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Comparison of the Petroleum Geology in the Deep-Water Basins between the Passive Margin of Morocco and Its Conjugate Margin of Canada

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ABSTRACT: This paper systematically investigates and compares the petroleum geology elements and oil and gas exploration potential in the deep-water basins along the conjugate passive margins between Morocco in NW Africa and Nova Scotia in Canada. Both the deep-water basins along the passive margin in Morocco and its conjugate passive margin deep-water basin in Nova Scotia have undergone similar multiple stages of tectonic evolution. These conjugate basins both have Jurassic and Cretaceous source rocks; Triassic sandstone, Jurassic–Cretaceous carbonate and sandstone, and Miocene–Pliocene sandstone reservoirs; multiple sets of mudstones and regional Triassic salt as caprocks. These characteristics indicate good hydrocarbon accumulation conditions and exploration prospects. The comparison also reveals that the key exploration targets in the deep-water basins of Morocco should be Tertiary turbidite sandstone reservoirs and Jurassic–Cretaceous sandstone and carbonate reservoirs. Compared with the Scotian Basin, the Morocco deep-water basins may have Paleozoic play potential sourced from the mature Silurian hot shale source rock that extends from the onshore NW African Plate. The prospective exploration targets in the deep-water Scotian Basin should be focused on the Jurassic and Cretaceous deep-water turbidite sandstone reservoirs formed by widely-developed large river systems.

KEY WORDS: conjugate margins, Morocco, Nova Scotia, tectonic evolution, petroleum geology, exploration potential.

0 INTRODUCTION

Recently, conjugate margins have been a research focus for explorations of petroleum deposits and investigations of Earth history, plate tectonics, ocean science, basin evolution, etc. Atlantic margins are a type conjugate margin, and they have been studied to reveal the evolution process of rifted continental margins and lacustrine to deep-water turbidite depositional systems. Many of the major hydrocarbon-bearing basins of passive continental margins are distributed on both sides of the Atlantic Ocean. Most basins in the Atlantic margins remain under-explored despite ongoing production in some basins since the 1970s. At present, many hydrocarbon discoveries have been made in the passive margin basins of the Gulf of Mexico and Brazil and West Africa on both sides of the South Atlantic Ocean (Modelevsky and Modelevsky, 2016; Zou et al., 2015; Liu et al., 2008). However, due to differences in evolutionary time span and geologic history during the evolution between the basins at the passive continental margin of the Central Atlantic and the South Atlantic, these basins have different petroleum systems and hydrocarbon distribution characteristics (Tari et al., 2012). Fewer oil and gas exploration activities and limited oil and gas discoveries have occurred in the passive continental margin basins along the Mid-Atlantic Ocean compared with those along the South Atlantic Ocean. This difference is especially apparent in the Moroccan deep-water basins of the passive continental margin along the east coast of the Central Atlantic Ocean, which has a current water depth of 200+ m based on IHS or basin with deep-water deposits; in addition, the proven oil recoverable reserves of the basins are only 37 million bbls and natural gas recoverable reserves are only 0.68 Tcf (IHS Markit, 2017) and the majority of the oil and gas discoveries occurred on land. Compared with the onshore area, the offshore area of Morocco is characterized by limited hydrocarbon exploration activities, few discoveries and few drilled wells, e.g., only 1 subsea gas field and 2 subsea oil fields with relatively small reserves were found. In contrast, the Scotian Basin in offshore Canada, which represents the conjugate continental margin of the Moroccan offshore area, has proven recoverable reserves of 1.4 billion bbls of oil and gas (IHS Markit, 2017; Tari et al., 2012; Labails et al., 2010), which is almost 40 times more than that of the Moroccan offshore area. Therefore, the deep-water basins in the passive margin offshore

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Morocco may have good potential for oil and gas exploration since they have a similar geology as the conjugate Scotian Basin. The purpose of this study is to compare the geologic evolution and petroleum geology in the deep-water basins between the passive margin of Morocco and its conjugate margin to investigate the differences in geology and future exploration potentials. Based on the theory of plate tectonics and an analysis and compilation of regional geological data, including basin evolution, stratigraphic correlation, source rock and reservoir data, the characteristics of the oil and gas geology in the deep-water basins of offshore Morocco and along the Canadian conjugate passive continental margin were compared to reveal their similarities and differences in geologic history, basin evolution, petroleum systems and hydrocarbon exploration potential. The results can provide a reference for the study of tectono-sedimentary evolution, petroleum geology and hydrocarbon exploration in deep-water basins along the passive margins of the Mid-Atlantic Ocean and in other similar conjugate passive margin basins.

1 REGIONAL PROFILE

Classic shallow to deep-water basins widely developed in the passive margins along both sides of the Atlantic Ocean, and these basins are characterized by similar tectono-sedimentary evolution (Tari et al., 2012; Labails et al., 2010). Four sedimentary basins formed offshore Morocco: Rharb, Doukkala, Essaouira and Tarfaya from north to south (Davison, 2005). Across from the offshore Morocco region, the Scotian Basin formed along the Canadian Nova Scotian margin conjugates to Morocco (Fig. 1). The basins along the passive margin of Morocco have experienced evolutionary stages of Cambrian rifting, Ordovician–Devonian passive continental margin development, Carboniferous–Permian Hercynian foreland effects, Triassic rifting and passive continental margin development since the Jurassic. The Rharb, Ducara and Essaouira basins experienced uplift and denudation due to the Atlas orogeny (Davison, 2005; Hafid, 2000). The Scotian Basin of Canada and the sedimentary basins of offshore Morocco have experienced a similar evolution, including rifting and passive continental margin development since the Triassic, while the pre-Triassic strata developed in the Moroccan side seem to be absent in the Canadian side. With the gradual expansion of the Atlantic Ocean, these basins on both sides developed a similar paleogeography, basin structure and stratigraphic sequence (Campbell et al., 2015) , which can be clearly seen from the paleogeographic map generated by Gplate software constrained by tectonic setting and depositional environments (Fig. 2). However, the strata in the sedimentary basins offshore Morocco are more completely developed and include Paleozoic–Cenozoic sedimentary strata. During the Cambrian–Ordovician, the entire Moroccan region was part of Gondwanaland and dominated by sandy sediments; during the Silurian, extensive transgression created mudstone deposits rich in organic matter (Gambacorta et al., 2016); during the Late Carboniferous–Permian, the strata were uplifted and denuded due to the Hercynian orogeny; and since the Triassic, the Pangea continent has been gradually broken up and offshore Morocco has experienced an extensional movement. In addition to carbonate rock, sandstone and mudstone formations, regional evaporites also formed in a restricted environment (Michard et al., 2008; Davison, 2005). In particular, the Tafelney Platform area of Morocco shows widely developed evaporative salt rocks and thicker sedimentary strata above the salt compared with that in the corresponding parts of the Scotian Basin (Tari et al., 2012). These evaporites can provide

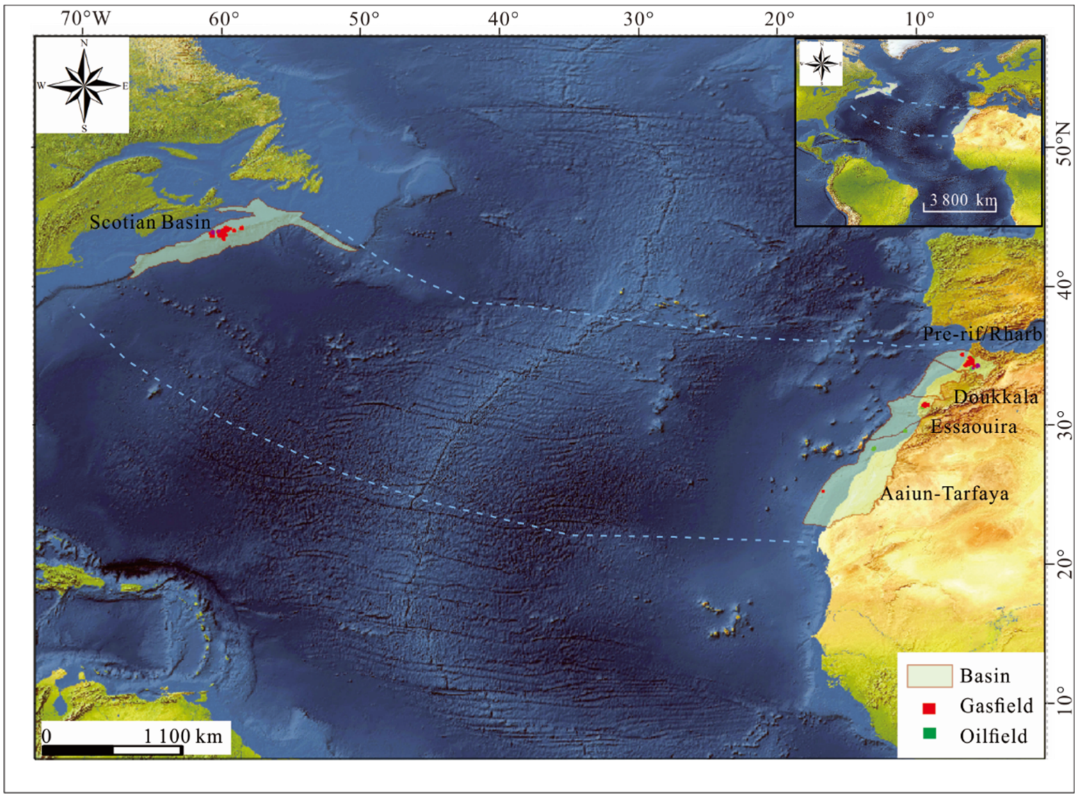

Figure 1. Regional map showing the distribution of conjugate passive continental basins in Morocco and Canada across the Central Atlantic Ocean.

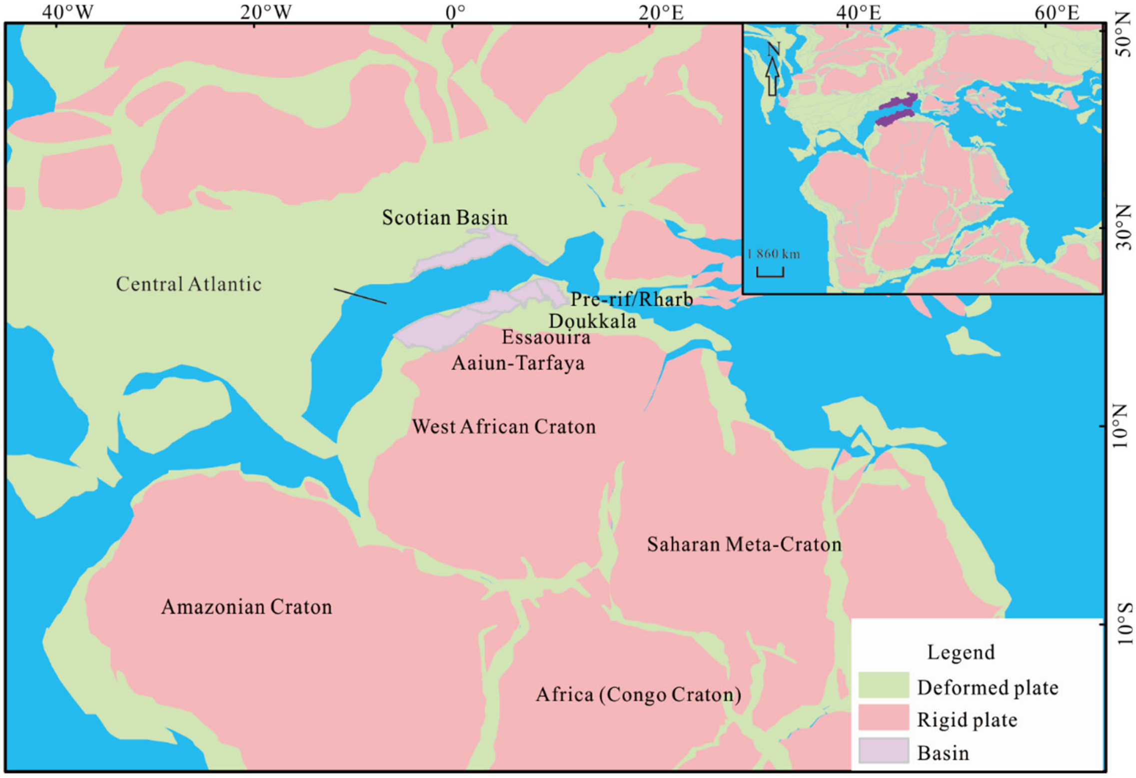

Figure 2. Paleogeographic map showing conjugate offshore basins in Morocco and Canada during the Jurassic (160 Ma).

good seals for oil and gas plays. The Scotian Basin of Canada formed on the Precambrian crystal basement of Laurasia and has undergone sedimentation since the Triassic breakup of Pangea.

In the sedimentary basins of offshore Morocco, Triassic evaporite, Triassic source rocks, and Cretaceous and Tertiary mudstone, shale, sandstone and carbonate reservoirs (Dutuc et al., 2017) provide good hydrocarbon accumulation conditions. In general, the deep-water basins along the passive margin in Morocco have experienced multiple stages of basin evolution during the Paleozoic, Mesozoic and Cenozoic; however, the Canadian deep-water Scotian Basin only experienced basin evolution during the Mesozoic and Cenozoic.

2 DATA AND METHODS

The research data of this paper are mainly compiled from a large number of published and unpublished data, including data from 115 wells and 22 seismic cross sections covering Novo Scotian Basin and its conjugate basins in Morocco. In addition, the geologic, reservoir, source rock and production data from several commercial databases from IHS and Wood Mackenzie are also used to analyze the geologic evolution and petroleum systems regionally and locally. Gplate software was employed to reconstruct the paleoplate locations of Morocco and Nova Scotia in Canada and their surrounding regions during the Early Silurian to reveal the paleogeography. Based on seismic data and drilling data interpretations and statistical and analysis results for the source rocks, reservoirs, and reserves between the different basins, systematic investigations and comparisons have been performed for the petroleum geology elements, such as source rocks, reservoirs, and cap rocks, in the deep-water basins along the conjugate passive margins of Morocco and Nova Scotia, Canada. In combination with the structural and sedimentary evolution of the two sides of the Central Atlantic Ocean, the differences and similarities in hydrocarbon source rocks, reservoirs, traps, seal, and play types in basins on the two sides are analyzed. Finally, the deep-water oil and gas exploration potential of the Atlantic Ocean passive margin basins are discussed based on the geology, petroleum system, and reserve characteristics.

3 COMPARISON OF THE PETROLEUM GEOLOGY BETWEEN OFFSHORE MOROCCO AND NOVA SCOTIA IN CANADA

The Morocco area experienced multiple stages of geological evolution and has undergone sedimentation since the Precambrian. The area hosts multiple sets of marine and continental deposits from the Precambrian, Paleozoic (Cambrian, Ordovician, Silurian, Carboniferous and Permian), Mesozoic (Triassic, Jurassic and Cretaceous) to Cenozoic as well as multiple sets of source, reservoir and cap rocks from the Paleozoic to the Cenozoic, which constitute multiple sets of source-reservoir assemblages. In comparison, the strata developed on the Canadian side include only sandstone, mudstone, carbonate rock and salt rock from the Triassic to the Tertiary, and the plays were mainly deposited during the Jurassic and Cretaceous (Fig. 3). Triassic, Cretaceous, Jurassic and Tertiary plays have been discovered in the onshore Morocco area. Oil and gas discoveries have also been made in the offshore Morocco area. In 1969, the Ras Juby Oilfield in the Upper Jurassic carbonate was discovered offshore in the Tarfaya Basin. In 2009, the Anchois Gas Field in the Eocene–Miocene deep-water turbidite sandstone was discovered in the Rharb Basin. In 2014, the Sidi Moussa 1 Oilfield in the

Upper Jurassic shallow-water carbonate was discovered in the Aaiun-Tarfaya Basin (IHS Markit, 2017). The above findings show that the deep-water basins along the passive continental margins offshore Morocco should also have favorable conditions for hydrocarbon accumulation. According to the Canadian Association of Petroleum Producers, the first offshore well in Nova Scotia was drilled in 1967 and the first offshore discovery occurred at Sable Island in 1971. To date, approximately 127 exploration wells have been drilled in offshore Nova Scotia, resulting in 23 significant discoveries. Petroleum exploration has been conducted in the onshore sedimentary basins of Nova Scotia since the 1860s. More than 125 exploration wells have been drilled in various onshore areas, with small amounts of petroleum discovered in approximately one-third of these wells. To date, there has not been any commercial production of oil or natural gas resources in onshore Nova Scotia.

3.1 Comparison of Source Rocks between Offshore Morocco and Nova Scotia

The geochemical parameter total organic carbon (TOC) of the shale/mudstone and marl in the offshore Morocco area and Canada, which are along the eastern and western sides of the Central Atlantic Ocean, respectively, indicates that the Jurassic and Cretaceous mudstones are two major source rocks rich in organic matter (Davison, 2005) (Table 1). Potential source rocks could be found in the unexplored Silurian, Devonian, Carboniferous and Triassic strata. The Jurassic source rock, which mainly formed in a shallow sea to bathyal environment during the passive continental margin stage, has primarily Type II organic matter, TOC contents of 0.4%–4.3% (1.6% on average), and R_o values of 0.8%–1.8%. The Jurassic source rock began to generate oil and was also in the gas generation stage in the Late Cretaceous. The Upper Jurassic Oxfordian shales in the Essaouira Basin are a good source rock with Type II kerogen, TOC up to 4.3%, and thickness of at least a 10 m (Davison, 2005). The Cretaceous source rock, which mainly formed in an open bathyal to deep-sea environment during the passive continental margin stage, largely presents Type II/III organic matter and has TOC contents of 1.6%–2.8% (1.8% on average) and R_o values>0.5%. The Cretaceous source rock began to generate oil in the Pliocene and has remained in the oil generation stage. Five sets of hydrocarbon source rocks are observed in the Scotian Basin, and they range in age from Aptian, Valanginian, Tithonion-Kimmeridgian, and Callovian to Early Jurassic (Association (OERA), 2016). The hydrocarbon source rocks of the lower cretaceous Aptian and Valanginian deltaic mudstone have Type III kerogen and the average TOC values of 2% and 1.5%, respectively (Association (OERA), 2016). The Upper Jurassic carbonate platform-delta transitional mudstone of the Tithonian Verrill Canyon formation is the main hydrocarbon source rock of this basin, and it presents Type II-III kerogen and an average TOC values of 3% (Association (OERA), 2016). The source rock of Middle Jurassic Miaine stage fluvial mudstone has Type II, III kerogen and a TOC value of 2% (Association (OERA), 2016). The hydrocarbon source rock of Lower Jurassic drift stage marine mudstone has Type II kerogen and a TOC values of 0.5%–2.49%, which is similar to that of Morocco. In general, the main hydrocarbon source rocks on both sides are distributed in Jurassic and Cretaceous mudstone strata. However, due to the differences in sedimentary environments after the rifting of the Atlantic margins, the Mesozoic delta in the Scotian side is more widely developed and the high amount of terrestrial input produced more gas-prone source rocks, whereas the Moroccan side has more oil-prone source rocks.

Table 1 Petroleum system elements for hydrocarbon accumulation factors in conjugate sides of Central Atlantic passive margin basins

Region	Basin	Oil and gas accumulated elements		
		Source rock	Reservoir	Seal
West coast of Central Atlantic	Scotian Basin	Jurassic–Cretaceous shale, Type II/III kerogen, with an average total organic carbon (TOC) of 3%, up to 10%	Upper Jurassic to Lower Cretaceous sandstones, with porosity of 2%–39.1% and permeability of 0.12–2 380 md	Jurassic–Cretaceous shale
East coast of Central Atlantic	Rharb Basin	Lower and Middle Jurassic shale and marl, mainly Type II/III, with the TOC values of 1%–7%	Paleozoic fractures and decomposed granite, Lower Jurassic sandstone and carbonate rocks, and Miocene sandstone and limestone; up to 8% porosity and 700 md permeability in the fractured granite reservoirs; 20% porosity and 1 000 md permeability in the Lower Jurassic sandstone reservoir	Tortonian mudstone of the Miocene
	Doukkala Basin	Silurian black shale, mainly Type II/III kerogen, with a maximum TOC value of 2.4%	No proven reservoir, potential Jurassic submarine fan sandstone with average porosity of 15%	Paleozoic–Cenozoic multiple mud-rock layer
	Essaouira Basin	Oxfordian Marine shale of Upper Jurassic, Type II kerogen, with the TOC values of 0.49%–4.3%	Upper Jurassic Oxfordian sandy dolomite with a porosity of 5%–20%, and a permeability of 2–80 mD, Upper Triassic fluvial sandstone and Lower Jurassic marginal Marine sandstone	Triassic–Jurassic evaporite and inner shale
	Tarfaya Basin	The Lower Jurassic–Middle Jurassic mudstone with TOC values of 0.5%–2.49%, Type II/III kerogen, and HI of 500–700 mghc/gTOC; Upper Cretaceous shale with a TOC values of 1.6% to 2.8% and Type II kerogen	Upper Jurassic limestone with porosity of 5%–35% and average porosity of 10%	Upper Jurassic and Lower Cretaceous shale and Upper Cretaceous and tertiary shale

3.2 Comparison of Reservoirs and Caprocks between Offshore Morocco and Nova Scotia

In the offshore Morocco area, the proven reservoirs are mainly observed in the Upper Jurassic carbonate rock and Miocene–Pliocene sandstone reservoirs (Table 1), while the potential reservoirs are observed in Triassic sandstone, Lower–Middle Jurassic sandstone and carbonate rock, and Cretaceous sandstone and carbonate rock (Fig. 3). The Upper Jurassic carbonate reservoirs mainly formed in the shallow sea environment of the passive margin (Addi and Chafiki, 2013). The Upper Jurassic carbonate reservoir in the Cap Jub Oilfield of the Tarfaya Basin has a depth of 2 982 m, a porosity range of 5%–35%, and an average porosity of 10% (IHS Markit, 2017). The Early Cretaceous Neocomian submarine delta fan developed in the Tarfaya and Essaouira basins of offshore Morocco, and they could host good sandstone reservoirs (Sibuet et al., 2012). The Miocene–Pliocene turbidite sandstone reservoirs were mainly formed in the deep-sea environment during passive continental margin. The Middle Pleistocene–Pliocene turbidite sandstone reservoirs in the Anchois Gas Field in the Rharb Basin have a depth of 2 359 m and a maximum net thickness of 40 m (IHS Markit, 2017). A fair amount of natural gas reserves have been found in the Triassic sandstone reservoirs in the Tendrara Oil Field of the Atlas Basin, indicating that Triassic sandstone reservoirs may also be deposited in the offshore Morocco area. Reservoirs of the Scotian Basin are from the Upper Jurassic to Lower Cretaceous deltaic sandstones sediments of the Missisauga and Logan Canyon formations, which have a thickness of several kilometers, porosity of 2%–39.1%, and permeability of 0.12–2 380 md (Zhang et al., 2015). In addition to the mudstone caprocks in the Middle Jurassic–Pliocene strata, Triassic evaporite (salt) rocks are distributed across the whole basin in offshore Morocco in the form of salt walls, salt domes and salt stock canopies, which pierce into the Tertiary strata (Fig. 3) and provide favorable structures for oil and gas accumulation (such as presalt anticlines and post-salt anticlines and monoclines) and capping conditions.

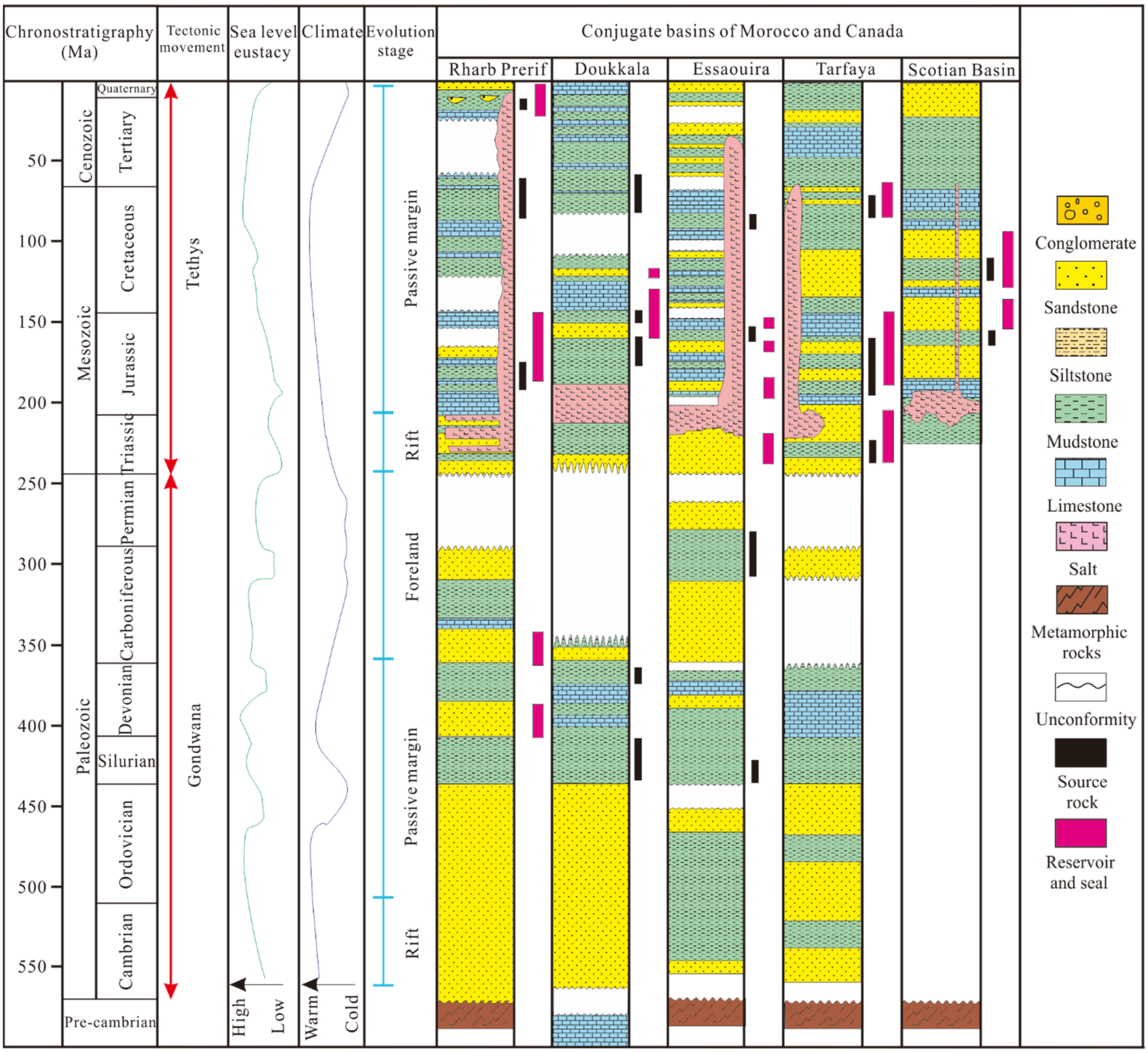

Figure 3. Columns of the strata and petroleum system elements (source rocks and reservoirs) in the conjugate passive margin basins in Morocco and Canada (synthesized based on data from various sources).

4 COMPARISON OF THE EVOLUTION AND RESERVOIRS OF THE DEEP-WATER BASINS IN MOROCCO AND CANADA

The deep-water basins along the passive margins in Morocco and Canada have undergone multiple stages of basin evolution but with some differences. The Moroccan deep-sea basins have undergone multiple stages of evolution from the Paleozoic to the present, while the Canadian deep-water Scotian Basin began to settle and has gradually formed since the Triassic. During the Cenozoic, the deep-water basins in Morocco were squeezed and uplifted due to the influence of the Atlas orogeny, while the deep-water Scotian Basin continued a passive margin evolution in an extensional environment (Fig. 4) (Kidston et al., 2002). In addition, due to the differences in tectonic evolution, the continental shelf of the deep-water Scotian Basin is wide and provides more lateral depositional space, whereas the continental shelf of the Moroccan deep-water basins is narrow and the steep continental shelf and continental slope allow for rapid settlement and provide ample space for vertical sediment accumulation (Tari et al., 2012).

The reservoirs in the terrestrial and offshore basins of Morocco are distributed in the Paleozoic, Triassic, Jurassic, Cretaceous and Neogene stratas (Table 2). Among these reservoirs, the Triassic sandstone reservoirs contribute the largest reserve of 78 mmboe (43% of total reserves). The Neogene and Jurassic sandstone and carbonate reservoirs are dominated by continental and neritic facies. The reserve of Neogene marine sandstone reservoirs is 48 mmboe (contributing 27% of the reserves), and the reserve of Jurassic neritic carbonate reservoirs is 38 mmboe (contributing 21% of the reserves). The Cretaceous sandstone reservoirs are dominated by deep-water facies. The reserve of Cretaceous sandstone reservoirs is 9 mmboe (5% of total reserves). In addition, continental Paleozoic granite and slate reservoirs have also been found in Morocco, and their reserves are 5 mmboe (2% of the total reserves). The reservoirs in the deep-water Scotian Basin are mainly distributed in the Jurassic and Cretaceous neritic facies of sandstone and carbonate rock strata. The reserve of shallow-water Jurassic sandstone reservoirs is 187 mmboe (13% of the total reserves), and the reserve of shallow-water Jurassic carbonate reservoirs is approximately 150 mmboe (11% of the total reserves). The reserve of the Cretaceous neritic sandstone reservoir is 287 mmboe (20% of the total reserves), and the reserve of Cretaceous deep-water turbidite sandstone reservoirs is 172 mmboe (12% of the total reserves). Most of the discovered reservoirs in the Moroccan deep-water basins are Triassic and Neogene deep-sea turbidite sand bodies, while most of the discovered reservoirs in the deep-water Scotian Basin are Jurassic and Cretaceous shallow marine delta sand bodies (Fig. 5).

Table 2 Reserves distribution in various types of reservoirs in Moroccan and Scotian basins

Region	Geological time of reservoir	2P reserves of different reservoirs (mmboe)			
		Carbonate	Sandstone	Granite	Total
Morocco	Cretaceous	0	9	0	9
	Jurassic	35	3	0	38
	Neogene	5	43	0	48
	Paleozoic	0	0	5	5
	Triassic	0	78	0	78
Nova Scotia	Cretaceous	23	499	0	521
	Cretaceous/ Jurassic	0	633	0	633
	Jurassic	153	92	0	245

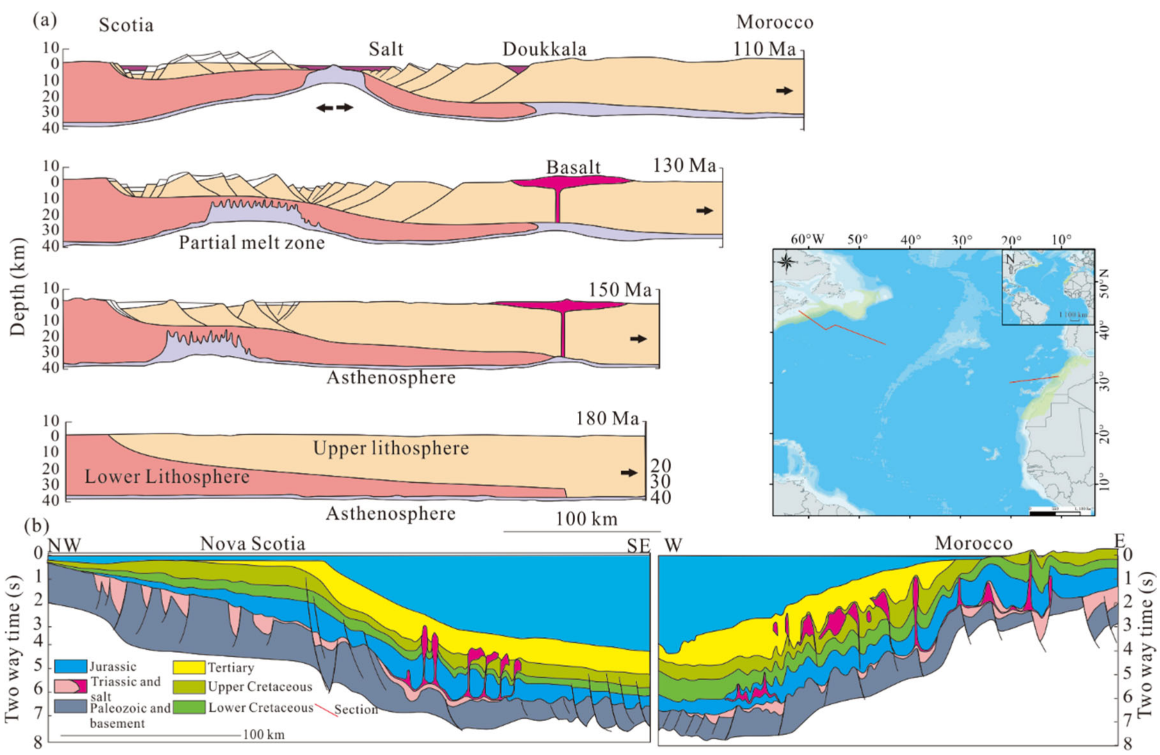

Figure 4. Tectono-stratigraphic evolution of the Moroccan margin and its conjugate Nova Scotian margin (compiled after Tari et al., 2012), (a) tectonic and basin evolution in the conjugate margins from 180 to 110 Ma; (b) stratigraphic correlation of the conjugate margins.

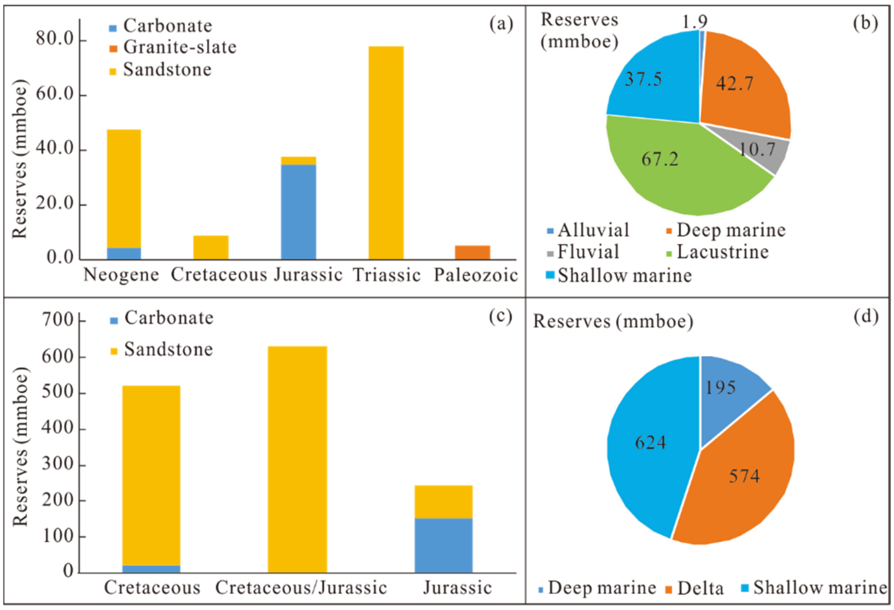

Figure 5. Comparative analysis of the reservoirs and reserve distribution features in the deep-water basins of Morocco and Nova Scotia. (a) Reserves from different types of reservoirs of different geologic periods in the basins in onshore and offshore Morocco areas; (b) reserve proportions among different depositional facies in the basins in onshore and offshore Morocco areas; (c) reserves from different types of reservoirs of different geologic periods in the Scotian Basin at different times; (d) reserve proportions among different depositional facies in the Scotian Basin.

The main reason for this difference in reservoir age and facies may be that in the Cenozoic, Morocco experienced uplifting and denudation due to the Atlas orogeny and a large amount of transportable materials formed at the source of rivers, which provided favorable conditions for the supply of clastic rocks into the deep-sea basins. However, the difference in the ancient river distribution among the geological periods between these two regions may be the main factor. According to Gabor Tari's study, the multistage Cretaceous delta deposits were formed in the Scotian Basin in the west side of the Central Atlantic, while the latest drilling in the offshore Moroccan area on the east side of the Central Atlantic indicates that only Tan-tan deep-water fan depositions were developed in the Early Cretaceous; therefore, oil and gas accumulation in Morocco depends on the presence of reservoirs (Tari et al., 2012). Additionally, there may be too few deep-water drilling wells in the offshore Morocco area to reveal the deep Jurassic and Cretaceous reservoirs.

5 COMPARISON OF THE REPRESENTATIVE DEEP-WATER OIL AND GAS FIELDS BETWEEN THE CONJUAGED MARGINS IN MOROCCO AND CANADA

Hydrocarbon exploration activities in the deep-water basins of Morocco started very early, and in 1919, a small number of oil and gas discoveries were made onshore. To date, 14 oil fields and 36 gas fields have been found onshore, and they have total oil reserves of 19.3 mmbbl and natural gas reserves of 0.5 Tcf. The Anchois 1 Gas Field discovered in 2009 was the first oil and gas discovery in the deep-water area of Morocco, and it has natural gas reserves of 0.1 Tcf. The Upper Jurassic shallow-water carbonate Sidi Moussa 1 Oilfield, which has reserves of 4 mmbbl, was discovered in the Moroccan offshore deep-water zone in 2014 (IHS Markit, 2017). In the Anchois 1 Gas Field, the water depth is 384 m; the reservoir is the abysmal facies of the Miocene–Pliocene turbidite sandstone (Fig. 6), which has a thickness of 90 m and a porosity of 26%; the source rock is Miocene–Pliocene shale with abysmal facies with Type III-II kerogen, which has reached the stage of gas generation; the caprock is shale from the same layer as the reservoir; and the trap is a stratigraphic-structural trap. The discovery of the Sidi Moussa 1 Oilfield and the Anchois 1 Gas Field reveals the development of deep-water Upper Jurassic shallow-water carbonate rock and Miocene–Pliocene turbidite sandstone in Morocco and indicates the future direction of oil and gas exploration in the area. Thus far, limited oil and gas fields with small gas reserves have been discovered in the offshore Morocco area.

Since the first oil and gas discovery in 1969, 25 oil and gas fields have been discovered in the deep-water Scotian Basin. The oil and gas fields are mainly distributed offshore, with oil reserves of 79 mmbbl and natural gas reserves of 7 Tcf (IHS Markit, 2017). The Annapolis G-24 Gas Field was discovered at a water depth of 1 678 m on the Nova Scotia slope in 2002 and was the first deep-water oil and gas discovery in the Scotian Basin. The Cretaceous Barremian–Hauterivian high-quality turbidite sandstone gas reservoir with a net thickness of 27 m was encountered in the gas field. The gas field is located in a large anticline development zone associated with the salt structure and has natural gas reserves of 1 Tcf (Fig. 7). The source rocks of this gas field are mainly Jurassic or Lower Cretaceous mudstone with Type III/II kerogen, and they have already entered the stage of gas generation (Mukhopadhyay et al., 2006). The main caprock is the mudstone in the Lower Cretaceous Barremian–Hauterivian Formation, and the gas reservoir is an anticline trap sealed laterally by the salt structure. The Lower Cretaceous Barremian–Hauterivian turbidite sandstone has not been drilled through in Well Annapolis G-24 (Association (OERA), 2016), indicating that there may be thick, high-quality Lower Cretaceous turbidite sandstone reservoirs in this area. The exploration results indicating a large amount of oil and gas reserves have been confirmed despite the limited discovery of oil and gas fields in the Scotian Basin in offshore Canada. Lower Cretaceous high-quality turbidite reservoirs have an enormous potential.

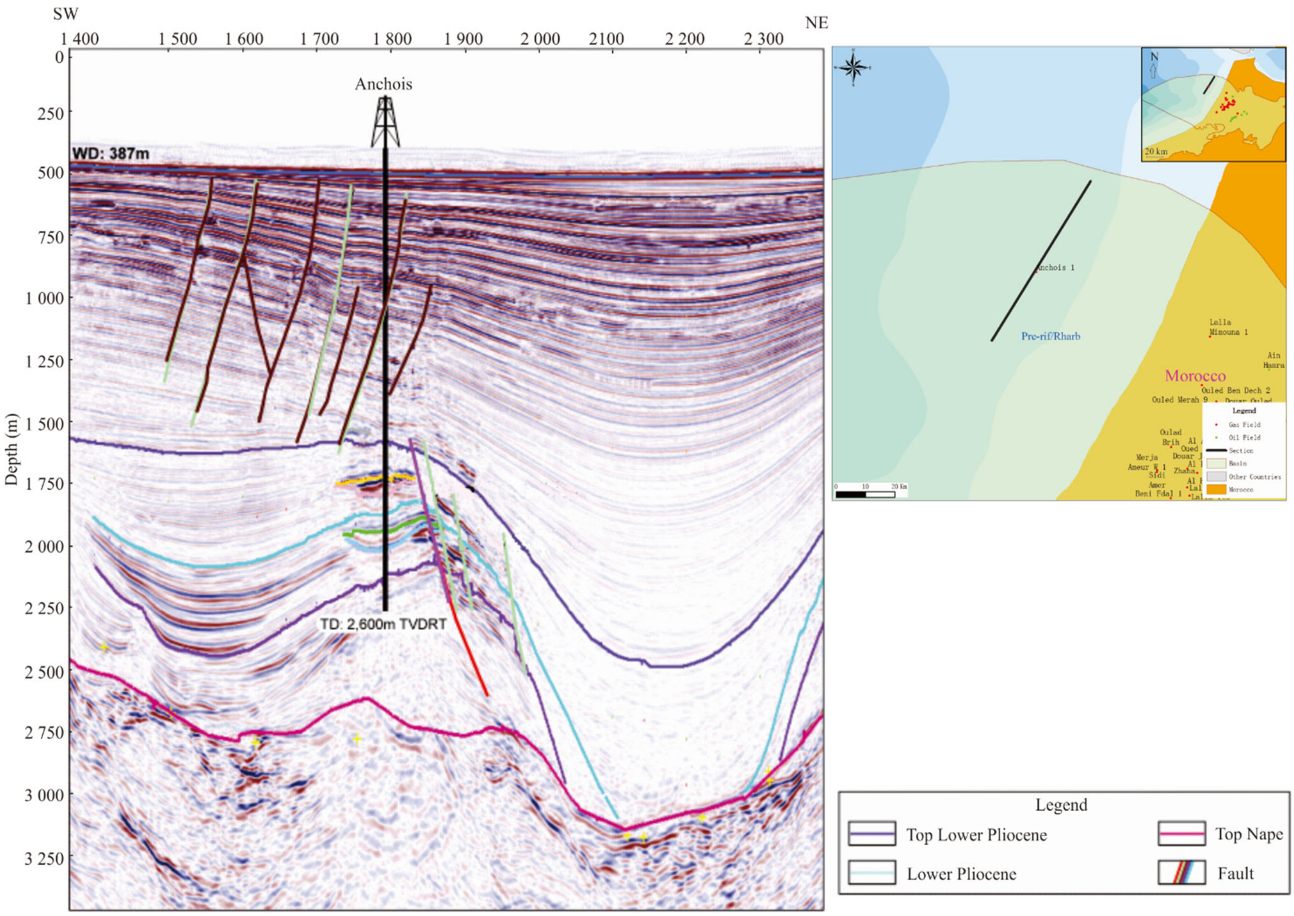

Figure 6. Interpreted seismic cross section showing the Middle Pleistocene–Pliocene turbidite sandstone reservoirs in the Anchois 1 Gas Field cross section of the Morocco Rharb Prerif Basin (modified after IHS Markit, 2014).

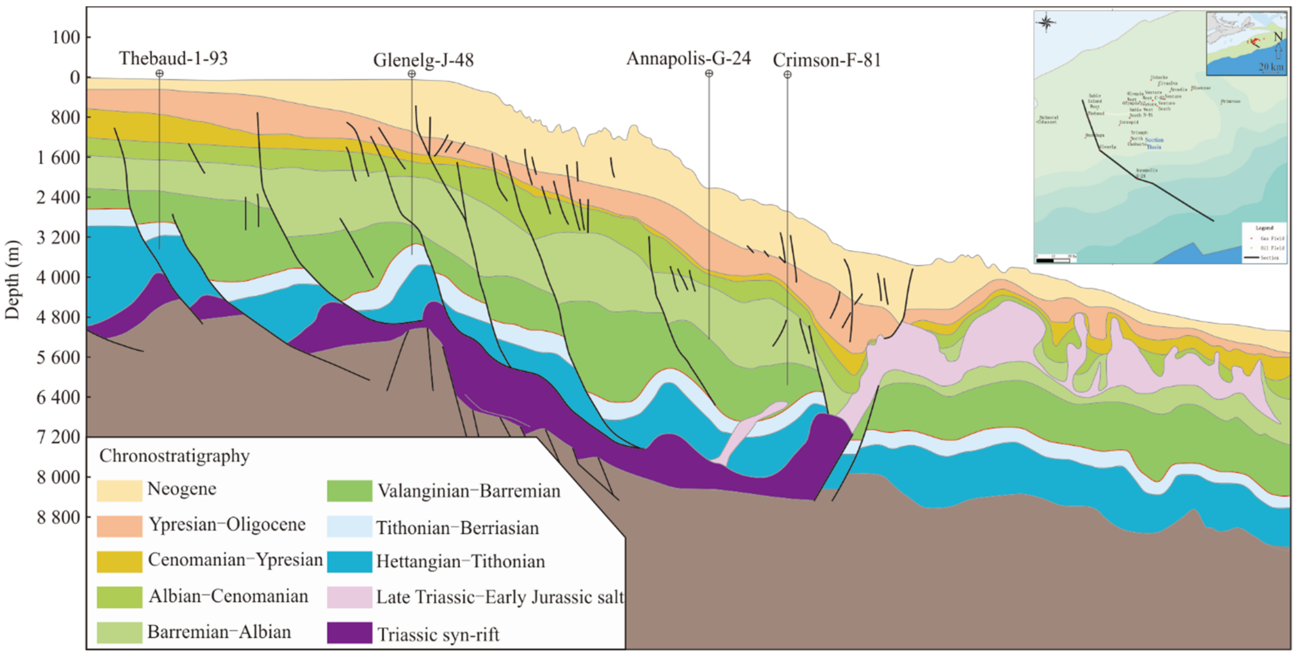

Figure 7. The interpreted tectono-stratigraphy showing the location of the Annapolis G-24 Gasfield with Barremian-Hauterivian turbidite sandstone reservoirs in the Scotia Basin (modified after OERA, 2016).

6 ANALYSIS OF THE TYPE OF PLAYS AND EXPLORATION POTENTIAL BETWEEN THE CONJUGATED MARGINS IN MOROCCO AND CANADA

Seismic data and regional geological profiles show that there are various hydrocarbon accumulation plays in the deep-water basins of the passive margin of offshore Morocco. Most of these plays are related to the salt structure, e.g., the presalt Triassic sandstone anticlinal plays, Middle Jurassic and Lower Cretaceous sandstone and carbonate post-salt reverse thrust plays, Cretaceous post-salt sandstone and carbonate anticline plays, and Tertiary turbidite sandstone plays. In addition, various types of salt diapir and stratigraphic pinchout plays are present (Fig. 8). Based on the stratigraphic development characteristics of the deep-water basins of the passive margin in Morocco, the key exploration target in Morocco should be the Tertiary turbidite sandstone play and the Jurassic and Cretaceous sandstone and carbonate plays. Currently, multiple oil and gas discoveries have been made in the deep-water Scotian Basin in the passive margin conjugate to Morocco and the deep-water Senegal Basin in the passive margin of southern Morocco, indicating that the Moroccan deep-water basins also have good potential for oil and gas exploration.

The available data show that similar to offshore Morocco, oil-gas accumulation plays related to salt structures have developed in the deep-water basin of the passive margin of Nova Scotia. These plays include the presalt Triassic sandstone anticlinal plays, the Jurassic and Cretaceous sandstone and carbonate plays (Tari et al., 2012), various types of plays associated

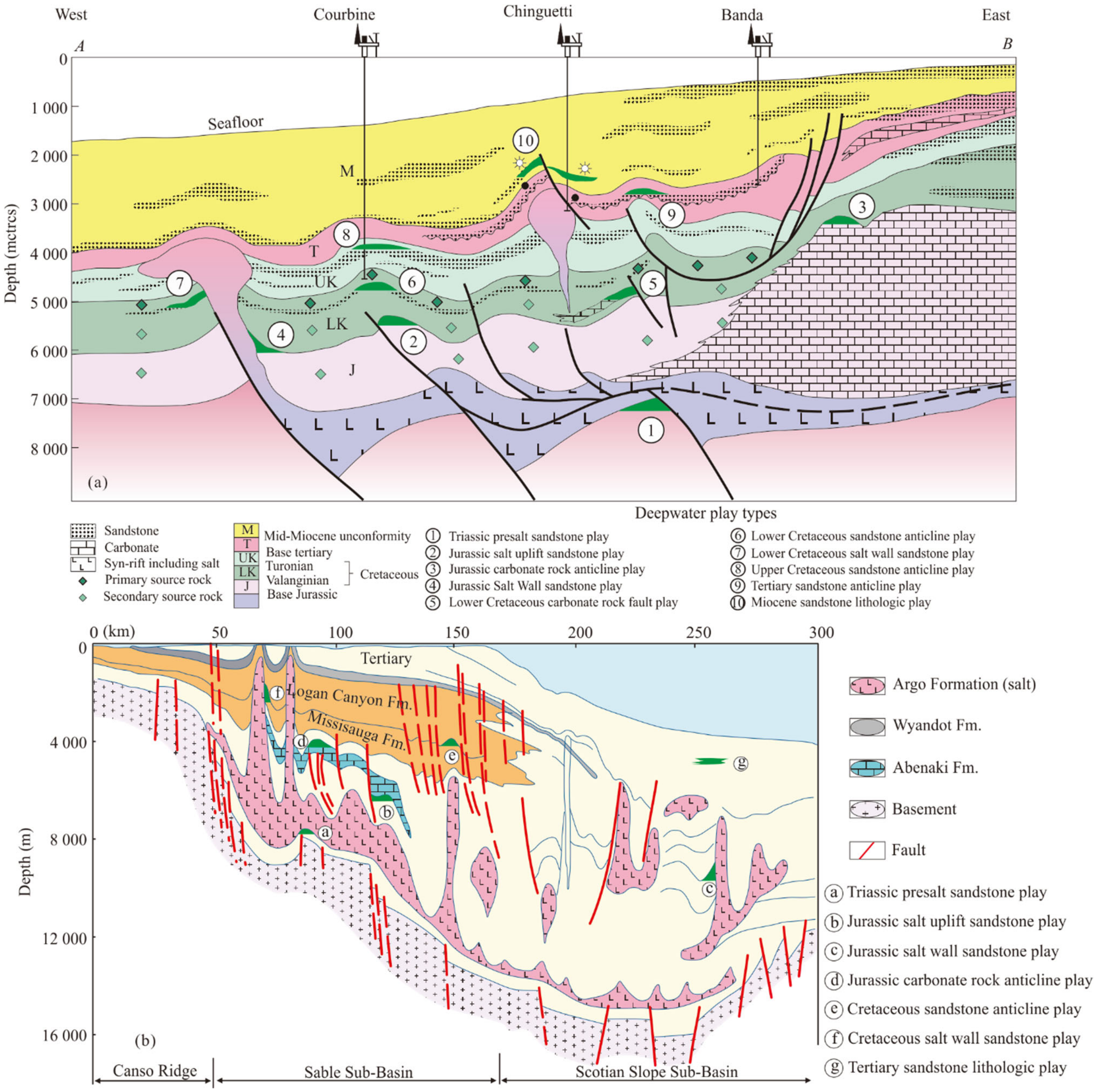

Figure 8. Play types of the Morocco and Nova Scotia deep-water basins (modified after IHS Markit, 2014; Davison, 2005). (a) Play types of the Morocco deep-water basin; (b) play types of the Nova Scotia deep-water basin.

with salt diapir, lateral fault sealing, salt diapirs and stratigraphic pinchout plays. Based on the stratigraphic development and exploration status of the deep-water basin along the passive margin of Nova Scotia, the key deep-water exploration target should be the plays of the Jurassic and Cretaceous deep-water turbidite sandstone. Compared with the Moroccan deep-water basins, in the Scotian Basin, the Triassic presalt sandstone and Tertiary turbidite sandstone plays may also have some exploration potential and should be considered in future work.

A comparison shows that similar reservoirs developed in the Mesozoic and Cenozoic formations in the deep-water basins of the conjugate passive margins of Morocco and Canada. However, the comparison and analysis of the Paleozoic granites and slate plays and the basin evolution of the onshore Sidi Fili, Baton and Bled Defa oil and gas fields show that Paleozoic strata may have developed in the passive continental margin on the Morocco (east) side of the Central Atlantic Ocean. According to the position of the ancient plates reconstructed by Gplate software, the Moroccan basins that formed on the African plate during the Ordovician–Silurian developed in a stage of passive continental margin development (Fig. 9). At this time, Silurian source rock probably developed in the offshore marine environment, which may have provided hydrocarbon to charge the Paleozoic strata (Gambacorta et al., 2016). Therefore, offshore Morocco may have Paleozoic plays.

7 DISCUSSION

Due to differences in the tectonic and sedimentary evolution of the passive continental margin basins on both sides of the Central Atlantic, the geological conditions for oil and gas accumulation vary. In the Jurassic and Cretaceous, because of the development of the extensive river system on the Scotian side, deltaic progradation resulted in the abundant sediment supplies for rich terrestrial gas prone organic matter (Type III kerogen), whereas because of the fewer rivers on the Moroccan side, the limited supply of terrestrial organic matter led to the predominance of oil-prone source rock (Type II/III kerogen). The offshore Morocco side likely has limited high-quality Jurassic and Cretaceous source rocks rich in organic matter but may also have Silurian source rocks as previously discussed.

Large differences in reservoir development are observed on both sides, with sandstone reservoirs mainly developed in the Scotian Basin in the Jurassic and Cretaceous due to the large terrestrial sediments input by deltaic progradation because of the extensive river systems and carbonate rock reservoirs mainly developed on the Moroccan side due to the less-developed rivers and reduced input of clastic sediments. In the Tertiary, the Moroccan side had more river systems and more dramatic tectonic uplifting than its conjugate Scotian Basin, which resulted in a greater clastic supply from Atlas orogenies and the development of more sandstone reservoirs in the Moroccan basins (especially Essaouira Basin). This result implies that exploration in the Scotian Basin should be focused on Jurassic and Cretaceous reservoirs while that on the Moroccan side should be focused on the Tertiary reservoirs in a deep-water setting.

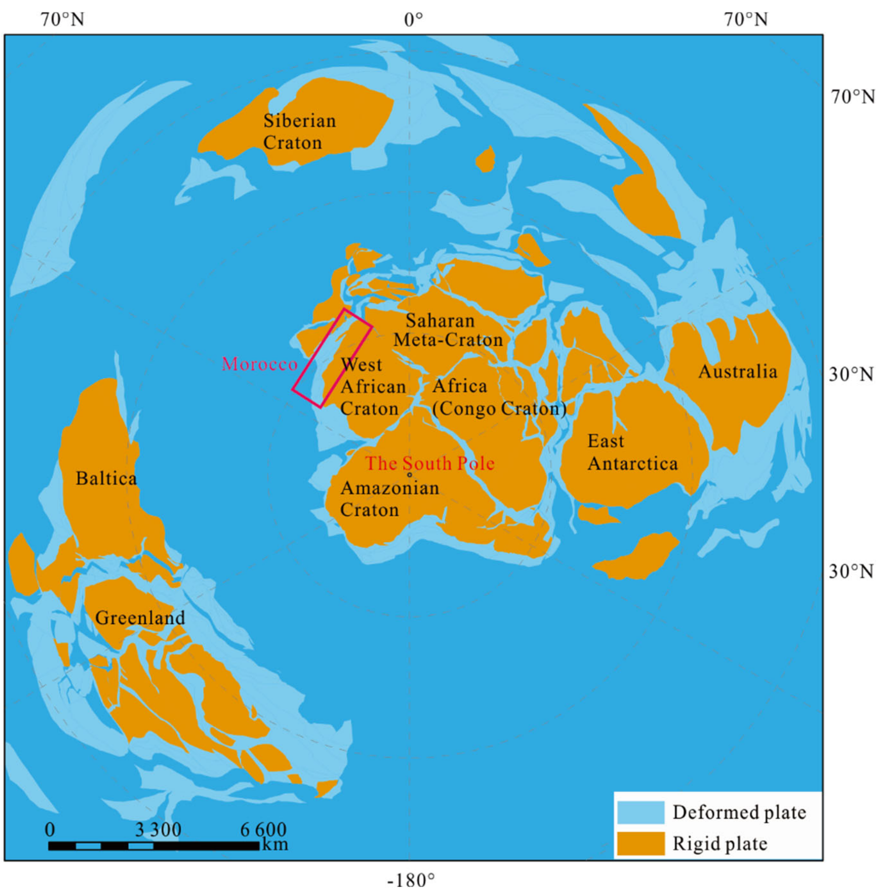

Figure 9. Paleoplate locations reconstructed by Gplate software during the Early Silurian in Morocco and Nova Scotia and their surrounding areas, which shows the favorable marine environment for the development of the Lower Silurian hot shale in current offshore area.

8 CONCLUSIONS

(1) Both the Mesozoic to Cenozoic deep-water basins along the passive margin in Morocco and its conjugate passive margin in Nova Scotia, Canada have undergone similar tectonic evolutionary stages of Triassic rifting, passive continental margin development since the Jurassic, and Tertiary compression, uplift and erosion.

(2) Due to the conjugate basin evolution, the plays on both sides of the Central Atlantic basins include presalt Triassic sandstone anticlinal plays, post-salt Middle Jurassic and Lower Cretaceous sandstone and carbonate reverse thrust plays, post-salt Cretaceous sandstone and carbonate anticline and unconformity plays, salt dome-related plays and Tertiary turbidite sandstone plays. In addition, various types of salt diapir and stratigraphic pinchout plays are observed. However, the Scotian Basin is dominated by gas-prone Mesozoic source rocks due to the development of large deltas while the conjugate Moroccan side is dominated by oil-prone limited source rocks due to the reduced sediment supply and development of a carbonate platform. Consequently, the producing reservoirs on the Scotian side are dominated by sandstones while those on the Moroccan side are dominated by carbonates. Turbidite sandstone reservoirs started to develop in the Essaouira and Rharb Prerif basins on the Moroccan side in the Tertiary due to the significant uplift of the Atlas Mountains.

(3) The discoveries in the deep-water basins of Morocco are mostly in Tertiary turbidite sandstone and Jurassic carbonate rock; however, these discoveries are much smaller in terms of number, reserves, and production compared to that of the conjugate deep-water Scotian Basin. The key near future exploration targets in Morocco should be the Tertiary turbidite sandstone plays and the Jurassic and Cretaceous sandstone and carbonate plays. The mature Silurian shale source rock that likely developed and the Paleozoic plays in the offshore Morocco area could be potential targets for Morocco, whereas the Jurassic and Cretaceous deep-water turbidite sandstones should be the key exploration targets in the deep-water Scotian Basin.

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REFERENCES CITED

Addi, A., Chafiki, D., 2013. Sedimentary Evolution and Palaeogeography of Mid-Jurassic Deposits of the Central High Atlas, Morocco. *Journal of African Earth Sciences*, 84: 54–69. https://doi.org/10.1016/j.jafrearsci.2013.04.002

Association (OERA), 2016. Central Scotian Slope Atlas. (2016-01-01)[2020-05-17]. https://oera.ca/research/central-scotian-slope-atlas-2016

Campbell, D. C., Shimeld, J., Deptuck, M. E., et al., 2015. Seismic Stratigraphic Framework and Depositional History of a Large Upper Cretaceous and Cenozoic Depocenter off Southwest Nova Scotia, Canada. *Marine and Petroleum Geology*, 65: 22–42. https://doi.org/10.1016/j.marpetgeo.2015.03.016

Davison, I., 2005. Central Atlantic Margin Basins of North West Africa: Geology and Hydrocarbon Potential (Morocco to Guinea). *Journal of African Earth Sciences*, 43(1/2/3): 254–274. https://doi.org/10.1016/j.jafrearsci.2005.07.018

Dutuc, D. C., Pe-Piper, G., Piper, D. J. W., 2017. The Provenance of Jurassic and Lower Cretaceous Clastic Sediments Offshore Southwestern Nova Scotia. *Canadian Journal of Earth Sciences*, 54(1): 33–51. https://doi.org/10.1139/cjes-2016-0109

Gambacorta, G., Caronni, V., Antonielli, E., et al., 2016. Hot Shale in an Ice World: Paleoceanographic Evolution of the Northern Gondwana Margin during the Early Paleozoic (Tanezzuft Formation, Tunisia). *Marine and Petroleum Geology*, 72: 393–411. https://doi.org/10.1016/j.marpetgeo.2016.02.015

Hafid, M., 2000. Triassic–Early Liassic Extensional Systems and Their Tertiary Inversion, Essaouira Basin (Morocco). *Marine and Petroleum Geology*, 17(3): 409–429. https://doi.org/10.1016/s0264-8172(98)00081-6

IHS Markit, 2014. Basin Moniter: North West African Basins. [2014-01-05]. https://edin.ihsenergy.com/portal/home.

IHS Markit, 2017. Edin Fields: North West African Fields. [2017-01-01]. https://edin.ihsenergy.com/edingis/dispatcher/openData.

Kidston, A. G., Brown, D. E., Altheim, B., et al., 2002. Hydrocarbon Potential of the Deep-Water Scotian Slope. *Canada-Nova Scotia Offshore Petroleum Board*, 1–22

Labails, C., Olivet, J. L., Aslanian, D., et al., 2010. An Alternative Early Opening Scenario for the Central Atlantic Ocean. *Earth & Planetary Science Letters*, 297(3–4): 355–368. https://doi.org/10.1016/j.epsl.2010.06.024

Liu, J. P., Pan, X. H., Ma, J., et al., 2008. Petroleum Geology and Resources in West Africa: An Overview. *Petroleum Exploration and Development*, 35(3): 378–384. https://doi.org/10.1016/s1876-3804(08)60086-5

Michard, A., Saddiqi, O., Chalouan, A., et al., 2008. Continental Evolution: The Geology of Morocco. Springer-Verlag, Berlin. 426

Modelevsky, M. S., Modelevsky, M. M., 2016. Assessment of the Discovered and Undiscovered Oil and Gas of Africa. *Russian Geology and Geophysics*, 57(9): 1342–1348. https://doi.org/10.1016/j.rgg.2016.08.019

Mukhopadhyay, P. K., Harvey, P. J., Kendell, K., 2006. Genetic Relationship between Salt Mobilization and Petroleum System Parameters: Possible Solution of Finding Commercial Oil and Gas within Offshore Nova Scotia, Canada during the Next Phase of Deep-Water Exploration. *Gulf Coast Association of Geological Societies Transactions*, 56: 627–638

Sibuet, J. C., Rouzo, S., Srivastava, S., et al., 2012. Plate Tectonic Reconstructions and Paleogeographic Maps of the Central and North Atlantic Oceans. *Canadian Journal of Earth Sciences*, 49(12): 1395–1415. https://doi.org/10.1139/e2012-071

Tari, G., Brown, D., Jabour, H., et al., 2012.The Conjugate Margins of Morocco and Nova Scotia A2-Roberts, D.G.. In: Bally, A. W., ed., Regional Geology and Tectonics: Phanerozoic Passive Margins, Cratonic Basins and Global Tectonic Maps. Elsevier, Boston. 284–323

Zhang, Y. Y., Pe-Piper, G., Piper, D. J. W., 2015. How Sandstone Porosity and Permeability Vary with Diagenetic Minerals in the Scotian Basin, Offshore Eastern Canada: Implications for Reservoir Quality. *Marine and Petroleum Geology*, 63: 28–45. https://doi.org/10.1016/j.marpetgeo.2015.02.007

Zou, C. N., Zhai, G. M., Zhang, G. Y., et al., 2015. Formation, Distribution, Potential and Prediction of Global Conventional and Unconventional Hydrocarbon Resources. *Petroleum Exploration and Development*, 42(1): 14–28. https://doi.org/10.1016/s1876-3804(15)60002-7