Tectonic history and hydrocarbon potential of the Moroccan rifted-passive margin

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Summary

This study of the Moroccan rifted-passive margin of the Central Atlantic Ocean interprets a grid of 8474 line-km pre-stack depth migrated 2D seismic reflection profiles, publicly-available gravity and well data, and 2D gravity models. Gravity and seismic interpretation reveal an elongate, 80-150-km-wide basement low or "marginal rift" that overlies the zone of continental necking and parallels the modern coastline of Morocco. These mapping results are then used to constrain 1D thermal stress models for two well locations to better understand the hydrocarbon potential of Jurassic-Cretaceous source rocks. 1D thermal stress modeling shows that Jurassic source rocks are mature for petroleum expulsion along the length of the marginal rift structure. A Late Cretaceous uplift and erosion of the margin elevated Cretaceous source rocks explain why these source rocks have remained immature.

Introduction and regional geology

Hydrocarbon exploration of the offshore Morocco margin over the past few decades has resulted in a series of unsuccessful shelf, slope, and deepwater wells drilled from the late 1960's through the early 2000's into Lower Cretaceous-Cenozoic clastic rocks and Jurassic carbonate rocks.

While the offshore Atlantic margin of Morocco remains a frontier area for hydrocarbon exploration (Neumaier et al., 2018), hydrocarbon shows and organic-rich source rocks have been documented in exploration and DSDP wells and demonstrate a working petroleum system along the Moroccan Atlantic margin (Galhom et al., 2022).

The Moroccan rifted-passive margin of the Central Atlantic Ocean extends 3500 km from the Straits of Gibraltar to the northern border of Mauritania (Tari et al., 2013) (Figure 1). This margin forms the conjugate rifted margin for much of the eastern margin of the USA and Maritime Canada. Rifting between the Moroccan Atlantic margin and its North American conjugate began in the Late Triassic with the development of grabens and half-grabens filled with clastic red beds on both margins (Davison, 2005). A major Jurassic salt province occurs as a locally reactivated, post-rift sag sequence along the northern margin of Morocco. The Atlas Mountains in northern Morocco include the same Jurassic rifts, inverted during the Late Cretaceous-Cenozoic convergence between the African and European plates. These tectonic events have affected the source rock distribution and burial thickness that controls the thermal stress both in the rifted- continental crust and oceanic crust (Powney et al., 2020).

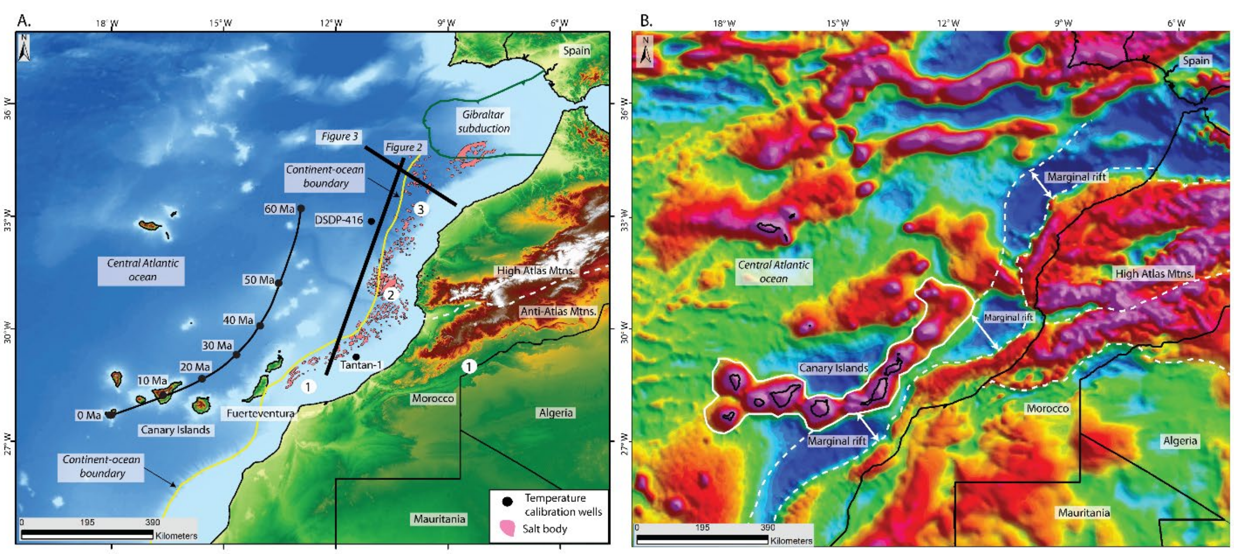

Figure 1: a) Topographic map of northwestern Africa showing the location of the seismic lines, well penetrations, and major basins (1- Tarfaya, 2- Agadir, 3- Safi basin). b) Free-air gravity map showing the 80-150-km-wide and elongate marginal rift that parallels the continent-oceanic boundary (shown by the yellow line) and the modern coastline of Morocco.

Petroleum potential of offshore Morocco

Methods

Seismic mapping of the major horizons and source rock intervals was carried out using the available seismic reflection dataset provided by Geoex MCG. These seismic interpretations constrain the different stratigraphic units' depths and shapes. The error between the observed and calculated gravity values was measured by generating the root-mean-square error, which measures the standard deviation of the calculated gravity values from the observed gravity values.

Borehole-corrected temperature and lithology information from published literature was used to evaluate the thermal stress and petroleum generation potential in the marginal rift (Tantan-1) and in the oceanic crust (DSDP-416) (Figure 1). The measured geothermal gradient in the marginal rift is 27.5° C/km in the marginal rift and 22° C/km in the oceanic crust. Heat flow is slightly cooler in the oceanic crust because of the absence of radiogenic heat generated from the continental crust (Allen and Allen, 2013). The paleo-water depth and initial high heat flow due to rifting were estimated and used for the basin model.

Spatial analysis of the marginal rift

We determined the faulted edges of the marginal rift structure using publicly-available free-air gravity data from Sandwell et al. (2014) (Figure 1b). The marginal rift structure is characterized by a prominent, elongated linear gravity low (Figure 1b). The elongate, regional gravity low is inferred to represent the relatively deeper crystalline basement with a higher density than the adjacent areas. The width of the marginal rift structure can be measured as 80-150-km wide and includes a 950-km long negative anomaly in the northern Moroccan rifted-passive margin that reflects the continent-ocean boundary.

The marginal rift structure of northern Morocco is part of a 3500-km-long, continuous rift system. A gravity high that crosses the marginal rift structure results from crustal uplift and folding during the Atlas orogeny in the late Cretaceous-Cenozoic period. The gravity map also reveals other prominent anomalies such as the Cenozoic High-Atlas Mountains, Canary Islands hotspot track, and Late Paleozoic Anti-Atlas mountains (Figure 1b).

Seismic interpretation

A 700-km long reflection seismic section oriented in the strike direction reveals the crustal and sedimentary domain of the basin (Figure 2). From north-northeast to the south-southwest, this line shows: a) 5-6-km-thick Jurassic oceanic crust with prominent half-grabens in the fractures zones related to Atlantic opening; b) thinned, continental crust of the marginal rift overlain by 1-4-km autochthonous salt deposits where salt diapirism is concentrated in the area of the thickest salt within the marginal rift; and c) full-thickness (30-40 km) continental crust. A step-up fault with distinct reflection shown as a dotted line in figure 2 marks the transition between the necked zone of the thinned continental crust and marginal rift and the adjacent oceanic crust of Late Jurassic age.

Landward of the necked domain, a prominent roll-over anticlinal structure can be observed along this faulted boundary of the marginal rift. No allochthonous or secondary salt body placement is observed in the marginal rift, which is a common feature of other rifted-passive margin salt basins (Hasan and Mann, 2021). The seismic line also shows the Late-Cretaceous-Tertiary deformation and folding of oceanic crust expressed as Cape-Tafelney foldbelt (figure 2).

The 277-km long dip-oriented seismic reflection line shows a variety of salt-associated structures (Figure 3a). Tilted blocks along listric, normal faults mark the transition between the necked zone of continental crust and full-thickness, continental crust that underlies the modern coastline of Morocco. The necked domain is dominated by

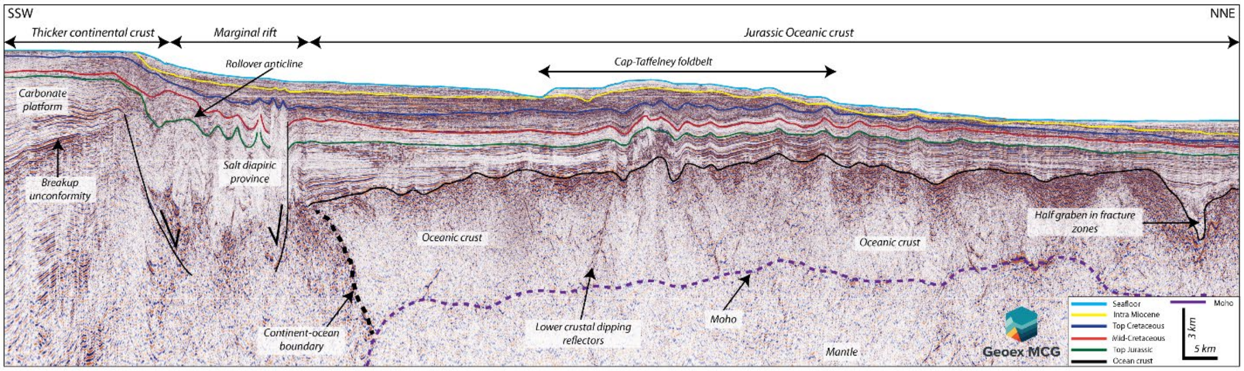

Figure 2: Interpreted regional seismic line showing the major tectonic elements of the margin, including the Jurassic carbonate platform, salt basin, oceanic crustal deformation of the Cape Tafelney foldbelt, and normal oceanic crust. Seismic data courtesy of Geoex MCG.

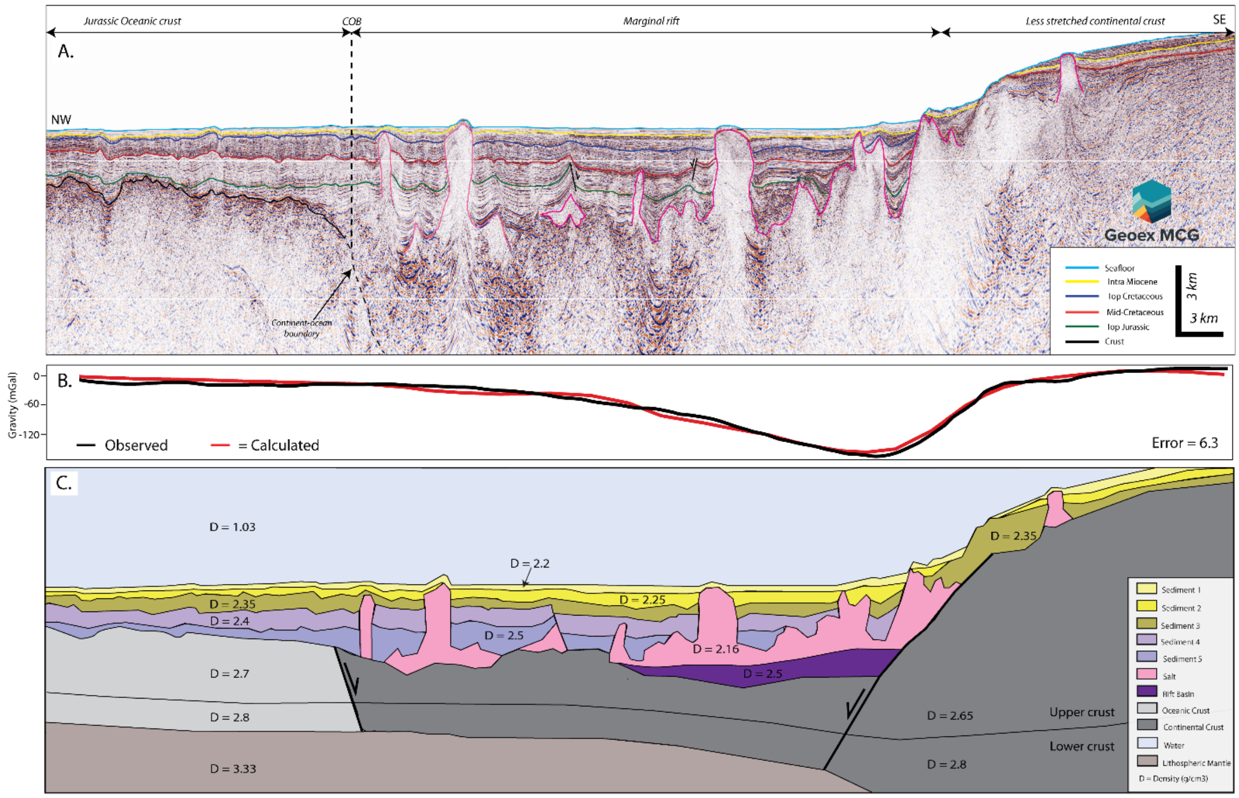

Figure 3: a) Structural and stratigraphic interpretation of dip-oriented seismic line showing the crustal types and sedimentary fill of the basin. b) Graphical comparison of observed and calculated gravity values. c) Gravity model along the 2D seismic line shown in fig. 4a that constrains the deeper crustal structure of the margin. Seismic data courtesy of Geoex MCG.

diapiric salt structures, some of which are active today, as seen from the elevated seafloor. The salt concentration over the marginal rift likely reflects the rift-related accommodation space and a restricted environment. Jurassic to present sediment thickness in the marginal rift ranges 4-6-km in this domain, higher than the adjacent full thickness continental crust and oceanic crustal domain.

Crustal structure and its implications on petroleum potential

Because current seismic reflection imaging cannot penetrate through the thick salt cover, 2D gravity modeling along the same line shown in figure 3a was performed to better infer the deeper crustal structure of the elongate marginal rift that overlies the area of thinned continental crust (Figure 3c). The observed and calculated gravity values in our model show an excellent fit with a root mean square error of 6.3.

The gravity modeling reveals the south-east to northwest transition from the full-thickness continental crust (30-40 km) to thinned, transitional crust (6-10 km), and to oceanic crust underlying the deepwater area (6-7 km). The necked domain of thinned continental crust shows 5-6-km thickness and appears to be completely filled by evaporites or clastic rocks. The structure varies in the thinned continental crustal domain as the result of full- and half-grabens. Both types of sediment-filled rifts raise the possibility of deeper (Triassic?) hydrocarbon plays. We were also able to define the density contrast between the upper and lower crust through gravity modeling. The 2D gravity model (Figure 3c) reveals that the continental-oceanic boundary aligns well with the marginal rift interpretation in the free-air gravity map (Figure 1b).

Integration of the crustal structure from seismic interpretation and gravity modeling helps us constrain the heat flow of the margin that we can then integrate into our basin modeling. The necked zone of the rifted continental crust is known to contain more hydrocarbons for several reasons: a) higher heat flow from a combination of radiogenic heat and shallower lithosphere, b) presence of massive salt in the restricted grabens and half-grabens that provides seals and various types of hydrocarbons traps.

Petroleum potential of offshore Morocco

Thermal stress modeling

There is limited source rock information in the Moroccan deepwater margin from previous oil exploration and academic DSDP drilling.

Using the results of the mapping from this study, previous studies of source rocks from onshore Morocco, and proven source intervals in conjugate Nova Scotia margins (Galhom et al., 2022), possible source rocks interval along offshore Morocco include: 1) Upper Cretaceous (89-87 Ma), Lower Cretaceous (115-112 Ma), Upper Jurassic (150-148 Ma), Middle Jurassic (168-166 Ma), and Lower Jurassic (184-183 Ma).

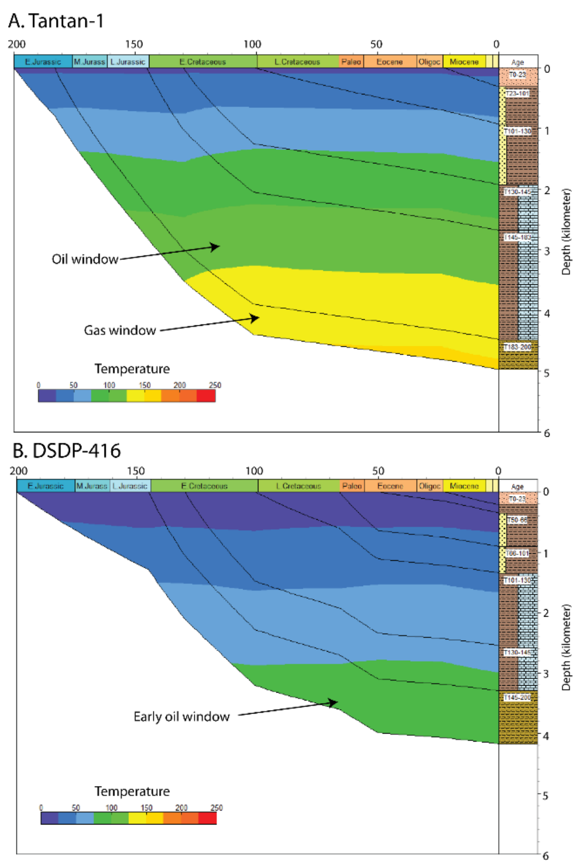

Figure 4: 1D thermal stress modeling along two well locations: a) Tantan-1 and DSDP -416. Modeling shows that the Jurassic source interval attained the required thermal stress for hydrocarbon generation and expulsion in the area of the marginal rift that overlies the thinned continental crust zone.

Lower Jurassic organic-rich mudstone has been documented from DSDP- 416 and from outcrop exposures on Fuerteventura Island in the Canary Islands (Figure 1A). The Middle Cretaceous source rocks that are well-documented from onshore Morocco (Powney et al., 2020) were locally eroded during the late Cretaceous during the Atlas orogeny (Powney, et al., 2020; Galhom et al., 2022).

1D thermal stress modeling along the Tantan-1 well located in the marginal rift shows that: a) the Lower Jurassic source interval occupies the present-day gas window (140° C), b) the Middle Jurassic source interval occupies the present-day peak oil window (125° C), and c) the Upper Jurassic source interval is either presently immature or occupies the early oil expulsion window (110° C). The Jurassic source rocks entered the oil window early in the Early Cretaceous period and had ample geologic time to migrate into the younger Cretaceous and Cenozoic reservoir rocks. The potential Upper and Lower Cretaceous source rocks remain immature in the marginal rift described in this study (Figure 4a).

Thermal stress modeling at the DSDP-416 drill location shows that the Jurassic section is presently in a temperature range of 75-100° C and immature for petroleum generation. Similarly, the potential relatively younger source rocks of Cretaceous age remain immature (<50° C) (Figure 4b). Lower thermal maturity above the oceanic crust results from a combination of Late Cretaceous tectonic uplift event and the cooling effect of oceanic crust that underlies the deepwater areas (Figure 4b).

Conclusions

- Integrated gravity and seismic data analysis reveals an 80-150-km wide marginal rift of Triassic-Jurassic ages that overlies the necked zone of the rifted continental margin; this rift structure contains 2-3 km of salt and clastic sedimentary rocks of Jurassic age.
- Jurassic source rocks are mature in the marginal rift for petroleum generation, whereas Cretaceous source rocks remain immature or were eroded during a tectonic uplift in the Late Cretaceous.
- The absence of radiogenic heat in the oceanic crust results in relatively lower geothermal gradients and can explain the immaturity of source rocks in these deepwater areas.

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Petroleum potential of offshore Morocco

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