Abstract: The Atlantic margin between Africa coastline and the Lanzarote and Fuerteventura islands (Canary Islands) has a complex geological evolution that can be summarized in the following tectono-sedimentary stages: 1) Triassic rift evolving from platform deposits into a thick saline basin towards the deep offshore; 2) Jurassic drift with development of three carbonate megasequences; their westward progradation promoted a large sedimentary crest parallel to current coastline that separated the oriental platform and the deep-water facies of the Fúster Casas Trough; 3) Thin carbonate Berriasian-Valanginian sequence; 4) First episode of deltaic type sedimentation occurred in the Barremian to Albian that promoted a first sedimentary bypassing and the remarkable E-W extension of the thick delta slope and its subsequent contraction toward west deep waters. This was linked to diapiric extrusions of Triassic salt that also promote the first structural deformation in deep water areas; 5) Late Cretaceous transgression and deposition of marine organic-rich facies; 6) Paleocene-Lower Eocene unconformity filling pre-existing topography (sag basin?) with presence of thin phosphatic facies evolving to thin turbiditic deposit; 7) Eocene to Miocene development of three main turbiditic intervals (Fuerteventura, Lanzarote and Hespérides fans) and associated incised valleys; 8) Miocene-Pliocene deposits characterized by limited thin sandy turbiditic channels and deep-water shales. Deposition in external platform and basin was synchronous with: a) Active tectonic diapirism sourced by mobilization of the deep Triassic salt, with diapiric extrusions reaching the seabed during the Early Cretaceous to Quaternary time interval; b) From Paleocene times the occurrence of marine volcanic flows sourced from Lanzarote and Fuerteventura and increasing their activity during the Eocene and Pliocene times.

Keywords: Sedimentary evolution, salt deformation, Atlantic margin, east of Lanzarote and Fuerteventura islands, Spain.

Resumen: El margen tipo Atlántico existente entre Marruecos y las islas de Lanzarote y Fuerteventura es fruto de una compleja historia geológica que puede ser resumida en los siguientes episodios: 1) Rift Triásico con desarrollo de una gruesa capa salina en aguas profundas y subcuenas desprovistas de sal en la plataforma oriental; 2) Drift Jurásico que promueve tres megasecuencias carbonatadas que progradan hasta una larga cresta sedimentaria, paralela a la actual línea de costa, que muy tempranamente individualizó las facies de la plataforma africana de las de aguas profundas del surco Fúster Casas; 3) Berriasien-Calampiense delgado y carbonatado; 4) Primer episodio de tipo deltaico ocurrido en el Cretácico Inferior ocasionando un primer bypass sedimentario y la extensión
El margen atlántico de España, este de Lanzarote y Fuerteventura, España.

Palabras clave: Evolución sedimentaria, diapirismo salino, Margen atlántico, este de Lanzarote y Fuerteventura, España.


Introduction

The Atlantic margin between Morocco and the Canary Islands contains a dense seismic coverage, sourced from different seismic vintages (CAN, CAP, ECI, ECX, MO, MAP, SM, ROC) totaling 6,214 Km 2D and 3,249 km 3D within Spanish waters, and more than 10,000 km 2D in the Moroccan side. These seismic campaigns resulted on a total of 14 exploratory wells (13 on the Moroccan side and 1 on the Spanish side) drilled between 1983 and 2015. This seismic and well database, combined with geological cartography of onshore area (Fig. 1) allow a deeper and more complete geological interpretation of this passive margin than those partially published in previous short notes and publications (Martínez del Olmo y Buitrago Borrás, 2002; Buitrago Borras et al., 2003; Martínez del Olmo, 2004a, b, 2005, 2019).

The objective of this work is to synthetize the tectono-sedimentary evolution of the area from Triassic to Pliocene, based on the analysis of the geological maps and wells and seismic transects collected during 40 years of exploration activity. This database allows the tectono-sedimentary differentiation of the margin that constitutes the object of this work.

Sedimentary record

Triassic

Two separate sets of red bed facies can be differentiated from wells located at the currently emerged margin and internal platform (Figs. 2 and 3): a first set characterized by sandy facies, and a second one represented by shale facies with either anhydrite or gypsum. Towards the deep waters, thick Triassic salt deposits are inferred from the occurrence of large diapiric extrusions of up to 5,000-6,000 m high, which occasionally reach the sea floor. The absence of well penetrations deep enough into the Triassic sequences within the external platform, impedes to corroborate the presence of Muschelkalk carbonatic facies and its potential lithostratigraphic correlation with the Triassic of the Iberian Peninsula or Algeria, where the upper sandy-shale interval are respectively correlated with the Arenisca de Manuel (Ortí Cabo, 1974) and the Triasique Argilo-Greséux Inferieur “TAGI” (Boudjema, 1987), both Keuper in age.

Jurassic

The Jurassic sedimentary record at the inner and external platform is mainly composed by carbonate facies that are segregated in three second-order depositional sequences (J1, J2 y J3), each one initiated by a thin dolomitic interval interpreted as Transgressive System Tract (TST) and followed by a westwards prograding pattern (Figs. 2 and 3). Despite the lack of a precise chronostratigraphic assessment, these successions probably cover the Hettangian-Tithonian time lapse. Sequence J1 is thin and most likely represents a distally attenuated ramp; sequence J2 is the thickest one (up to 1,000 m); and finally, sequence J3 shows evidences of exposure with probable development of a paleokarst with associated secondary vacular porosity at top, similar to that described in other sequence boundaries (Delfaud, 1972; Martínez del Olmo y Esteban, 1983).

The sedimentation pattern resulted on a well-defined shelf edge preserved from erosion (Turfaya crest in Fig. 2). Within this architecture, which can be followed on seismic lines and confirmed by well penetrations (wells MO-2, MO-8 and Cap Ruby-1), shelf and ramp environments are clearly differentiated from the western deep-water setting of the Fúster Casas Trough (Figs. 1 and 3).

In the simple stratigraphic scheme (Fig. 2) elaborated from final well reports and guidelines from Pomar (2001), a particular sedimentary feature in NE platform area can be identified (MO-4 and Tan Tan-1 wells). In these two
wells, below the Lower Cretaceous succession (deltaic sequences of Barremian-Aptian Tan Tan Fm), a thick siliciclastic interval (+/- 2,000 m) with thin calcareous levels with abundant Jurassic fossils can be recognized. These data contrast with the non-evidences on seismic surveys of features of large distributary channels associated with a probable deltaic system. Saying that, these local sandy deposits in wells MO-4 and Tan Tan-1 could be explained as terrigenous sediments that were sourced from external platform and bypassed a possible talus, and were accumulated in deep water (Fig. 2). However, none of the other existing wells have reached the Jurassic deep-water sediments, so their facies remain unknown. In addition, some outcrops previously assigned to the Toarcian-Oxfordian (Robertson y Stillman, 1979; Barrera Morales et al., 1981) in the western coast of the Fuerteventura island, have been recently reinterpreted as Cretaceous (Balcells Herrera et al., 2004; Barrera y Bellido, 2014). However seismic velocity analysis in west waters of Fuerteventura and Lanzarote islands also suggests a high percentage of hemipelagic limestones intercalated within the Middle and Upper Jurassic shale facies, and even, although unlikely, also associated with a Lower Jurassic platform-basin geometry developed instead of a ramp model. With all of this, we can conclude that the final interpretation of this sedimentary anomaly remains uncertain.

**Berriasian-Valanginian**

The Berriasian-Valanginian succession corresponds to a thin carbonate formation (50 to 150 m), which follows the preexisting Upper Jurassic geometry, and eventually evolves onto a more siliciclastic facies towards the eastern margin (Figs. 2 and 3). There, the unit probably has been integrated together with the fluvial-deltaic deposits of the Tan Tan Fm of Barremian-Aptian age.

West MO-7 well, there is no well penetration down to this level in the outermost part of the external platform to test the composition of the deep-water facies. In addition, the likely condensed sedimentation results on thin deposits not imaged by the existing seismic resolution.

**Barremian-Aptian-Early Albian**

Deposition during this time interval is represented by the so-called Tan Tan Fm that extends its deposits onto the African craton (Figs. 1-4). It represents a notable deltaic episode characterized by sands, shales and a visible basinal downlap following a classical model of progradation in a thickening- and coarsening-upward sequence. Three facies associations are present: 1) fluvial sandstones with some shales; 2) marine sandstones and shales in middle and internal platform; and 3) a well-developed delta slope, where the thick sedimentation together with high shale content derives in extensional collapse (Fig. 5).

The extension is characterized by low-angle growth faults, which produce a significant structural deformation of the Atlantic margin and it is represented by the thick deltaic interval between 2,500 and 3,000 m encountered in wells MO-6, MO-7 and Haute Mer-1 (Fig. 2). The extension of the external platform is much important in the north area, where it develops larger extensional stress and deformation. In the external platform (close Lanzarote and Fuerteventura islands) it results in compressional features “toe thrust type” below the their volcanic flows. This deformation is related to a gravitational origin rather than to a compressive tectonic pulse.
Fig. 2. - Lithostratigraphic chart showing key wells (see location in Fig. 1A) and interpretation of their position in reference with the different paleogeographic segments described throughout the text.

Fig. 3. - Dip seismic, 290 km-long transect (A) and tectonostratigraphic interpretation (B) illustrating the platform to basin setting between wells Sandia-1 and D-29 (see location in Fig. 1A), and showing the projected location of most representative wells.
In summary this thick deltaic sedimentary episode substantially modified the margin of the passive margin. As observed in many wells, the Tan Tan Fm is not present west of the Haute Mer-1 well, where a significant amount of shales can be already observed (Figs. 2 and 3). This assessment is based on the observations made in the final 7-8 m of the Sandia-1 well and on seismic data interpretation. It is possible to link these deposits with the cap rock associated with the diapiric extrusion, which generated the structural deformation targeted by this exploratory well.

**Late Albian**

The Upper Albian succession consists of a thin (75-150 m) sandstone sequence with thin interbedded carbonates identified by wells from shelf to external platform and being absent at the Tarfaya crest probably due to erosion (Fig. 2). Its thin sedimentary thickness and fining-upward trend and its continuity suggest it represents a Transgressive System Tract (TST) widely characteristic of this time (Vail et al., 1979; Haq et al., 1987a, b). This interpretation is supported by well data from Alisio 15-A1 and Spansah 51-A1 wells (see transgressive deposits below mfs 6 in Fig. 4A), where good quality gamma ray, lithology records and biostratigraphy control support interpretation of genetic sequences.

**Cenomanian-Santonian-Early Campanian**

The sea level rise initiated during the Late Albian corresponds with one of the largest registered in the geological history, which continued into the Cenomanian, Coniacian, Turonian and Early Campanian, represented in the studied area by the Tarfaya oil shales (Bouchta, 1984). Due to erosion, this unit shows a variable thickness, with a maximum thickness of 500 m in Alisio15 A-1 and Spansha 51 A-1 wells (Fig 2). The unit is characterized in several intervals by shale and carbonate sequences with high organic content (TOC), high hydrogen index (HI) and excellent hydrocarbon generation potential (S2) (Fig. 4B).

The areal distribution of these rich TOC Late Albian-Early Campanian successions could be interpreted related to its relative position within the inner platform (Tarfaya coast; Fig. 3) where the occurrence of upwelling currents could have favored the organic richness. However, the extensive erosion suffered by the Upper Cretaceous makes the palaeogeographical reconstruction of the area very challenging, especially considering that the only well in the deep-water environment (Sandia-1) is placed on top of a diapiric feature, missing the geology of the diapiric flanks. In addition, the seismic quality of the deep-water seismic profiles in the area does not resolve the uncertainty related to the Upper Albian-Lower Campanian deposits thickness and facies.

The Tarfaya oil shales are also present at wells Amber-1 and Rak-1 located 2,000 m water deep offshore the Agadir canyon and a few hundred kilometers towards the north respectively, where the Cretaceous and Cenozoic successions are separated by a deep water seismic paraconformity and the Tarfaya oil shales have minor TOC values that Spansah-Alisio wells located in platform environment (Figs. 1, 2 and 6). The two well data supported the upwelling origin of the Tarfaya oil shale.

**Late Campanian-Maastrichtian**

The youngest known Cretaceous successions are locally found at the inner platform geological map outcrop where they are preserved from the erosion linked to the Cenozoic unconformity (Fig. 1A). These deposits characterize the Agudir Fm and cannot be identified at any other of the existing well penetrations (Fig. 2). From regional understanding it is reasonable to interpret that this interval starts after the regional upper intra-Campanian unconformity.

From the limited information provided by few dispersed outcrops, this formation is described as formed by limestones and calcarenites with occasional shale intervals. Wells Haute Mer-1 and Sandia-1 respectively did not reach this interval in the external platform and deep waters. Meanwhile, at ultra-deep waters (Rak-1 and Amber 1 wells), the interval is probably not segregated from the previous Upper Cretaceous sediments.

---

Fig. 4.- A. Alisio 15 A-1 and Spansah 51 A-1 reference wells used to define a partial depositional sequence framework. Oligocene and Miocene turbiditic sands are labelled in red (a, b) and represent forced regression episodes from probably glacial-eustasy origin (Abreu and Anderson, 1998). B. Geochemical logs of Alisio 15 A-1 well (for well location see Fig. 1B).
The Agadir Fm represents the end of the drift episode initiated during the Jurassic and initiates a new episode interpreted as sag basin during the Paleocene-Early Eocene (Boukra Fm), which precedes youngest Cenozoic turbiditic deposits (Fig. 7). As previously described, the deep-water facies remain unknown, and their correlation with the fini-Cretaceous regressive cycle allows interpreting a notable sedimentary condensation below seismic resolution.

The Main Cenozoic unconformity and Cenozoic deposits

The existence of a well-developed angular and erosive unconformity is confirmed by several wells and seismic sections at the inner, outer shelf and deep water (Sandia-1, Haute Mer-1), which even extends onto the deep waters of the Fúster Casas Trough. Precise timing of this event is not easy to assess, remaining the uncertainty if it is pre-, syn- or post-sedimentary to the probable sag episode represented by the Boukra Fm (Figs. 8 and 9). The main Cenozoic unconformity is not always visible on the N-NE direction where is a paraconformity (sequence boundary) representing the ultra-deep waters at the abyssal plain. A similar display occurs within the small inter-diapiric sub-basins penetrated by the wells Rak-1 and Amber-1 (Fig. 6). The two seismic expression, unconformity and paraconformity, allow the identification at the Early Cenozoic time the deep waters and platform paleogeographic areas.

The Cenozoic cycle is characterized by the presence of forced regressions, which starts with incised valleys (Fig. 10) characteristic at the external platform. They represent the distributary channels of sand prone turbiditic systems (the so-called Fuerteventura, Lanzarote and Hespérides fans) with a bypass area of 50 to 60 km from platform to basin, capable to generate thick and a high-quality turbidites reservoir facies.

The Sandia-1 exploratory well was an oil target in this interval (Buitrago Borras et al., 2003; Martinez del Olmo, 2004a, b, 2005, 2018), but unfortunately a thick water wet sandstone interval of about 130 m net with porosities of 19% was encountered. This sand and water bearing interval provided weak shows of gas components C1, C2, C3, ic4 and ic5 and was reached 300 m below the top of the structural trap investigated by the exploratory well (sondeo Sandia-1x, Archivo Técnico de Hidrocarburos, Ministerio para la Transición Ecológica, 2019), reason that not invalidate the structural top of Sandia trap and the regional possibilities.

Some authors suggest that incised valleys are filled during the sea level rise following the time incision by river systems; however, in our case this hypothesis is difficult to check. We link theses deposits to forced regressions based on the deep-water location of the turbidite fills (Figs. 10–12) and their similarities with other examples described in several works (Mutti, 1985; Hunt and Tucker, 1992; Pickering et al., 1995; Martinez del Olmo, 1996a).

The Fuerteventura (Eocene-Oligocene), Lanzarote (Oligocene) and Hespérides (Late Oligocene-Miocene) fans are named in reference to the geographical source of their sediments. However, drifting and avulsion of distributaries and fans result in a wider and more complex juxta-position of fans on the Fúster Casas Trough deep-waters. Modern 3D seismic data have resolution to delineate some characteristic features and morphologies as high sinuosity channels, abandoned meanders and locally hydraulic drops. Distal facies are represented by lobe deposits with avulsion patterns in sequences of 75-150 m thick (150-300 T.W.T. milliseconds), resulting in thick sandstone intervals as those recognized at the Sandia-1 well. Forced regressions reached the Fúster Casas Trough in similar direction as the NW-SE incised valleys, and progressively sifted its orientation towards SW-NE direction (Fig. 12) following the regional dip. Seismic control disappears below the Fuerteventura and Lanzarote volcanic flows.

Volcanic flows

Seismic control of the post-rift sedimentation is lost when approaching Fuerteventura and Lanzarote islands, as a result of poor seismic image below the volcanic flows, which constitute the nature of the volcanic islands. Few seismic sections and 2D-3D seismic regional and local correlation allow determining that the submarine volcanic flows at least begin in Late Cretaceous-Eocene and later...
are covered by Oligocene, Miocene and Pliocene sediments in onlap configuration (Fig. 13). These flows do not represent the basal complex related with the volcanic eruption, which resulted on the creation of the archipelago.

Outcrops of the basal complex at the Pájara region to the SW of Fuerteventura and the Lanzarote-1 well (Figs. 1B and 2), are described as formed by turbiditic sandstones, and black shales intersected by a lot of vertical dikes. These sedimentary sequences have ages from Berriasian-Valanginian to Late Cretaceous (Fúster et al., 1968a, b; Stillman et al., 1975; Balcells Herrera et al., 2004; García-Navarro, 2006; Gutiérrez et al., 2006; Barrera y Bellido, 2014).

In summary, seismic data indicate that the volcanism episode resulting on the creation of the archipelago was initiated in Fuerteventura and Lanzarote islands in the Cretaceous.

Salt diapirism

As mentioned previously, a thick Triassic salt layer is recognized over a large portion of the deep waters. The confirmation of its further extension in the edge area of the external platform is prevented by the volcanic flows overlaying the salt sediments in the vicinity of Lanzarote and Fuerteventura.

Based on seismic data observations (Fig. 14) salt diapirism can be interpreted to present the three classical phases (reactive, active and passive) with respect to its associated tectonic settings: tectonic extension, differential overburden load and diapiric rise to surface, where deep-water sedimentation between crest and peripheral rings is reduced. A more problematic phase of “contractive diapirism” is also visible but difficult to date. Known that the salt tectonics is always triggered by faulting of extensional or compressional origin, which creates differential pressure allowing salt to move (Jackson and Talbot, 1986; Jackson and Vendeville, 1994; Martinez del Olmo, 1996; Tari et al., 2000; Hudec and Jackson, 2007; Martinez del Olmo and Motis, 2015) it is possible to differentiate the following diapiric phases, their preferential location and their timing:

- Reactive diapirism was produced during the late stage of the Late Jurassic-Late Cretaceous drift, and specially was developed in east platform area.
- Active diapirism was triggered by the thick deltaic overburden occurred during the Barremian-Aptian-Early Albian (Tan Tan Fm). According with thickness variation, two segments from N to S along the external platform can be differentiated: 1) The diapirism at the Fuerteventura area, which usually does not reach the seafloor; and 2) The diapirism at the Lanzarote area where salt domes frequently reaches the sea-bottom.
- Contractive diapirism was probably related with the Late Cretaceous extensional collapse resulting on shortening and collapse of delta slope (Tan Tan Fm) in the Lanzarote area. Early folding and complex tectonic features are explained as result of contraction of diapiric chimneys both vertically along salt dikes, “salt scar” and horizontally “salt welds or salt windows” (Fig. 14).
- Passive diapirism. Late Cretaceous and especially Cenozoic overburden produced a reactivation of diapirism, which remains active to present day in deep water. Several salt chimneys are visible and active at present, showing circular sea mounds by salt movement or insoluble cap rock at top. These sea mounds are vertical and do not produce

Fig. 6.- Diapiric flank penetrated by the Rak-1 well and lithostratigraphic columns of three deep water reference wells (for well location see Fig. 1B). Note the significant thickness of the Tarfaya oil shales Fm (800-1,000 m).

Fig. 7.- Preferential depositional areas of the turbidite fans of the Fuerteventura (1), Hespérides (2) and Lanzarote (3). Fan names derived from their main sedimentary areas.
typical mushroom, overhang or canopy structures, frequent features below the break-up unconformity, a fact that is interpreted as a result of active erosion destabilizing the differential overburden.

As normally occurs, salt mobility produces different deformation along the shelf to margin, and salt extrusions on seabed are more frequent towards east, to the extent that none of the diapirs manage to penetrate the volcanic flows from Lanzarote and Fuerteventura. This could be interpreted as a result of active erosion destabilizing the differential overburden.

As normally occurs, salt mobility produces different deformation along the shelf to margin, and salt extrusions on seabed are more frequent towards east, to the extent that none of the diapirs manage to penetrate the volcanic flows from Lanzarote and Fuerteventura. This could be interpreted as a result of active erosion destabilizing the differential overburden.

Poor imaging below the volcanic flow does not allow confirm this ideas, but could be supported by the proposed tectonic inversion at the basal complex described in the west of Fuerteventura island in the Pájara region (Robertson and Stillman, 1979).

Discussion and conclusions

Summary of unresolved questions

The objective of this work is to synthetize the tectono-sedimentary evolution of the area from Triassic to Pliocene, based on the analysis of the geological maps, well data and seismic transects collected during 40 years of exploration activity and can be anticipated and summarized in the differentiation of four main geological episodes: rift, drift, sag and passive margin. The text above has aimed to illustrate and explain the main structural and sedimentary events described for the three paleogeographic sectors: 1) The platform and the western margin of the African craton; 2) The deep water and the Fúster Casas Trough; and 3) The narrow eastern continental platform of Fuerteventura and Lanzarote islands.

After revisiting and interpreting the extensive database there are still several unresolved questions which are summarized as follow:

1) Proper assessment of Triassic formations. These formations are generally attributed to the Buntsandstein in both the clastic margin and the saline deep-water depocenters. However, the absence of proper biostratigraphic data, together with geological models from the Iberian Peninsula and Algeria, provide an alternative age correlation with the Keuper facies. The absence of well penetrations deep enough into the Triassic sequences within the external platform, impedes to corroborate the presence of Muscheskalk carbonatic facies and its potential lithostratigraphic correlation with...
Fig. 10. - A. Two dip (SSW-NNE) seismic lines parallel to Africa shoreline (15-25 km) showing the expression of the Oligocene incised valley fill promoted by forced regressions. B. Their control by some wells of the area (for well location see Fig. 1B).

Fig. 11. - Tectono-stratigraphic sketch representing the forced regressions sourcing the Fuerteventura, Lanzarote and Hesperides fans. Note the bad correlation with the sea level charts established by Haq et al. (1987b).
the Triassic of the Iberian peninsula or Algeria, where the upper sandy-shale interval are respectively correlated with the Arenisca de Manuel (Ortí Cabo, 1974) and the Triasique Argilo-Greséux Inferieur “TAGI” (Boudjema, 1987), both Keuper in age.

2) Middle and Upper Jurassic lithofacies westwards of the submarine Tarfaya crest are unknown and are inferred from the depositional model and their slope geometry. The uncertainties on this geometry are associated with poor seismic velocities data and its effect on the structural reconstruction of the palaeoslope. Saying that, the local deltaic deposits in NE platform area (wells MO-4 and Tan Tan-1) could be explained by sandy deposits provided by the Agadir and El Aaium canyons (Fig. 7) anticipating one of the bypassing events which characterize in seismic the external platform and the deep waters of the Jurassic. In addition, some outcrops previously assigned to the Toarcian-Oxfordian (Barrera Morales et al., 1981) in the western coast of the Fuerteventura island, have been recently reinterpreted as Cretaceous (Balcells Herrera et al., 2004; Barrera y Bellido, 2014). However seismic velocity analysis in west waters of Fuerteventura and Lanzarote islands also suggests a high percentage of hemipelagic limestones embedded within the Middle and Upper Jurassic shale facies, and even, although unlikely, also associated with a Lower Jurassic platform-basin geometry developed instead of a ramp model.

3) Linking of the thick deltaic sequence assigned to the Jurassic identified at wells MO-4 and Tan Tan-1 with a distributary channel system non-identified with the available data. This thick deltaic sedimentary episode substantially modified the margin of the passive margin. As observed in many wells, the Barremian-Aptian Tan Tan Fm has not reached the west of the Haute Mer-1 well, where a significant amount of shale can be already observed (Figs. 1B and 2). This assessment is based on the observations made in the last 7-8 m of the Sandia-1 well. Based on seismic data interpretation, is it possible to link these deposits with relicts of cap rock associated with the diapiric extrusion, which generated the structural deformation targeted by this exploratory well.

4) Origin and genesis of the extensional collapse at the slope of the Barremian-Aptian Tan Tan Fm. Is this a result of combination of unconsolidated sediments, sedimentary slope angle, and shale content? or could it be related with an extensive regime (second rift phase) in a late drift stage?

5) Which is the origin of the high TOC content of the Upper Albian-Lower Campanian Tarfaya black shales Fm? Does it relate to upwelling currents, as traditionally interpreted in many other basins, or to worldwide Late Cretaceous anoxia or a combination of both? The areal distribution of these rich TOC deposits could be interpreted related to its relative position within the inner platform (Tarfaya coast) where the occurrence of upwelling currents could
have favored the organic richness. However, the extensive erosion suffered by the Upper Cretaceous makes the paleo-geographical reconstruction of the area very challenging, especially considering that the only well in the deep-water environment (Sandia-1, 2019) was placed on top of a diapiric feature, missing the geology of the diapiric flanks.

6) What is the origin of the Paleocene-Lower Eocene Boukra Fm? Does it represent a sag episode before the main Cenozoic unconformity?.

7) Correlation resolution of the three proposed turbidite cycles, the so-called Fuerteventura (Eocene-Oligocene), Hespérides (Oligocene-Miocene) and Lanzarote (Miocene) (Figs. 11 and 12), do not allow to precise whether the turbiditic flows represent one super-cycle sea level fall or many (more likely case). A more detailed seismic 3D interpretation would resolve this question.

**Tectono-sedimentary evolution and sedimentary record at the Fúster Casas Trough**

Well dataset and seismic information make it possible to describe the evolution of the area during the rift, drift and passive margin phases and summarize the lithostratigraphy proposed for the Fúster Casas Trough in two north and south cross sections, showing the distinct patterns in sedimentation (Figs. 15–17):

---

**Fig. 13.** Volcanic flows from Fuerteventura and Lanzarote and its relationship with packages of 2D seismic reflections of the Eocene, Oligocene, Miocene, Pliocene and Pleistocene.

**Fig. 14.** Southeast of the Fúster Casas Trough from 3D seismic area (3D in Fig. 12A). A. Diapiric extrusions with clear overhangs. B. Submarine mountain created by a salt diapir and their not soluble cap rock. C. Salt scars and a likely canopy. D. Deformation under the main Cenozoic unconformity (four images in milliseconds t.w.t.)
1) In absence of precise biostratigraphic data the main rift phase of the area is associated to Pangea disegregation during the Early Triassic resulting in the differentiation of a margin with absence of salt deposition and a basin with a well-developed salt sequence of probable Keuper age.

2) The drift phase becomes notorious during the Middle and Late Jurassic, developing a progradation of a thick carbonate platform, which culminates with an evident shelf edge. This phase is characterized by the development of the so-called Tarfaya crest at the edge of the inner platform and a possible deltaic system with sandstone and calcareous deposits at northeast of the Fúster Casas Trough (Fig. 15). On the contrary it is difficult to visualize this platform-slope-basin geometry during the Early Jurassic, when most likely the platform geometry corresponded to an accentuated distal ramp.

3) During the Berriasian-Valanginian sedimentary rates were very low and promoted a thin carbonate unit, which covered the preexisting Upper Jurassic geometry and probably did not reach the east margin and was notably condensed in deep waters.

4) From Barremian to Late Albian a deltaic system generated a significant modification in the area, as deltaic facies reached the deep waters of southern (Fuerteventura) and northern (Lanzarote) areas. The northern area developed a thick fine-grain siliciclastic slope, which suffered an extensional collapse resulting on folding and deformation of the preexisting deposits. The extensional collapse enhanced by the thick Tan Tan Fm triggered an intense salt tectonics activity by low-angle faults.

5) The Late Cretaceous was a period of a notable sea level rise extending the area of sedimentation towards the platform and margin, with probable upwelling currents and/or anoxia inducing the development of the spectacular black shales conforming the Tarfaya Fm. Although this sequence has been seriously affected by erosion, its preservation at the edge of the external platform can be interpreted as part of the prograding system of this margin.

During previous phases 3 and 4 it is assumed a normal basinward facies evolution from fluvial-deltaic to deep-water condensed deposits. Phases 4 and 5 are syn-sedimentary with active salt tectonics and its associated extrusions / diapirs, scars and possible development of canopy’s.

6) The Cretaceous sedimentary cycle culminates in the outcrop (Fig. 1A) as Late Campanian-Maastrichtian with the Agadir Fm. This sedimentary unit was intensively eroded and has not been recognized by wells (its character is provided from outcrop lithological descriptions), reason why its thickness and sedimentary model remain unknown. Despite it represents a regressive cycle, seismic interpreta-
tion suggests the shift of the shelf edge towards the basin. The Agadir Fm represents the end of the drift episode initiated during the Jurassic and initiates a new episode interpreted as sag basin during the Paleocene-Eocene (Boukra Fm), which precedes the youngest Cenozoic turbiditic deposits (Fig. 3). As previously described, the deep-water facies remain unknown, and their correlation with the fini-Cretaceous regressive cycle allows interpreting a notable sedimentary condensation below seismic resolution.

7) The main Cenozoic unconformity occurred during or after a possible sag basin episode represented by the phosphatic Boukra Fm of Paleocene-Early Eocene age and represent a dramatic change in the regional depositional model characterized by successive forced regressions with its associated turbidite systems. These systems are easily depicted from 2D and 3D seismic data (Figs. 11 and 12) and are perforated by the well Sandia-1, where these deposits constituted the main exploratory target. Other authors suggested that the incised valley was filled during the sea level rise following the incision by river system; however, in our case is a difficult hypothesis but we known their turbidite fill and their deep water location (Figs. 12 and 13) and their similarities with other examples described (Mutti, 1985; Pickering et al., 1995; Hunt and Tucker, 1992; Martinez del Olmo, 1996).

In summary, we can conclude that the Fuster Casas Trough presents four sedimentary super-cycles, correlated with these four events:

1) Triassic rift phase. Relates to the opening of the basin and sub-basins at margin, this may or not extends to the Early Jurassic, which can be also explained as an accentuated distal ramp.

![Synthetic stratigraphic evolution](image-url)
2) Jurassic-Cretaceous drift phase, represented by carbonate platforms and deltaic systems. These sediments are affected by low-angle extensional and local compressional tectonics with associated salt tectonics.

3) Probable Paleocene-Lower Eocene sag phase, inferred from some 2D seismic lines and the regional geological maps of the West Sahara.

4) Post-rift or passive margin phase, initiated at the Late Eocene and extended to nowadays, characterized by forced regressions with their associated incised valleys feeding and well developed turbiditic systems and a large bypassing area of up to 50 km reaching the deep-water areas of East Fuerteventura and Lanzarote.

Acknowledgments

To the editor Beatriz Bádenas, by her continue help, and two anonymous reviewers because their observations improved the final text. Also to the professor José María Fúster, who contributed to my interest in geology at college from his classes in Igneous, Metamorphic and Sedimentary Petrology. Also to the geoscientists Consuelo García, Nuria Antich, Javier Buitrago, Carlos Díaz and Pujianto Lukito, who contributed with the 3,250 km$^2$ of the 3D seismic interpretations that are partially described in this paper. To the ONHYM which facilitated the Morocco wells data used on this study, and finally to my dears and young granddaughters Lola and Anni who translated the Spanish text into English.
References


Martínez del Olmo, W., 2005. Bloques Canarias 1 a 9. Curso en el Ilustre Colegio Oficial de Geólogos, 60 PPT.


MANUSCRITO RECIBIDO EL: 4-10-2019
RECIBIDA LA REVISIÓN EL: 22-1-2020
ACEPTADO EL MANUSCRITO REVISADO EL: 20-2-2020