Salt Tectonics of the Offshore Tarfaya Basin, NW Africa

Tectónica Salina del offshore de la Cuenca de Tarfaya, África Noroccidental

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Abstract: *Salt tectonics has a critical role in basin analysis. However, research integrating a salt tectonics perspective is scarce in regional studies along the NW Africa Atlantic passive margin. This study focuses on regional interpretation of unpublished 3D/2D seismic data from the offshore Tarfaya Basin to explore the main controlling factors that influenced its evolution from a salt tectonics approach.*

Tarfaya Basin constitutes a rifted passive margin developed over thinned continental crust located at the Atlantic margin of southwestern Morocco, east from Fuerteventura and Lanzarote islands. The main factors that conditioned the basin's evolution can be summarized as follows: (1) irregular thickness and distribution of the original salt layer (Upper Triassic); (2) basin tilting caused by thermal subsidence and initial sea-floor spreading phases (Lower Jurassic); (3) development of a mainly carbonatic shelf wedge related to the onset of the incipient Atlantic passive margin (Upper Jurassic); (4) progradation of the Tan Tan delta complex (Lower Cretaceous); (5) compression related to the convergence between African and Eurasian plates (Upper Cretaceous – Recent).

Keywords: *Salt tectonics. Factors. Passive Margin. Atlantic. NW Africa.*

Resumen: a te tóni a salina es esen ial en el an lisis de en as Sin em argo, s integra ión en est dios regionales es escasa a lo largo del margen Atlántico del Noroeste de África. El presente trabajo se basa en la interpretación de sísmica 2D y 3D inédita del offshore de la cuenca de Tarfaya con el objeto de investigar los principales factores regionales que condicionaron la evolución tectónica de esta cuenca que involucra una formación salina.

La cuenca de Tarfaya se constituye como un margen pasivo desarrollado sobre corteza continental fallada y adelgazada ubicada en el suroeste de Marruecos y al este de las islas de Fuerteventura y Lanzarote. Los principales factores y eventos que condicionaron su evolución tectónica pueden resumirse en los siguientes: (1) espesor y distribución original de la sal irregular (Triásico Superior); (2) aumento en la inclinación de la cuenca asociado a subsidencia térmica y al comienzo de la generación de corteza oceánica (Jurásico Inferior); (3) evolución de una plataforma principalmente carbonática relacionada al desarrollo del margen pasivo Atlántico (Jurásico Superior); (4) progradación del complejo deltaico de Tan Tan (Cretácico Inferior); (5) Compresión asociada a la convergencia entre las placas Africana y Euroasiática (Cretácico Superior-Actualidad).

Palabras clave: Tectónica Salina. Factores. Margen pasivo. Atlántico. África Noroccidental

INTRODUCTION

The Atlantic passive margin of Morocco extends for more than 1000 km and constitutes the largest salt-bearing basin in NW Africa containing one of the oldest records that document the opening history of the Central Atlantic (Tari, 2012). During the Triassic, extensional basins developed along the future continental margin and in the Atlas rift system. The Tarfaya Basin (Wenke, 2014) extends for an area of approximately 50000 km^2 (Fig. 1) both onshore and offshore southern Morocco and East of Fuerteventura and Lanzarote Islands (Spain). According to Tari (2012), Tarfaya basin's conjugate margin corresponds to the southernmost region of the Nova Scotia Basin in Canada.

Only few wells have explored the hydrocarbon potential of the Moroccan Atlantic margin, and most of them are located on the shelf region. At least two working petroleum systems have been documented onshore, in the Essaouira/Agadir Basin (Fig. 1). As for the Tarfaya Basin, the discovery of the Cap Juby well (CJ-1 in Fig. 1) proved the presence of an active petroleum system (Sachse et al., 2016). The main reservoir facies tested were carbonate build-ups from Lower and Middle Jurassic, but oil and gas shows were also described from Lower Cretaceous and Tertiary sandstones. This undeveloped heavy oil discovery appears to point to an effective Jurassic source rock.

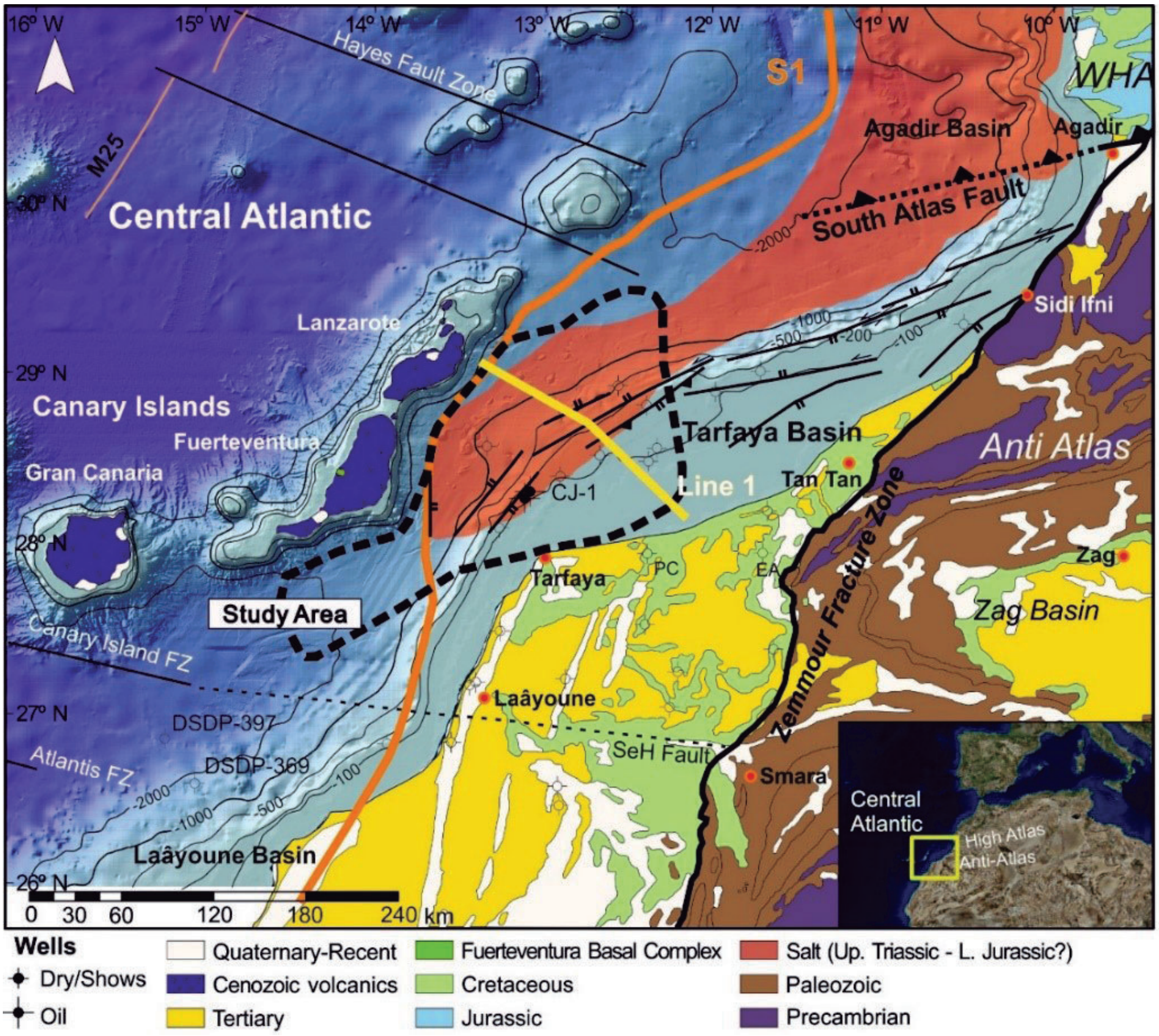

FIGURE 1. Location map. Modified from Wenke (2014). Fracture zones after Klitgord & Schouten (1986), S1 magnetic zone after Roeser (1982). Faults outside the study area from Le Roy et al. (1997).

In this study, previously unreleased 2D and 3D seismic data integrated with well data from an area covering 32000 km^2 from the offshore Tarfaya Basin (Fig. 1) is interpreted in order to describe the main structural styles in the basin and understand the key factors controlling its evolution. Depth conversion was carried out through a velocity model containing 6 layers (Fig. 2), separated by key stratigraphic surfaces. The interpretation of 15 horizons was calibrated with 11 wells and the picking followed stratigraphic criteria proposed by Wenke (2014). The good continuity of the reflectors allowed extrapolating the interpretation to the deep offshore.

GEOLOGICAL SETTING

The Pre-Rift basement of the Tarfaya Basin consists of low-grade metamorphosed Paleozoic rocks (Figs. 1 & 2) related to the Hercynian orogeny (Le Roy et al., 1997). The evolution of the Tarfaya Basin begins with the deposition of a siliclastic to evaporitic (mainly halite) syn-rift sequence from Late Permian to Triassic (Hinz, et al., 1982). Grabens and half grabens controlled the sedimentation with a general NE-SW structural trend mainly controlled by the preexisting structural fabric. These structures are compatible with a WNW-ESE extension direction (Le Roy et al., 1997). Transfer zones linking these depocenters strike in a general E-W direction (Heyman, 1989).

According to Le Roy et al. (1997), rifting probably began in the Late Permian to Early Triassic migrating through time from East to West (Fig. 2). While rift activity proceeded toward the west, brittle extension proceeded northward through the Agadir, Essaouira and Doukkala basins and affected the entire margin during the Rhaetian? – Hettangian period (Figs. 1 & 2). By then, salt was mainly deposited on the western or Proto-Atlantic depocenter (Fig. 3), on highly compartmentalized sub basins and over an irregular basal topography.

During the sag stage (Hettangian to Early Pliensbachian), thermal subsidence increased basin tilting, affecting mainly the Proto-Atlantic depocenter (Fig. 3). The onset of drifting between Toarcian and Bajocian times drove incipient seafloor spreading (Klitgord & Schouten, 1986). The S1 magnetic anomaly (Roeser, 1982) represents the ocean-continent transition (Figs. 1 & 3) and coincides closely with the edge of the salt basin. From a lithostratigraphic point of view, Middle to Upper Jurassic units consist mainly of ramp and shelf carbonates (Fig. 2), distally grading to marls (Wenke, 2014). Afterwards, during the Early Cretaceous, a basin wide regression exposed and eroded the Jurassic carbonate platform (MDU in Fig. 2). The supplied sediments bypassed the shelf and formed the Tan Tan delta complex, active until Albian times.

Through the Late Cretaceous, the initial phase of compression related to the convergence between the Eurasian and African plates took place (Frizon de Lamotte et al., 2009). Following, the Base Tertiary Unconformity (BTU, Figs. 2 & 3) marks the limit between the Mesozoic and the Cenozoic. This erosional surface caused by tectonic uplift cut through most part of the Upper Cretaceous stratigraphic record on the slope and the proximal deep basin.

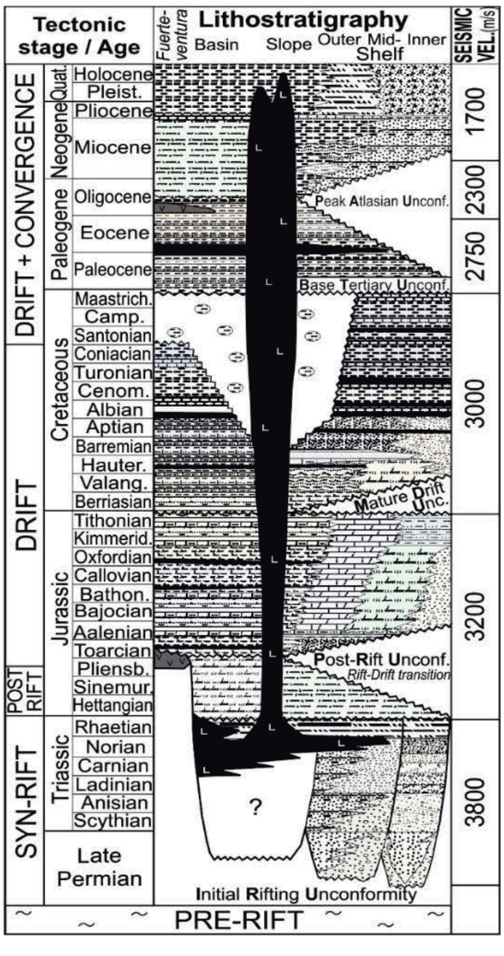

FIGURE 2. Tectono-stratigraphic chart.

The widespread tectonic inversion and orogenesis of the Atlas System mainly occurred during two distinct episodes, the first one from the Middle to Late Eocene until the Oligocene, and the second one from the Late Miocene to Pliocene (e.g. Frizon de Lamotte et al., 2009). The Peak Atlasian erosional uncomformity (Fig. 2) evidences the first event, which is best observed on the shelf and slope regions of the Tarfaya Basin. From Late Paleogene to Neogene times, major erosion in the High Atlas and the Anti-Atlas significantly increased the sediment flux to the basin, which bypassed the shelf and accumulated at the slope and deep offshore as channelized turbiditic systems (Wenke, 2014).

RESULTS

From the interpretation of seismic Line 1 (Fig. 3), it is possible to observe how basement faults control salt thickness, distribution and basal relief. The Proto Atlantic depocenter exhibits thicker salt deposits that thin towards Cap Juby Horst, which acted as a high where a little amount of salt was originally deposited. Moreover, no evidence of salt deposition is observable in the Chebeika graben in this section, indicating that the connectivity of the different depocenters was a primary control on the original salt distribution. In this sense, E-W transfer zones could have played a significant role in either isolating or connecting the aforementioned depocenters.

One striking aspect of line 1 is to note the difference in maximum depth of the two depocenters (Fig. 3). The Proto-Atlantic depocenter subsided much more than Chebeika graben during the sag and initial sea-floor spreading phases. In consequence, tilting and deepening of the Proto-Atlantic depocenter imposed an uneven sediment and water load on the salt layer which, in turn, increased its dipping angle in a basin ward direction. Onlap terminations observed on Lower Jurassic beds (Fig. 3) indicate that salt movement began early during basin evolution (Hettangian?), probably triggered by the aforementioned mechanisms. Sediment load exerted by Upper Jurassic shelf carbonates and marls exerted an extra weight over the previously formed salt structures amplifying them and causing a general basin ward migration of salt. Thickness variation in the Middle to Upper Jurassic sediments indicate that proximal areas (thinner beds over Cap Juby Horst) developed less accommodation space than more distal areas (thicker beds over the Proto-Atlantic depocenter).

As shown in Figure 3, the Berriasian to Aptian sediments display a general progradational pattern (Tan Tan delta), with an erosional base surface affecting the Upper Jurassic shelf carbonates. The Tan Tan delta has a radial distribution pattern in map view that seems to correlate with the salt structures (mainly diapirs) distribution pattern. This indicates that spreading could have acted, at some point, as a mechanism responsible for the migration and evolution of these salt structures (Ge et al., 1997). Moreover, turtle structures and proximal peripheral normal faults are evidences that the Proto-Atlantic depocenter acted as a linked salt-related extensional system during, at least, the Lower Cretaceous. Subsequently, primary welding isolated the autochthonous salt layer located over the Cap Juby Horst

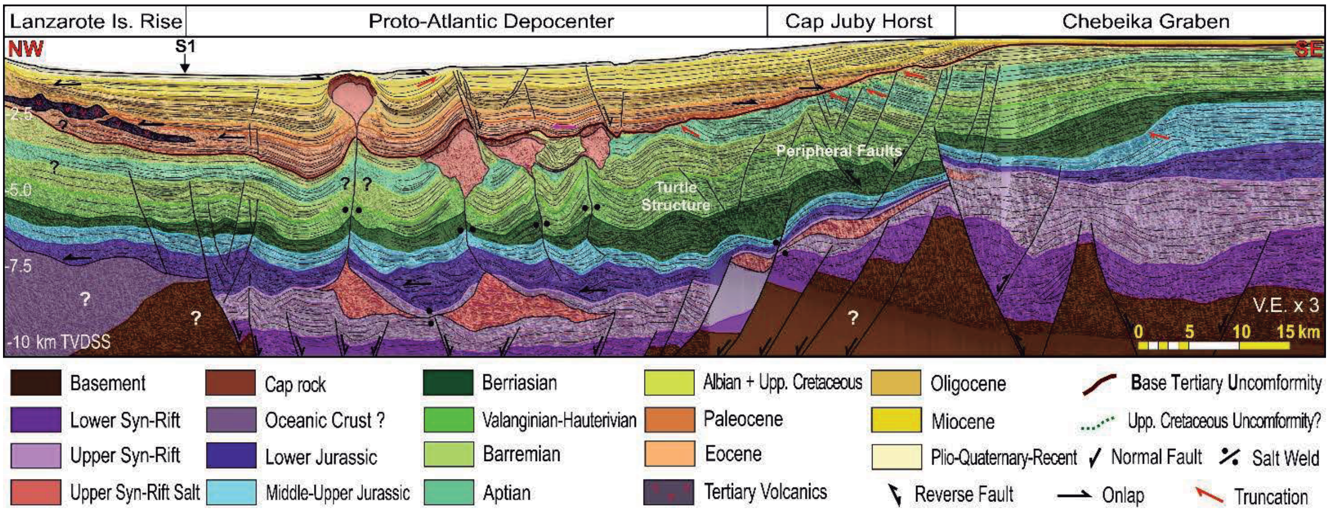

FIGURE 3. Interpretation of Seismic Line 1. For location reference, see Figure 1

region from the one located on the Proto-Atlantic depocenter where salt structures continued evolving. During this phase, sediment aggradation and progradation promoted pulses of passive and active diapirism.

Tectonic inversion of preferentially oriented faults began during the Late Cretaceous, causing occasional buckling and thick-skinned inversion of normal faults that led to the squeezing of diapirs and, in some cases, promoted salt sheet extrusion and secondary welding. However, the most conspicuous feature that marks the onset of the convergence between African and Eurasian plates took place at the limit between the Mesozoic and Cenozoic (BTU in Fig. 3). This event had a profound impact on the evolution of the margin, and promoted the erosion of a thick Upper Cretaceous succession.

Compression related to the Atlasian orogeny during the Cenozoic had a strong impact mainly on the outer, distal fringe of diapirs that were not welded by then. Pulses of passive and active diapirism are evidenced by strata termination geometries against the salt walls. From Figure 3 it is possible to observe that the north westernmost diapir acted most likely as a passive diapir during Paleocene and Eocene times, whereas, from the Late Eocene to Early Oligocene, different pulses of active rise are observed. In fact, the bathymetric bulge noted at the sea bottom suggests that active rise is still happening. Additionally, the strongly convex-upward salt crest suggest that this rise could be driven by compression. Though in the section the structure appears to be welded, a connection with the autochthonous layer is still maintained out of plane, to the northeast.

CONCLUSIONS

The main factors that conditioned the evolution of the offshore Tarfaya Basin can be summarized as follows: (1) Late syn-rift (Upper Triassic – Hettangian?) salt deposition conditioned the general distribution, thickness and base relief of the salt layer; (2) Thermal subsidence related to sag and initial sea-floor spreading phases (Lower Jurassic) promoted the preferential tilting of the Proto-Atlantic depocenter, causing an uneven sediment and water load distribution that triggered initial salt movement; (3) the development of a carbonatic shelf wedge related to the onset of the incipient Atlantic passive margin (Upper Jurassic) exerted an additional load that amplified previously formed structures and expelled salt basin ward; (4) the progradation of the Tan Tan delta caused radial spreading and additional basinward expulsion of salt with late development of primary welds; (5) Compressional events spanning from the Late Cretaceous to recent caused local thick skinned inversion of structures with a subsequent squeezing and frequent secondary welding of diapirs. Occasional salt sheet extrusion is observed. The regional erosion event that took place at the Base of Tertiary promoted the unroofing of buried structures (6) Atlasian orogeny related compression during the Cenozoic caused pulses of passive/active rise of diapirs that still act nowadays and prompted frequently secondary welding and tear drop diapirs.

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