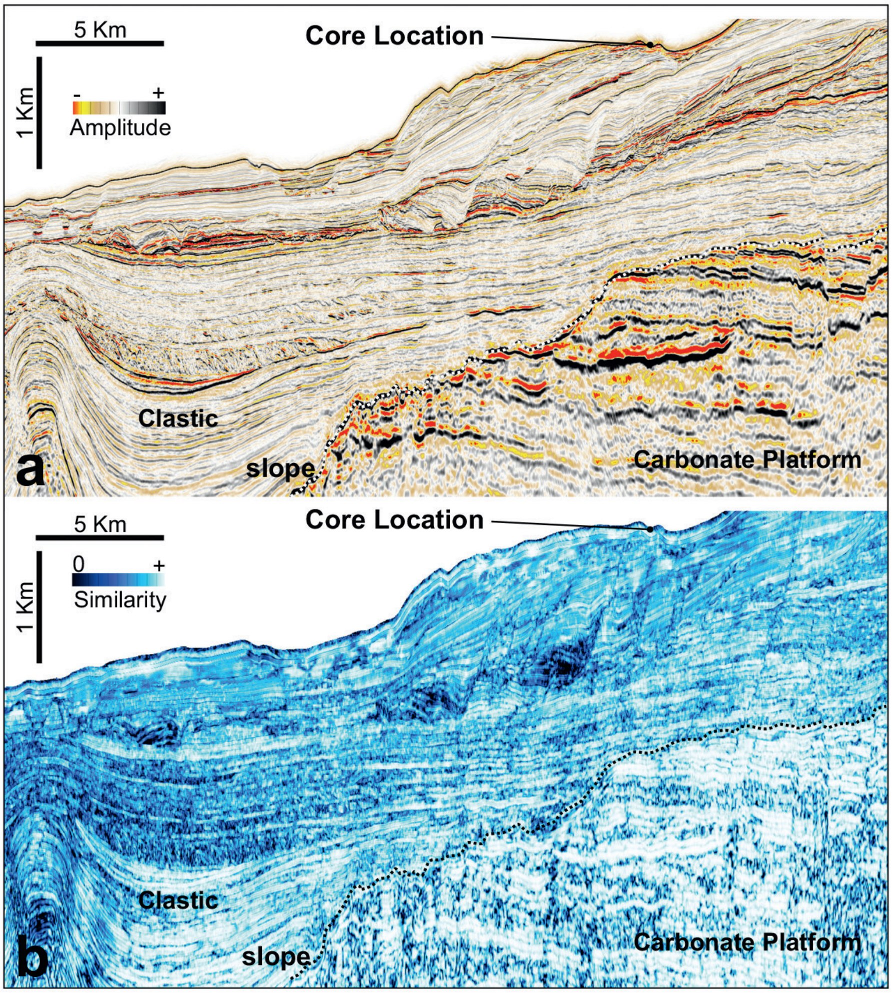

Figure 4 Joint analysis of 3D seismic and core samples in the MSGBC Basin. This oil-bearing core is located over a fractured overburden along a regional migration pathway, connecting the Cretaceous carbonate platform with the clastic basin; a) Kirchhoff pre-stack depth migrated section; b) depth similarity attribute. Data was produced in partnership with TGS, PGS, GeoPartners.

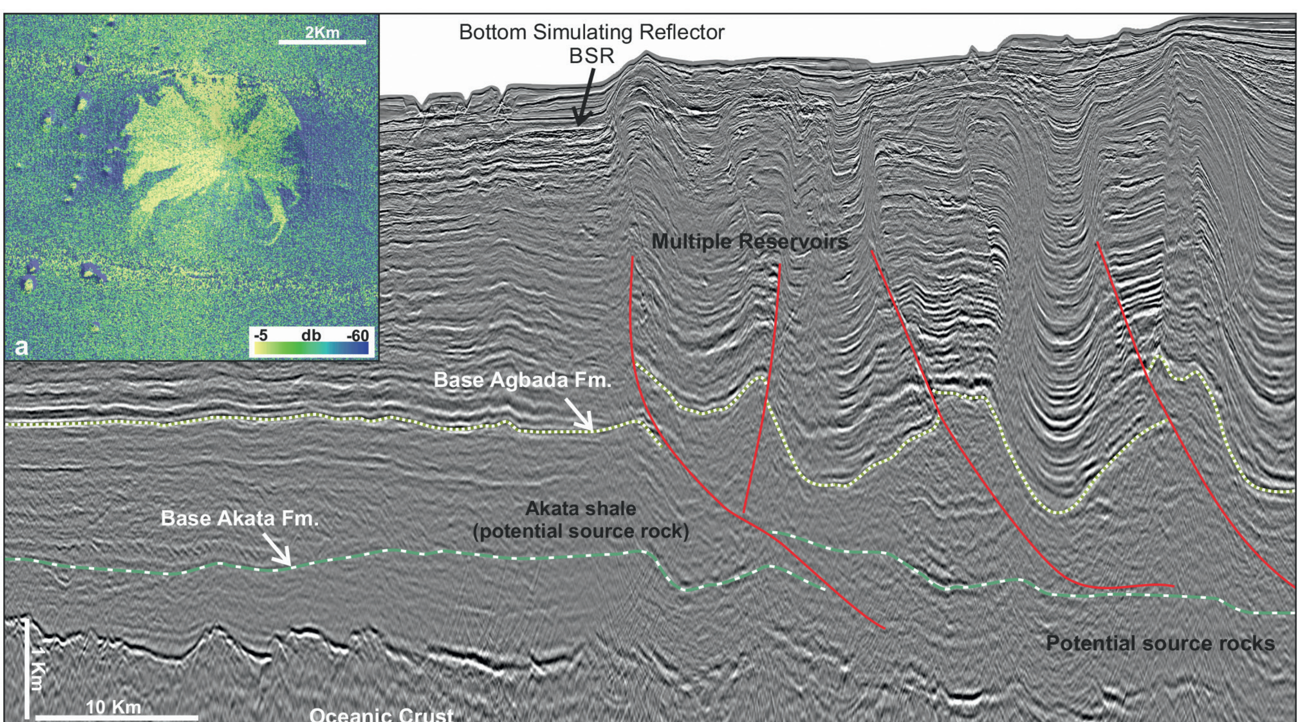

Figure 5 The 2D Kirchhoff pre-stack depth-migrated section from deepwater Nigeria shows the main petroleum system elements. Inset figure a) shows the backscatter over a mud-volcano, the active seepage is visible of the bright flows on its flanks, presumably tars. Data was produced in partnership with TGS and Petrodata.

Hydrocarbon exploration is relatively mature in the nearshore and in shallow water where numerous oil and gas discoveries have been made and are currently in production. Exploration did not extend much into the deepwater domain as the effectiveness of the petroleum system is challenged by various factors, among others: 1) the reduced sediment thickness in the overburden (less than 3000 m); 2) the uncertainty of the source rock presence and maturity; 3) the presence of oceanic crust, providing a cooler thermal regime.

Offshore Nigeria the MB&SS effectively de-risked the deepwater petroleum system. These campaigns were focused on extending the inboard petroleum system to include the outermost deepwater fold and thrust belt and even beyond (Figure 2b).

The petroleum potential is mainly related to the Cretaceous-Quaternary intervals which have a thickness of 10-12 km in the shallow water and 5000-6000 m in the deepwater domains (Figures 2b and 5). This interval is subdivided in two regional *megasequences* named as the Akata and Agbada Formations. Their boundaries have been defined from onshore analogues (Morgan, 2004), and based on seismic characters. The Akata shales have a widespread thickness of approximately 1000-1500 m; however, this may be underestimated. The 2D seismic data shows similar seismic facies down to the first post-rift record, above the extended continental and oceanic crusts (Figure 5). The Akata formation is known to be a source rock in the inboard, and an excellent candidate for the deepwater once organic contents and thermal maturity are proven. The Akata shales are overlain by several potential reservoirs of to the Agbada Formation.

The Agbada Formation is a clastic deltaic system, developed from deepwater conditions since the Miocene period and during the Quaternary period. It reaches 5000 m in thickness at 2000 m water-depth, and gradually reduces to 2500 m in the most distal sectors. The lower reservoirs are expected to be in the deepwater lobes of the delta, providing stacked reservoirs in the inboard and outboard fold and thrust belts, changing upward into channelized systems in the fold valleys. These structures partially breach the seafloor and are controlled by the local sedimentation of the Agbada Formation (Figures 6a and 6b). The seal is provided by interbedded shales.

The MB&SS has confirmed that the hydrocarbon-bearing cores often align with the large folds and thrust-related anticlines that breached the seafloor surface and extended deep enough to reach the top Akata Formation (Figures 5, 6a and 6b). Those structures were assumed to be the best migration pathways to be tested for seepage, as detachment levels run in the Akata Formation, and are potentially related to oil-prone overpressured shales. This hypothesis was confirmed by the presence of mud diapirs in the subsurface, later proven by the recovery of hydrocarbons directly flowing to the seafloor from a mud volcano (Figure 5a).

The MB&SS campaign identified several oil families that now can tentatively be correlated with structural trends in the reservoirs mapped. Single anticline structures may have multiple charged reservoirs, a trapping mechanism already established by the inboard discoveries, and suggested by seismic DHIs (Figure 6a and 6b). Further exploration will also confirm if the oil generative source rock outboard can be related to the Akata shales or to a deepwater equivalent. New 3D seismic data is required to determine the full model of migration, charge, and retention, and to confirm the presence of economical hydrocarbons in the deep water.

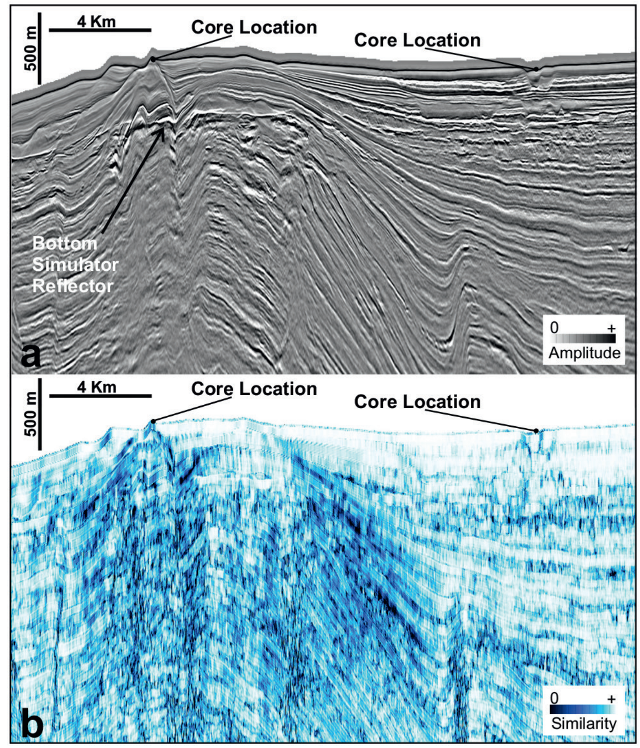

Figure 6 Joint analysis of 2D seismic data and core samples in deepwater Nigeria. The cores are hydrocarbon-bearing, which are leaking to the seafloor from shallow fractures. Several stacked reservoirs are present in the subsurface fold, featuring a gas hydrate signature below seabed (bottom simulating reflector) a) Kirchhoff pre-stack depth migrated section; b) depth similarity attribute. Data was produced in partnership with TGS and Petrodata.

Conclusion

MB&SS campaigns are strategic tools in hydrocarbon exploration, for complementing and adding value to the existing seismic and to address future acquisitions. We presented a workflow to sample and interpret the marine hydrocarbon seepages from seafloor coring campaigns based on seismic and multibeam surveys (Figure 1). The workflow is aimed at de-risking basin-wide elements of the petroleum system, as source rock presence and maturity. Where 3D seismic is available, the MB&SS can be focused on de-risking migration, charge, and retention, in specific hydrocarbon prospects and/or set of prospects.

Recovery of hydrocarbons is the main objective and the geochemical categorisation of the seeps according to their attributes will provide the basis for source-to-source and oil-to-source correlations, crucial information to develop new and existing exploration targets. All cores sampled, with or without hydrocarbons, may contribute to refining the migration and charge-retention models, as result of a joint analysis with seismic and other geophysical data available (Figures 3a, 3b, 3c).

The MB&SS collected in MSGC and Nigeria have facilitated the evaluation of the entire basin and provided a robust de-risking tool for source rock presence, hydrocarbon migration and charge (Figures 2a and 2b).

In the MSGBC new insights are helping to de-risk migration and retention of the hydrocarbon in the numerous prospects identified from the 3D seismic data, some of which is already proven (e.g., Sangomar oilfield). In deepwater Nigeria, the presence of a working hydrocarbon system has been confirmed. The high rate of success in recovering hydrocarbon-bearing cores suggests that new exploration opportunities are waiting to be unlocked, among those are thrust-related anticlines, with multiple pays vertically stacked.

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