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Predicting Early Cretaceous deepwater turbiditic successions in the offshore Aaiun-Tarfaya Basin, southern Morocco: constraints from new data from Fuerteventura

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ABSTRACT

This paper re-examines the sedimentology and biostratigraphy of the Early Cretaceous Main Clastic Unit (Steiner et al., 1998) exposed in Fuerteventura, and provides a correlation to the proximal equivalent of the system onshore Morocco, to assess the implications for the petroleum system and potential reservoir distribution.

Lower Cretaceous coarse clastic-dominated continental to shallow-marine successions are extensively exposed in the onshore Aaiun-Tarfaya Basin, Morocco. The deep-water distal counterparts of these systems are less well-documented, and only exposed on Fuerteventura, where they have been exhumed by tectonic uplift associated with volcanism. The studied section is dated as pre-late Berriasian based on previous work and the discovery of a well-preserved ammonite as part of this study. It is made of thin bedded clastic turbidites with occasional coarser and thicker bedded intervals exposed in a succession of overturned and sub-vertical outcrops, intruded by igneous bodies, with local repetitions of the succession due to tectonic folding.

Three large-scale cycles can be identified; two coarsening-upward, interpreted to represent the progradation of lower and middle lobes of a large submarine fan and an overall fining-upward cycle with increasing contribution of calciturbidites and limestone beds. The latter is interpreted to reflect the sea-level rise during Aptian and Albian times and the associated development of carbonates on the shelf, resedimented into the deep basin as calciturbidites.

The sand content in the lower part of the three cycles can reach up to 95 %, deposited as high density turbidites. This can be correlated with the low stand wedge seen in seismic, draping the older Jurassic carbonate platform. Detailed logging and new biostratigraphy further constrain understanding of these depositional systems and their evolution, helping to reduce uncertainty in exploration for these important reservoir systems that are targets for offshore exploration.

1. Introduction

The Early Cretaceous is a time of significant offshore clastic delivery in southern Morocco associated with the Tan-Tan delta. Thick clastic-dominated continental and shallow marine succession of the Tan-Tan Fm (Martinis and Visintin, 1966). are well exposed onshore, and have also been drilled by exploration wells. Although there are three non-commercial discoveries in the offshore basin, suggesting an effective petroleum system, the distribution, quality, and potential of the associated deep marine clastic reservoirs are poorly understood. The

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Mesozoic offshore succession in the Aaiun-Tarfaya Basin exceeds 10 km (Hinz et al., 1982; Ranke et al., 1982). Records of the lower Cretaceous distal equivalents of the onshore and shallow shelf deposits are limited to a few wells drilled by the IODP/DSDP program, partial penetrations by commercial wells on the continental slope and the Mesozoic succession exposed in the volcanic island of Fuerteventura (Canary Archipelago, Spain).

The Cretaceous sequence on Fuerteventura was first recognised in the 19th century (e.g. Hartung, 1857) and its stratigraphy and true deep-marine origin established by Robertson and Stillman (1979) and Robertson and Bernoulli (1982). Due to the challenges posed by the high level of igneous intrusions and thermal metamorphism, a detailed stratigraphy was not presented until Steiner et al. (1998) defined five units ranging from Toarcian to Campanian in age.

The aim of this paper is revisiting the lower Cretaceous interval of the succession (Main Clastic Unit of Steiner et al., 1998) to improve the sedimentology, biostratigraphy, its link with the proximal equivalent of the system offshore Morocco and its importance as a potential reservoir.

2. Study area

The Canary Islands are an archipelago composed of seven volcanic islands off the west coast of Morocco (Fig. 1) stretching for 450 km along an E-W direction. The archipelago sits on the passive margin within the Jurassic Magnetic Quiet Zone. Four main hypotheses have been invoked to explain the genesis of the Canary archipelago; propagating oceanic fractures (Anguita and Hernan, 1975), local extensional ridges (Fúster, 1975) or uplifted tectonics blocks (Araña and Ortiz, 1986) hypotheses and a mantle plume hypothesis (Morgan, 1971) that has been invoked extensively for the Canary Islands (e.g., Carracedo et al., 1998; Holik et al., 1991). All these hypotheses have limitations and most recently Anguita and Hernán (2000) combined some of them into an integrated model (Fig. 2).

A feature that the Canaries share with other volcanic islands groups is that in the most complete sections up to three genetic units can be identified, i) a turbiditic basal unit, intruded by swarms of dykes, ii) shield edifices and iii) post-shield cones. Each one of these units is consistently older in the eastern islands of the archipelago than their comparable units on the west.

The closest island to the African continent is Fuerteventura, which lies approximately 100 km ENE from the coastal city of Tarfaya (Fig. 1). It is the second largest island in the archipelago with an elongated NE-SW shape aligned with the island of Lanzarote extending into the submarine structure of Conception Bank. Together they form the volcanic structure of the Eastern Canary Ridge (Fig. 1). The volcanic history of Fuerteventura can be traced to the Late Cretaceous (80 my; Le Bas et al., 1986).

The Basal Complex of Fuerteventura (Stillman et al., 1975) is best exposed on the central west side of the island, in the Betancuria Massif (Fig. 3). The Basal Complex consists of a Mesozoic deep marine sedimentary succession (Robertson and Bernoulli, 1982; Robertson and Stillman, 1979; Steiner et al., 1998) intruded by several generations of dykes, sills and plutons, unconformably overlain by volcanics.

The pre-volcanic sedimentary succession of Fuerteventura has been studied since the 19th century (e.g. Hartung, 1857; von Fritsch, 1868). Initially interpreted as Palaeozoic shallow-water sediments, the age of the sedimentary succession was later revised to Mesozoic and placed within a shallow continental shelf environment (Rothe, 1968). The succession was thought to be repeated by a major east-west-trending isoclinal syncline (Fig. 4). The succession was reinterpreted in the last decades of the 20th century as representing deep-water sedimentation (Robertson and Bernoulli, 1982; Robertson and Stillman, 1979; Steiner et al., 1998). The succession crops out in a series of subvertical and overturned outcrops (Figs. 4 and 5). Polarity of sedimentary structures and dating with microfossil assemblages and ammonites has demonstrated that the succession becomes younger towards the north (Renz et al., 1992; Robertson and Bernoulli, 1982; Steiner et al., 1998). The exposed Mesozoic succession exceeds 1500 m in thickness and has been subdivided into several units (Robertson and Stillman, 1979; Rothe, 1968; Steiner et al., 1998). Five sedimentary units (Figs. 3 and 5) were

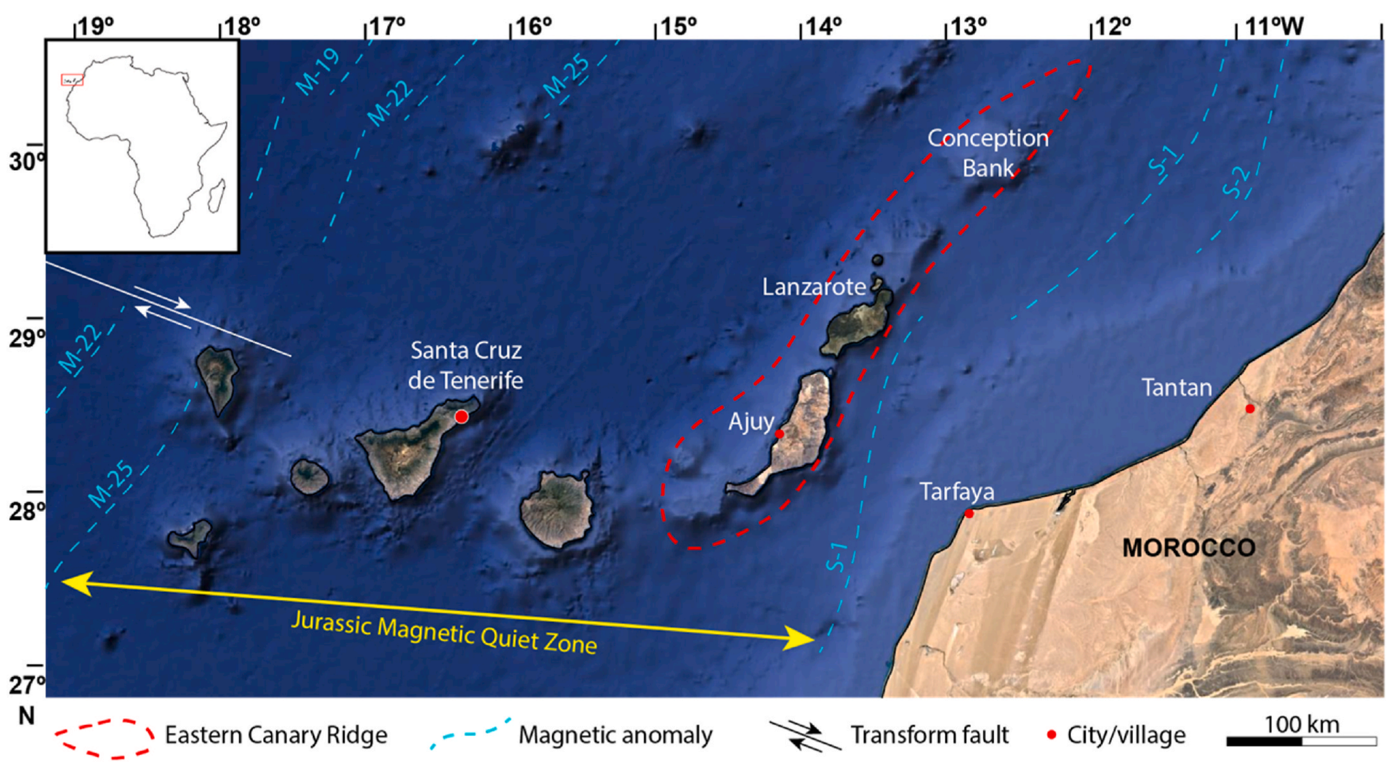

Fig. 1. Location map and main tectonic elements of the Canary Islands. Satellite scene from Google Earth™. Magnetic anomalies and oceanic transform faults after Steiner et al. (1998).

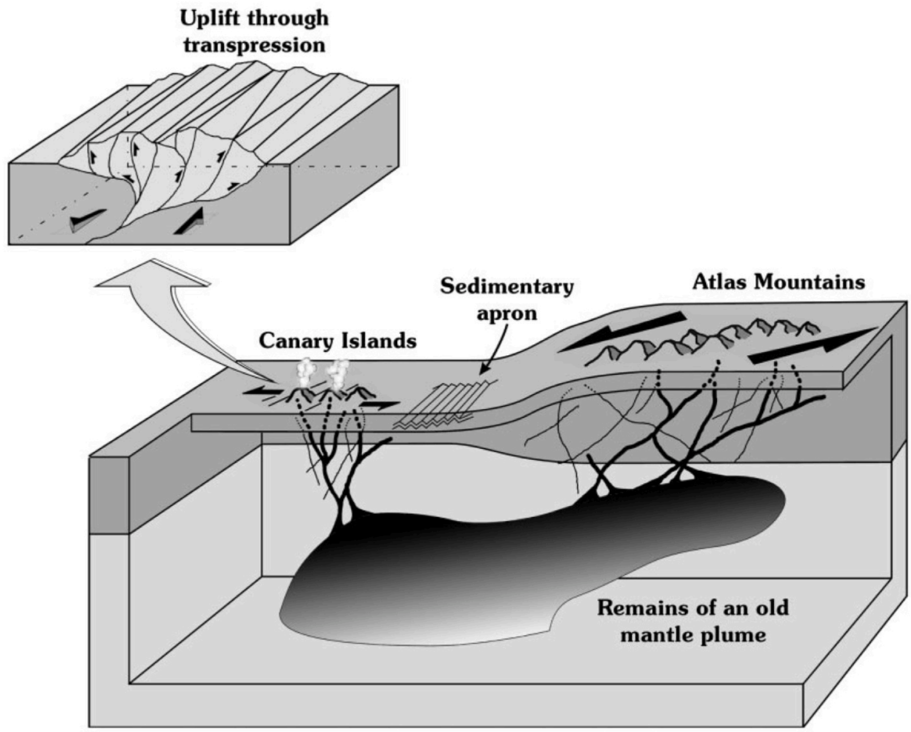

Fig. 2. Genetic model for the formation of the Canary archipelago (from Anguita and Hernán, 2000).

defined by Steiner et al. (1998) and are summarised below.

Basal unit: This is the lowermost unit and mainly crops out in the SW part of the area near the Playa de los Muertos and the Barranco del Aulagar (Fig. 3). It is subdivided into a basalt- and a sediment-dominated sub-unit. The cumulative thickness of basalt in the lower sub-unit, interbedded with siltstones and claystones, was reported to range between 63 m and 320 m.

The upper sub-unit is 130–150 m thick and composed of thinly bedded dark claystones and yellow siltstone, interpreted to represent turbidite deposition from the lower lobes of a deep-sea fan. The siliciclastic succession is punctuated by limestone beds in the lower part, which are absent in the middle and then replaced by calcareous turbidites towards the upper 30 m.

Pelagic Bivalve Limestone Unit: This unit consist of 120–150 m of limestones, claystones and marlstones. Bioclastic or nodular limestones are recorded to alternate with green marls in the lower 50–60 m. Upsection, distal turbidites, with a SE-NW paleoflow direction, become more frequent. The uppermost interval is dominated by marlstones and claystones. This unit is interpreted to have been deposited between the lower slope and abyssal plain above the CCD (calcite compensation depth). This unit has been dated as Toarcian to Oxfordian based on the presence of Bositra buchi (Roemer, 1836).

Mixed Clastic Unit: This unit is exposed along the coast and it is reported by Steiner et al. (1998) to be 470 m thick. Sedimentation is dominated again by clastic sandy turbidites and claystones with occasional green marlstones and black shales. Two calciturbidites are intercalated in this unit. The overall deposional environment was interpreted to exhibit a progradation from a lower fan at the base to upper fan and slope at the top. Steiner et al. (1998) suggests a Tithonian to early Valanginian age based on the age of the base of the overlying unit, fauna and flora assemblages and facies correlation with the DSDP Site 370/416.

Main Clastic Unit: This unit is mainly exposed along the Barranco de la Peña and Barranco de los Sojames. The unit is made of 600 m of sandy turbidites subdivided into two sub-units.

The lower sub-unit is made of poorly developed fining- and thinning-upward cycles, approx. 10 m thick, of facies C, D and E (sensu Howell and Normark, 1982) interpreted as middle fan fringe to outer fan. Upsection, both beds and cycles get thicker and coarser. The trend changes to coarsening- and thickening-upward cycles around 30 m thick representing progradation of sand lobes. A 40 m thick cycle of amalgamated sandstones showing a fining- and thinning-upward trend represents the filling of a middle fan channel. The unit is capped by 100 m of thinly bedded claystones, siltstones and sandtones of interchannel or outer fan fringe setting. The overall evolution of the subunit shows progradation from lower fan into middle fan and return to quiet sedimentation of outer fan or interchannel.

The upper sub-unit represents more proximal upper and middle fan facies. One meter thick amalgamated turbidites are interpreted as an upper fan feeder channel. Intercalated thin-bedded turbidites and slumps with small cm-scale channel are characteristic of levee deposits. This interval is capped by sandy debris-flow or shale-clast conglomerates. The last 100 m is made of claystone and siltstone with occasional thin sandy turbidites.

The age of the base of the unit is constrained by the presence of a Neocomites Uhlig, 1906, Valanginian to Hauterivian in age (Renz et al., 1992). The top of this unit is constrained by the next unit (Pelagic Limestone Unit) which is Albian to Cenomanian.

Pelagic Limestone Unit: This unit is made of 150 m of Albian to Cenomanian slope chalk deposits.

3. Methodology and results

The Mesozoic turbidites of Fuerteventura have been studied along two easily accessible transects along the Barranco de la Peña and Barranco de los Sojames (Fig. 3). Data collection involved detailed sedimentary logging of the upper part of the Mixed Clastic Unit, the Main Clastic Unit and the base of the Pelagic Limestone Unit. The thickness of the main dykes and the ratio of small-scale intrusions in the sedimentary sections was recorded. Biostratigraphic samples were collected at key stratigraphic levels.

A 1182 m thick stratigraphic log has been produced. This includes

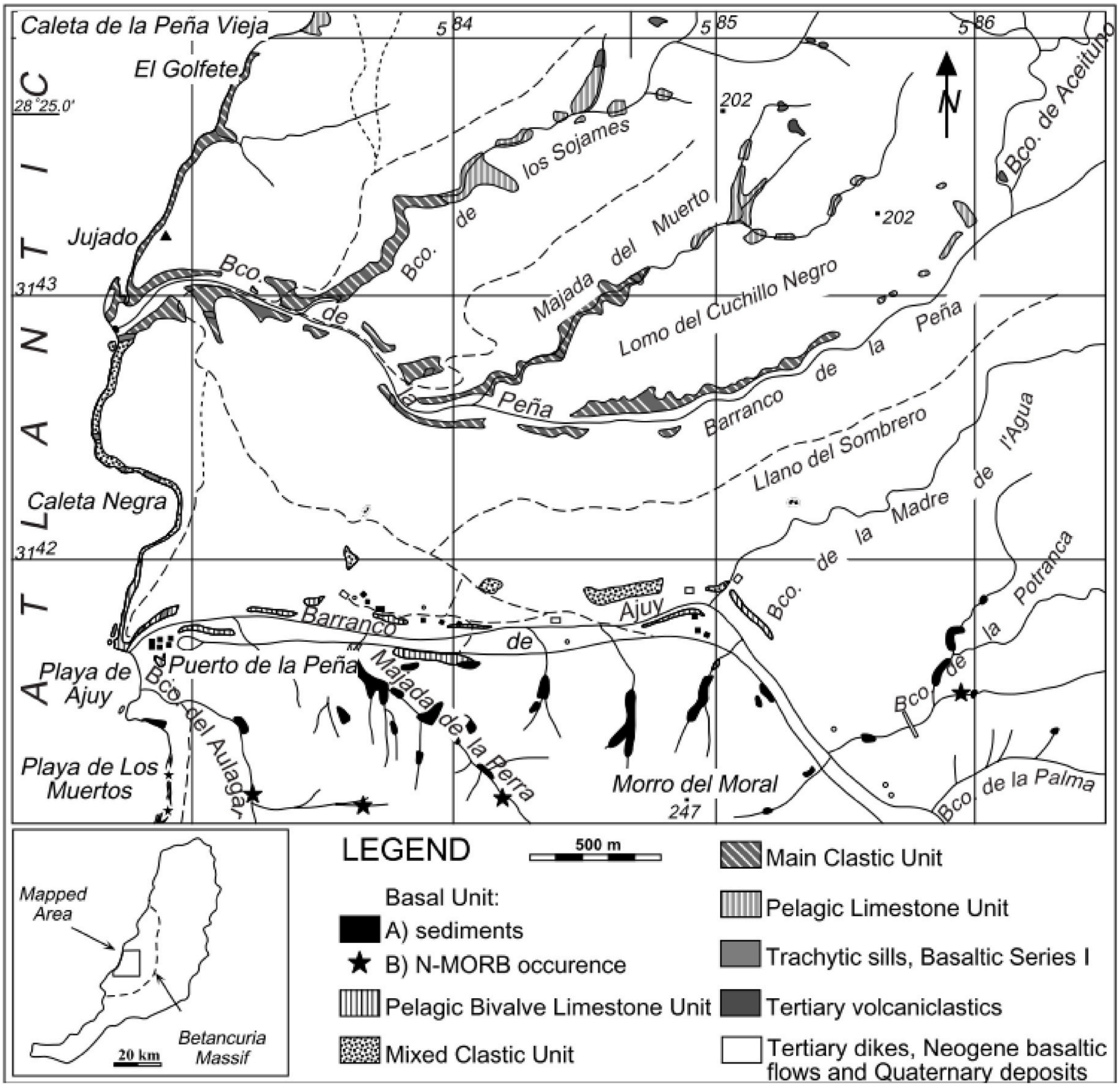

Fig. 3. Main depositional and igneous units in the Betancuria Massif (from Steiner et al., 1998).

high density of igneous intrusions that have increased the true thickness of the sedimentary succession considerably. The record of the main igneous units along with an estimation of the density of smaller sills has been considered in order to calculate the true thickness of the section of 708 m (see details below).

Our observations confirm the previous overall interpretation of the stratigraphy and main depositional environments. The Main Clastic Unit has been subdivided into smaller "Divisions" based on the number of igneous intrusions and sand/mud ratio along the succession. The density of intrusions is uneven along the succession, ranging from negligible to up to 100 %. Several generations of dykes, with different orientations, intrude the sediments, ranging from parallel to perpendicular to the bedding, generating different rates of expansion in the sedimentary host. Swarms of smaller cm-scale dykes may also have a significant effect on the total thickness, but these are difficult to measure accurately in the field.

The estimated thickness of each "Division" has been calculated by subtracting the thickness of dykes from the total thickness measured in the field. A structural map with the main outcrops mapped is presented in Fig. 5. The stratigraphic log presented in Fig. 6 represents the total thickness measured in the field, including the igneous intrusions.

3.1. Mixed Clastic Unit

Only the uppermost 5 m of this unit was logged. It is composed of cm thick rippled-laminated and occasionally parallel-laminated fine-grained calcareous sandstones, siltstone and claystone, displaying T_{bcde} turbidite divisions (Bouma, 1962), interpreted to be deposited by low density turbidity currents (sensu Lowe, 1982). Flute marks and small channels (Fig. 7A) are relatively common. Interbedded debris-flows are scarce.

The calciturbidites are interpreted as redeposited material derived from a carbonate platform and deposited in an upper fan to slope setting. Fossil assemblages yield an age ranging from Tithonian to early Valanginian for the top of this Unit, and suggest a Berriasian age (Steiner et al., 1998).

3.2. Main Clastic Unit

This new study suggests the Main Clastic Unit, including igneous intrusions, is about 950 m thick. Estimation of the igneous intrusions present in the section (as % of total thickness) yields an estimated total depositional thickness for this unit of 708 m (see details for each division below). The total thickness of this unit is about 15 % higher than

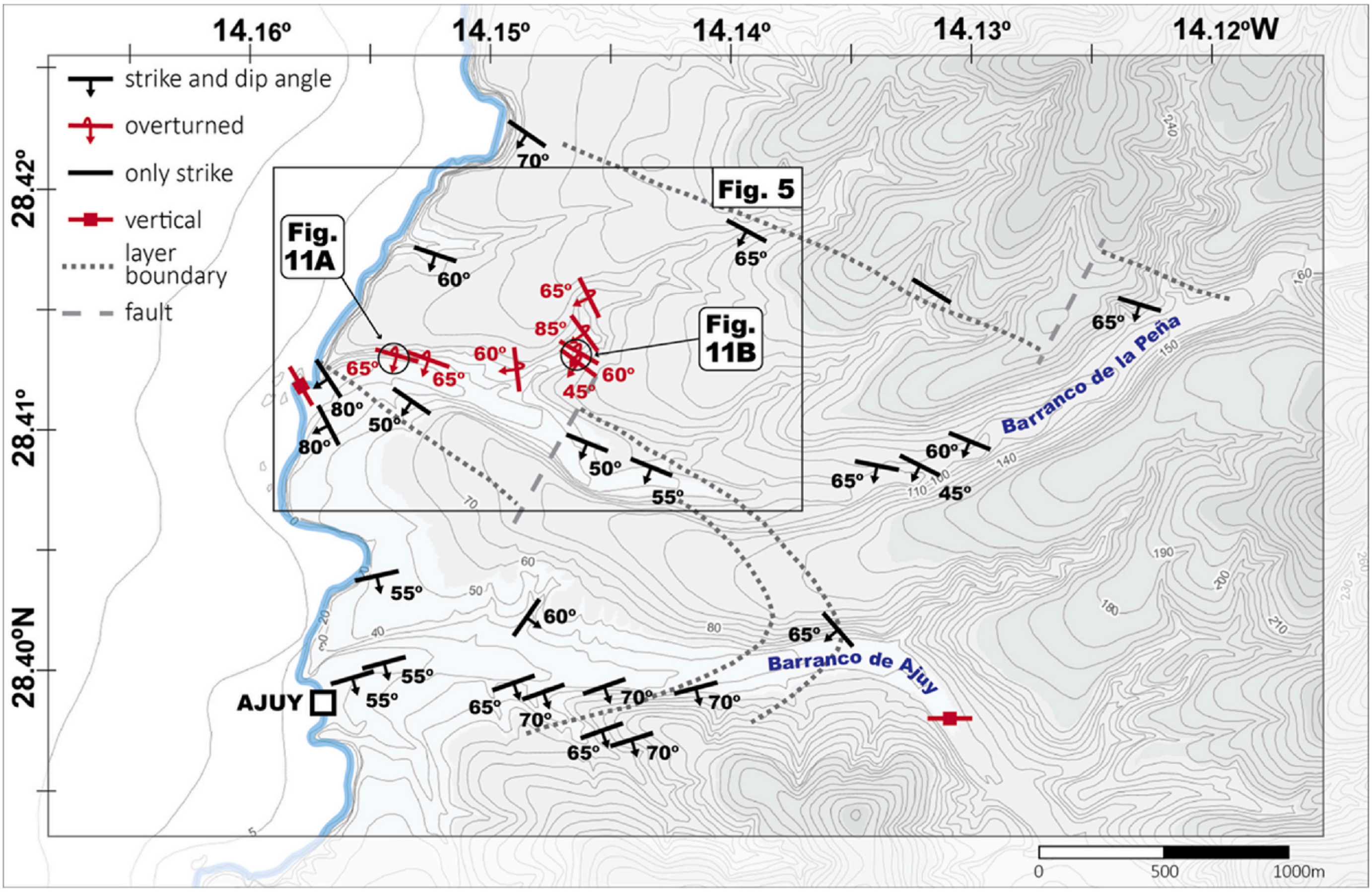

Fig. 4. Map of the study area showing previous interpretation of repeated succession by overturned syncline (modified from Rothe, 1968). Black circles indicate the approximate locations where folds have been found in the present study.

previously reported, which, due to the complexity induced by the level of intrusions, we consider within the error margin. It has been subdivided into 12 subdivisions, annotated in the stratigraphic log with a colour code (Fig. 6).

3.2.1. *Subunit 1*

A 60 m thick igneous intrusion marks the base of this subunit from the underlying Mixed Clastic Unit. The gross measured thickness is 25 m, with a calculated true thickness of 22 m. It is highly affected locally by dyke swarms, but only about 10 % of them have an influence on the thickness of the sedimentary deposits. Net sand content is 25 %.

It is mainly made of cm-thick light to dark mudstones interbedded with very fine-to fine-grained sandstones, occasionally up to 15 cm thick. Bouma units T_{cd}, occasional T_b and rare T_a can be identified, suggesting deposition by low density turbidity currents. Sedimentary structures include mud rip-up clasts, slumps, parallel-, wavy- and ripple-laminations. It is organized in two m-scale coarsening-upwards cycles with T_{cd} more common at the base and T_{abc} more common towards the top, suggesting progradation of lobes (sensu Prelat et al., 2009). Sedimentation is interpreted to have taken place as overbank or levee deposits on a deep-water lobe fringe.

3.2.2. *Subunit 2*

The base of this subunit is a 3.7 m-thick sill. About 35 % is made of igneous rocks, that increases the true thickness of 125m up to a measured thickness of 193 m. Occurrence of thick dykes between 2.5 and 20 m-thick becomes more frequent toward the top of the division. The average sand content in the whole unit is about 50 %.

The unit is composed mainly of dm-to m-scale thinning- and fining-upward packages in the lower part and thickening- and coarsening-upward packages towards the top. These can be grouped in coarsening- and frequently thickening-upwards m-scale packages up to 23 m thick.

The lower half is mainly made of thin turbidites, displaying T_{cde} units, comprising intervals of very fine-grained yellow sandstone interbedded with 1–6 cm-thick grey to black (occasionally greenish) mudstones. Minor slumps, flaser, lenticular and ripple lamination (Fig. 7B) and erosion surfaces resembling small-scale channelized flow structures can be observed. It is interpreted to represent deposition in a lower to middle fan setting of unconfined to poorly confined flows.

The upper half becomes slightly more calcareous and displays a coarser grain size. Sedimentary structures present include flute marks and load casts, ripple lamination, soft sedimentary deformation, channels, and fossil traces. The thickness of intermittent sandy pulses increases towards the top from 20 to 30 cm thick beds in the lower and middle part of the division to metre scale beds in the upper part. Paleocurrents in this interval show a flow direction towards the NW (Fig. 6). The coarsening-upward trend is interpreted to record progradation of a middle fan over the lower fan and small-scale channel sedimentation.

3.2.3. *Subunit 3*

This subunit (Fig. 7C) has a gross thickness of 75 m. It is intensely intruded by igneous dykes. Intrusions sub-parallel to the bedding reach 70 % of the total outcrop reducing the gross thickness of the interval to a true sedimentary thickness of 23 m. The net sand content is 95 %.

The subdivision comprises several m-scale fining- and thinning-upward cycles of thick bedded to massive fine-to medium-grained calcareous sandstones. Bouma cycles observed are restricted to T_a. Bed thickness can reach m-scale.

The sedimentary features observed are interpreted to record

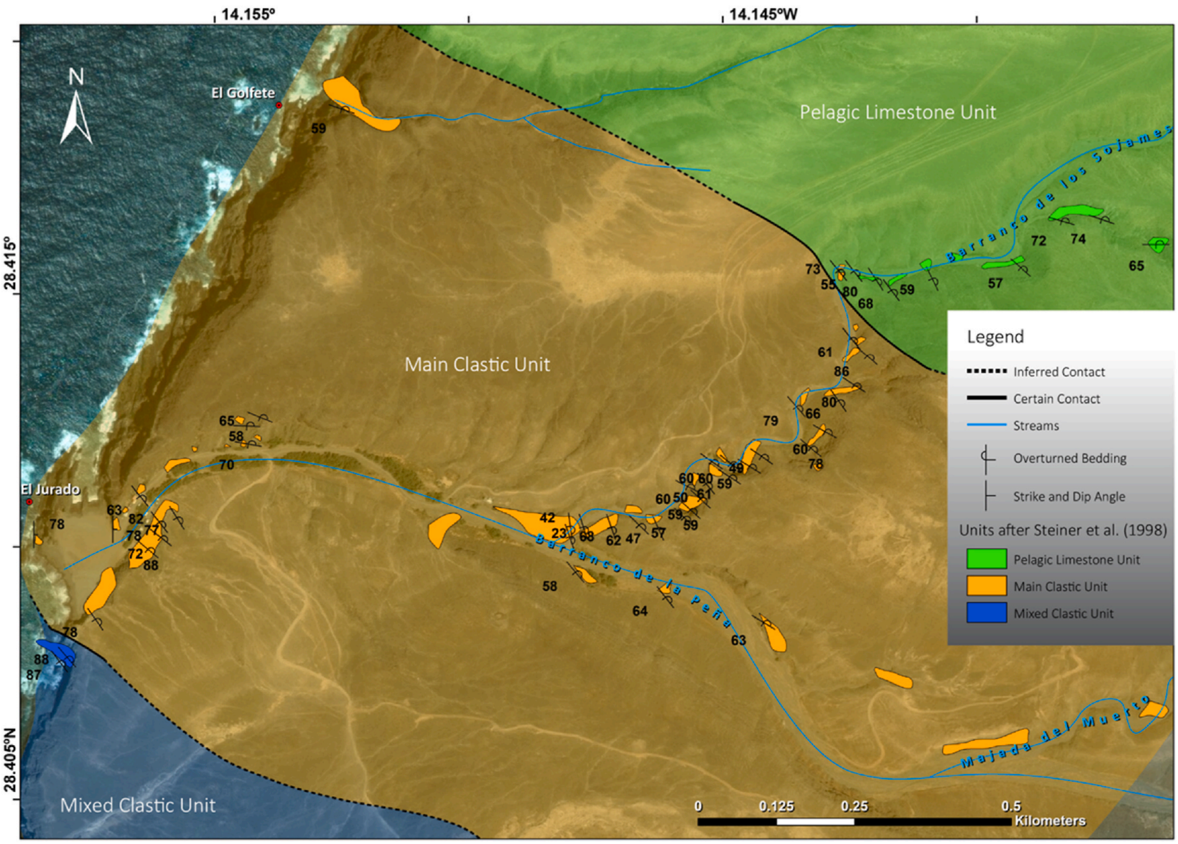

Fig. 5. Sedimentary units mapped, and structural information collected during fieldwork for the present study.

deposition from high density turbidity currents (sensu Lowe, 1982). The high density of igneous intrusions does not allow confident identification of larger-scale trends, however individual fining- and thinning-upward trends probably record the fill of small channels that amalgamate to form a leveed-channel (Arnott, 2010) although the expected fining- and thinning-upward overall trend is not clear. The channel could have been a feeder of an active lobe in a middle fan position.

3.2.4. *Subunit 4*

This subdivision has a gross thickness of 35 m, with a density of igneous dykes of 50 %. The true thickness is estimated at 18 m, with a net sand content of 75–80 %.

The subunit contains two smaller sub-cycles. The lower one is a thinning- and fining-upward alternation of siltstones and very fine-to fine-grained sandstones, each up to 20 cm-thick. The upper cycle consists of thickening- and fining-upward medium-to fine-grained sandstones, with thicker individual beds than the underlying sub-cycle.

The fining-upward trend is interpreted as small channel fills that form part of a leveed-channel unit. The presence of thinner beds, intervening silts and a higher position in the leveed-channel fill than that interpreted in subunit 3, suggest a more marginal position within the channel unit (Arnott, 2010). Due to the limited extent of the outcrop the base of the channel or channel fill/levee contact is not exposed.

3.2.5. *Subunit 5*

The subdivision has a gross thickness of 33 m and comprises an overall thickening- and coarsening-upward trend. It is not heavily affected by igneous intrusions (estimated 15 %) and the estimated true thickness of this interval is 28 m, with a relatively low 15 % net sand content.

It is mostly made of thinly bedded dark silts and clays with minor sandstones laminae, exhibiting mainly T_{de} units (Bouma, 1962). These are interpreted to be deposited by low density turbidity currents and suspension fallout. The upper 3m are made of alternating medium-to coarse-grained sandstones and dark siltstones/mudstones, interpreted as T_{cde} and occasional T_{bcd} Bouma units. Bioturbation is common and flute casts are also observed, mainly in the finer sub-units.

The change to a coarsening-upward trend, together with the predominance of T_{de} turbidites suggest overbank deposition in a middle fan position or deposition of unconfined low density turbiditic flows in a lower fan.

An ammonite (Neocomites sp.) was reported by Renz et al. (1992) the Main Clastic Unit (Unit D of Robertson and Stillman, 1979), which, together with lithological correlation to the DSDP Site 370/416 (Renz et al., 1992; Steiner et al., 1998) suggested a Valanginian age to be assigned to the base of the Main Clastic Unit. In this current study an ammoniate was found close to the base of this subunit 5, which has been identified as Tirnovella sp., (Fig. 8). The shorter stratigraphic range of this new ammonite, restricted to Late Berriasian, allows us to refine the age of the top of Subdivision 4 to late Berriasian and therefore we suggest a maximum early Berriasian age for the base of the Main Clastic Unit.

3.2.6. *Subunit 6*

The contact with the underlying subunit is a 10 m thick igneous intrusion. Gross measured thickness is 108 m, consisting of mainly grey to greenish clays and silts with subordinate thinly bedded very fine-to fine-grained cm-thick sandstones. The division is moderately affected by dykes (making up 30 % of the section) yielding an estimation of the real thickness of 76 m, with overall net sand content of 30 %.

Four coarsening- and thickening-upward cycles up to 37 m thick can be identified. Occasional individual heterolithic very fine-to fine-grained sandstone beds can be up to 15 cm-thick. T_{cde} Bouma divisions dominate this interval, exhibiting ripples, flaser bedding, with erosional contacts and soft sedimentary deformation, abundant sole casts

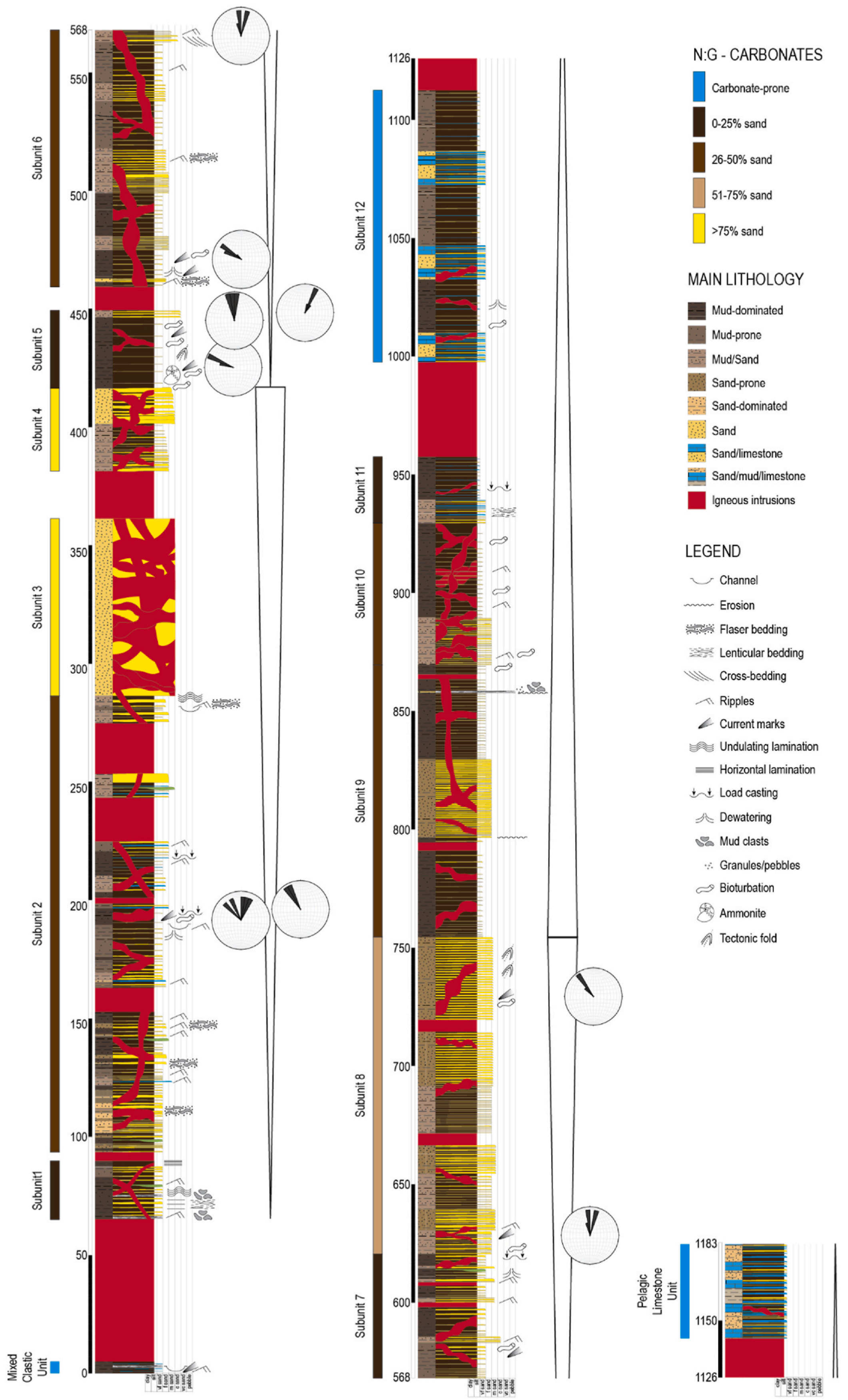

Fig. 6. (next page) | Stratigraphic log along Barranco de la Peña and Barranco de los Sojames. Divisions are explained in the text. Palaeoflow directions based mainly on current marks and minor crossbedding. Thicknesses shown corresponds to the total thicknesses measured in the field including the igneous intrusions.

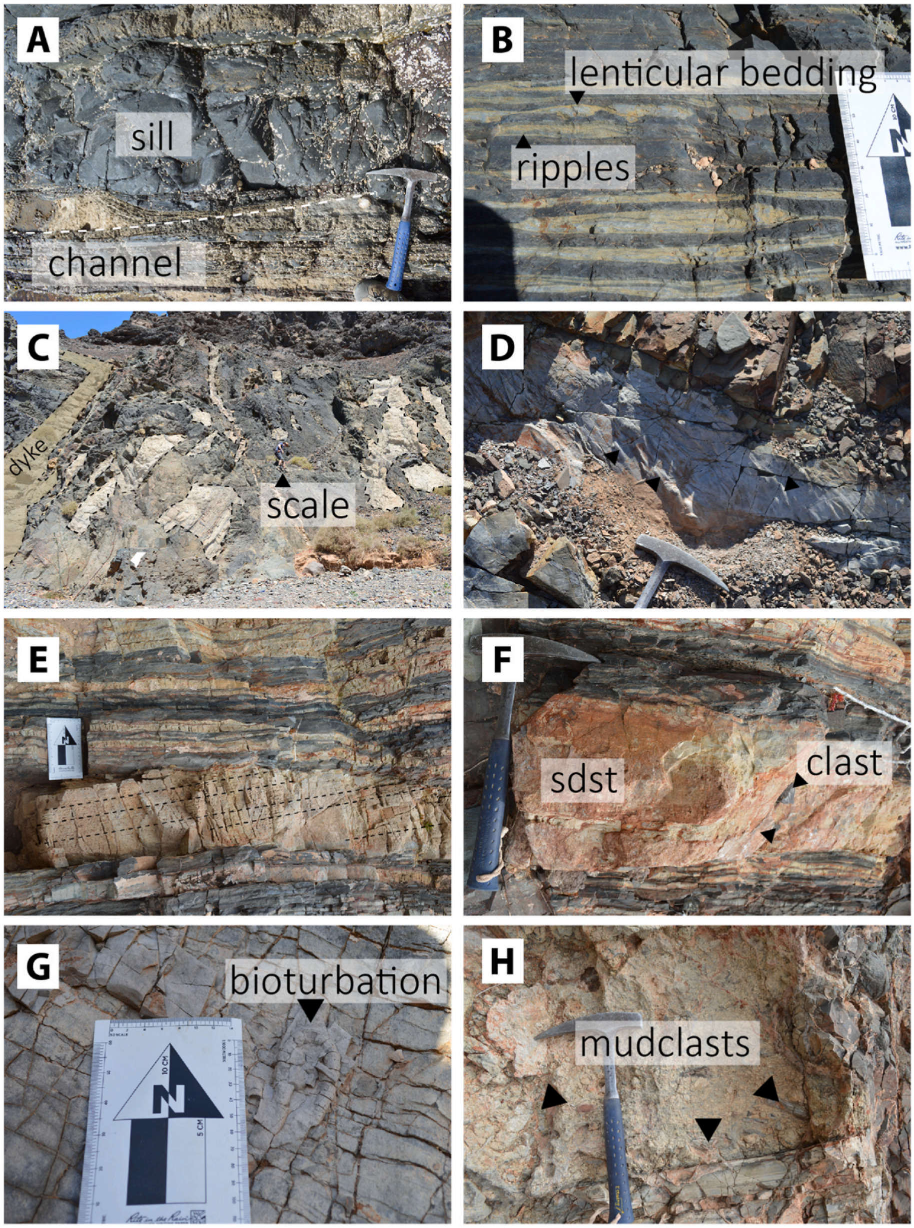

Fig. 7. Field photographs of several details throughout the succession. A) Small-scale channel from the uppermost Mixed Clastic Unit. B) Mud-dominated interval of thinly bedded turbidites of subunit 2 with ripples and lenticular bedding. C) Outcrop photograph of subunit 3 with turbidites highlighted. Note the high degree of igneous intrusions and discontinuity of outcrops. Mean stratigraphy-up is towards the bottom right corner of the image. D) Detail of paleocurrent indicators preserved as a positive relief on the base of an overturned bed. E) Planar cross-bedded medium-to coarse-grained sandstones in Subunit 6. F) Massive medium-to coarse-grained sandstones with granules and pebbles. G) Bioturbation in Subunit 8. H) Breccia with cm-scale mud rip-up clasts and pebbles intercalated within a mud-dominated interval in Subunit 9.

(Fig. 7D). Bioturbation is more frequent in the lower few metres of the unit.

One thickly-bedded fine-grained sandstone in the lower part of this unit has a variable thickness between 50 and 70 cm, and cuts into the underlying heterolithic bedding. This is interpreted as a small channel cutting into overbank/levee deposits. Another massive to thickly-bedded sandstone, 1.5 m thick, in the middle part of the division is also interpreted as a small channel fill but exposure did not allow observations of cross-cut relationships with the host sediments. The top of this unit includes occasional medium-to coarse-grained sandstones beds up to 20 cm thick with granules and well-developed low angle planar cross-bedding (Fig. 7E).

Each one of the four cycles is interpreted to represents overbank progradational episodes in the middle fan, occasionally interrupted by small-scale distributive channels feeding more distal lobes.

According to the position of the Neocomites sp. Described by Renz et al. (1992) we assign a probable Valanginian to Hauterivian age to Subunit 6.

3.2.7. Subunit 7

The Subunit has a gross thickness of 53 m thick and is composed of four thickening- and coarsening-upward packages. The overall trend of the subdivision is fining-upwards and individual cycles thin-upwards. The subdivision is intruded by two thick dykes (in total 3.5 m thick) and a number of smaller dykes, making up an estimated 15 % of the interval. The true thickness of sedimentary thickness is 45 m, and it has a net sand content of 25 %.

The four individual thinning-upward cycles range from 17.5 to 5.5 m

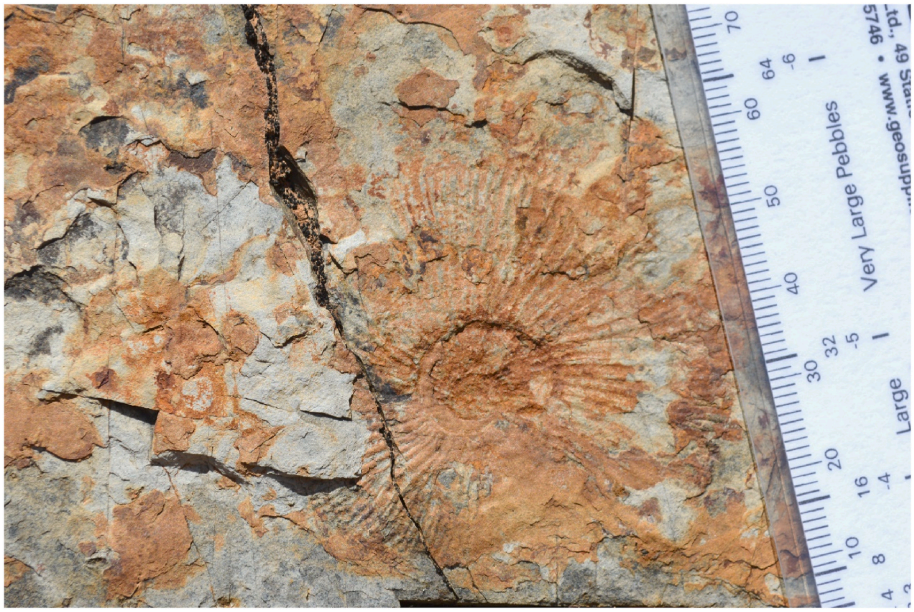

Fig. 8. Field photograph of the Tirnovella sp. (late Berriasian) from the lower Main Clastic Unit.

thick. Individually they are interpreted to represent discrete episodes of progradation, of an overall retrograding fan. They are composed of a thicker lower interval, dominated by dark grey cm-thick T_{de} Bouma divisions, and minor thinly bedded fine-grained sandstones. The upper part is made of slightly thicker turbidites incorporating thicker and more frequent sandy layers exhibiting Bouma T_{cde} divisions. Occasional medium-to coarse-grained sandstones with granules and pebbles up to 35 cm thick may exhibit the lower elements of the Bouma sequence (Fig. 7F). Occasional flute casts, bioturbation, slumps and loading surfaces are observed throughout the Subunit. The uppermost 5 m of the Subunit are made of turbidites exhibiting T_{de} units.

The reduction of thickness of the cycles, together with homogeneous thin bedding of silts and muds, suggest a progressive reduction of sedimentation rate. This could be due to a decrease in sediment input associated with a rise in relative sea-level or to autocyclic migration of the active lobe. Sand-rich intervals, including coarse-grained beds, indicate overspill from the active channel into the overbank/levee. Overall sedimentation is interpreted to have occurred in a middle fan location, but perhaps in a more distal position than previous Subunits.

3.2.8. Subunit 8

This Subunit comprises 136 m of sand-prone sediments forming three thickening- and coarsening-upward cycles. The subunit is not highly intruded by igneous rocks. The density of intrusions affecting the thickness of the sedimentary sequence is about 15 %, including two 5 m thick dykes. The real thickness of sediments is 116 m, with a net sand content of 65 %.

Sandstones are fine-to medium-grained, dm-thick and yellow to reddish in colour, with interbedded grey muds. Well-developed bioturbation (Fig. 7G) and current marks can be found, especially in the lower cycle. The higher proportion of coarser sand content of this Subunit indicates a more proximal setting compared to the underlying subdivision. The entire Subunit is interpreted to be part of a lobe complex (Prelat et al., 2009) and the overall sand-prone facies could indicate deposition in a lobe axis position.

3.2.9. Subunit 9

This Subunit has a gross measured thickness of 125 m and comprises three alternating decametric-scale mud-dominated and sand-dominated intervals. Each interval is quite homogeneous and no cyclicity is evident. Two thick dykes, 2 m and 3.5 m-thick, along with several small dykes result in a thickness increase of 20 %, yielding a true stratigraphic thickness of 100 m. The net sand content in the unit is 40 %. One structureless breccia (Figs. 7H), 0.5 m thick, with mud rip-up clasts up to 7 cm in size, scattered pebbles and very sharp base is intercalated within the upper mud-dominated interval. Occasional bioturbation and flute casts can be found through the whole unit.

The base of the middle sand-prone interval within this subdivision exhibits an erosive contact onto the lower mud-dominated interval (Fig. 6), interpreted to represent the migration of a lobe complex, sandwiched between two mud-dominated interlobe complexes (Prelat et al., 2009). The absence of a clear trend suggests an aggradational lobe complex.

3.2.10. Subunit 10

This subdivision has a gross thickness of 60 m and composed of two thick sandstone- and mud-dominated packages. It has a dyke density of 50 %, giving a true thickness of about 30 m and net sand content is 30 %.

Rippled- and small-scale trough cross-bedded, fine-grained sandstone beds dominate the lower package of the unit and can individually be up to 8 cm thick. Mud drapes on the cross-lamination may be present (Fig. 9A). These are interpreted as turbidites, usually exhibiting T_{cd} Bouma divisions. The hemipelagic mud is sometimes not preserved and occasionally the parallel-laminated sandstone division is deposited at the base of some of the turbidites (Fig. 9B). The Subunit exhibits bioturbation in the finer layers at the base of the package. Mudstones in the upper half of the Subunit are dark and massive towards the top and sandstone layers are rarely deposited.

The larger-scale trend is very similar to the underlying division, showing a dominantly aggradational pattern. This is also interpreted as a migrating lobe complex. In this case, the clear erosive base of the sand-prone cycle is missing.

3.2.11. Subunit 11

This gross 28 m thick unit comprises a thinning- and fining-upward mud-dominated subdivision. Most of the dykes strike north, so the density of intrusions affecting the thickness of the sedimentary sequence is very low and the true thickness is ~25 m. Net sand content is about 20 %.

This interval is dominated by thinly (mm-to cm-scale) bedded silts and muds with minor interbeds of very fine-grained, calcareous sandstones. Frequent lenticular bedding and sandstone lenses are affected by

Fig. 9. Field photographs from subunit 10. A) Mud drapes on cross-lamina. B) Thin-bedded turbidites with lenticular bedding and soft sediment deformation.

soft-sediment deformation.

Fine-grained sedimentation and thin bedding suggest quiet overbank deposition in the lower fan.

3.2.12. *Subunit 12*

With a gross thickness of 115 m, this unit comprises m-scale cycles composed of alternating limestones and very fine-grained calcareous sandstones and cycles of alternating mudstone and calcareous sandstones. The base of this subdivision is in contact with a 40 m-thick igneous intrusion. The density of the dykes is not very high, but some of them run parallel to the bedding, mainly in the lower part of the cycle, so the true thickness is estimated to be reduced to 100 m. Net sand content is 40 %.

The finer material in the lower cycle shows rare bioturbation and soft sedimentary deformation. Calcareous sandstone beds can be up to 2 m thick. The cycles become more calcareous towards the top.

According to the figures provided in previous work of Steiner et al. (1998), this Subunit corresponds to the upper part of the Main Clastic Unit; the Sandstone-Siltstone-Shale Unit of Robertson and Bernoulli (1982) and Robertson and Stillman (1979) or the Siltstones and Sandstones with clayey partings of Rothe (1968). These units are described entirely as clastic in the previous work, with no mention of carbonate components made. We identify an increasing carbonate content, which started in the previous subunit and suggests a gradational evolution into the overlying Pelagic Limestone Unit.

The presence of calciturbidites in this division is interpreted to be due to redeposition of carbonates developed on the shelf, suggesting clastic sediment input from the continent has lowered. Rothe (1968); Steiner et al. (1998) suggested an age for this part of the Mixed Unit of Albian, linked with a rising sea-level at this time that may have reduced the delivery of clastics to the deep basin and favoured carbonate production on the shelf.

3.2.13. *Sedimentary cycles*

Three large-scale sedimentary cycles are interpreted in this study (Fig. 6) that we interpret as tectonostratigraphic units resulting from the

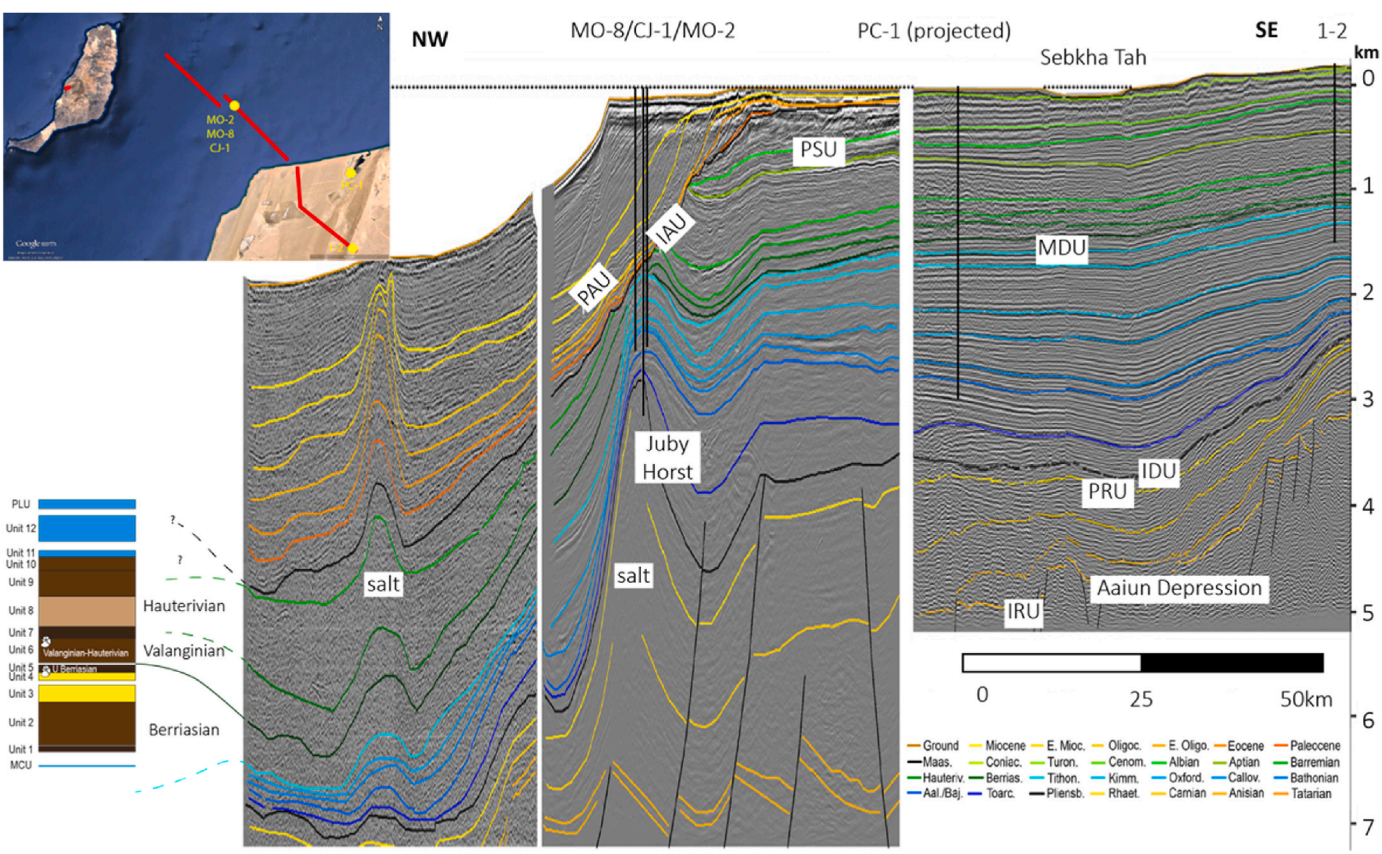

Fig. 10. Correlation of lower Cretaceous turbidites of Fuerteventura with seismic interpreted on the shelf and onshore Morocco. Seismic interpretation modified after (Wenke, 2015). Same horizontal and vertical scale for seismic and schematic succession.

interplay between eustacy and the complex post-rift tectonics in the Aaiun-Tarfaya Basin. These cycles can be correlated with the sedimentary sequences interpreted onshore Morocco (see Araña and Ortiz, 1986; Arantegui et al., this volume; Fig. 10). We interpret the last cycle, fining-upward and increasing carbonate components, can be correlated with the transgressive event registered onshore above SB2 + TS2. The increase in accommodation space in the proximal basin trapped large volumes of sediment and allowed carbonates to develop on the distal shelf.

3.3. Pelagic Limestone Unit

The base of this Unit is defined by a 30 m-thick igneous intrusion, after which there is notable facies changes to limestone dominated sediments. Scarce dykes running parallel to the bedding within the unit reduce the true sedimentary estimated thickness down to 36 m, and net sand content (mostly calcareous) is about 50 %.

This study has logged the lower 40 m of this unit, exhibiting stacked decimetre-scale cycles of alternating calcareous sandstones, siltstones, and limestones. Micritic limestones frequently appear nodular. The limestones are variable, sometimes replaced by very fine-grained non calcareous sandstones.

This unit is interpreted to be the lower part of the Pelagic Limestone Unit (Steiner et al., 1998). The upper part of the unit was not investigated.

3.4. Repetition of stratigraphy

Large-scale folding of the succession was first proposed by Rothe (1968) who interpreted the entire Mesozoic succession exposed in the Betancuria Massif to be part of an E-W isoclinal overturned syncline and therefore partially repeated (Fig. 4). Later work by Robertson and Stillman (1979) suggested the succession uniformly becomes younger towards the north. This study supports an overall complete succession, with the presence of only small-scale folding (Fig. 11). The folding could be later tectonics or related to syn- or early post-depositional sliding.

At Barranco de la Peña, within Subunit 5, a small tight isoclinal fold was observed (Fig. 11A) with a subvertical axial plane. The geometry of the fold, class 2 or 3 of Ramsay (1967), suggests a tectonic origin, produced during uplift of the sediments to the present location. At Barranco de los Sojames, a small outcrop exhibits several small-scale folds and associated thrusts (Fig. 11B). The fractures indicate a post-depositional event when the sediment was already lithified. Furthermore, restoration to horizontal of the hinge lines of these features, using the average bedding of their surroundings, yields an azimuth of 350N and 040N. These directions would correspond with the line of smallest σ3 stress. A hypothetical syn-sedimentary displacement of sediments would be expected at about 90° to these directions, which seems unlikely in a fan system being fed from the SE. In the absence of larger exposures that allow a better assessment of these structures we interpret these folds as tectonic generated during the construction of the island.

This implies that, although repetition of large parts of the stratigraphy has been ruled out, repetitions at a smaller scale are likely. This fact requires further study and should be considered when estimating the total thickness of the succession.

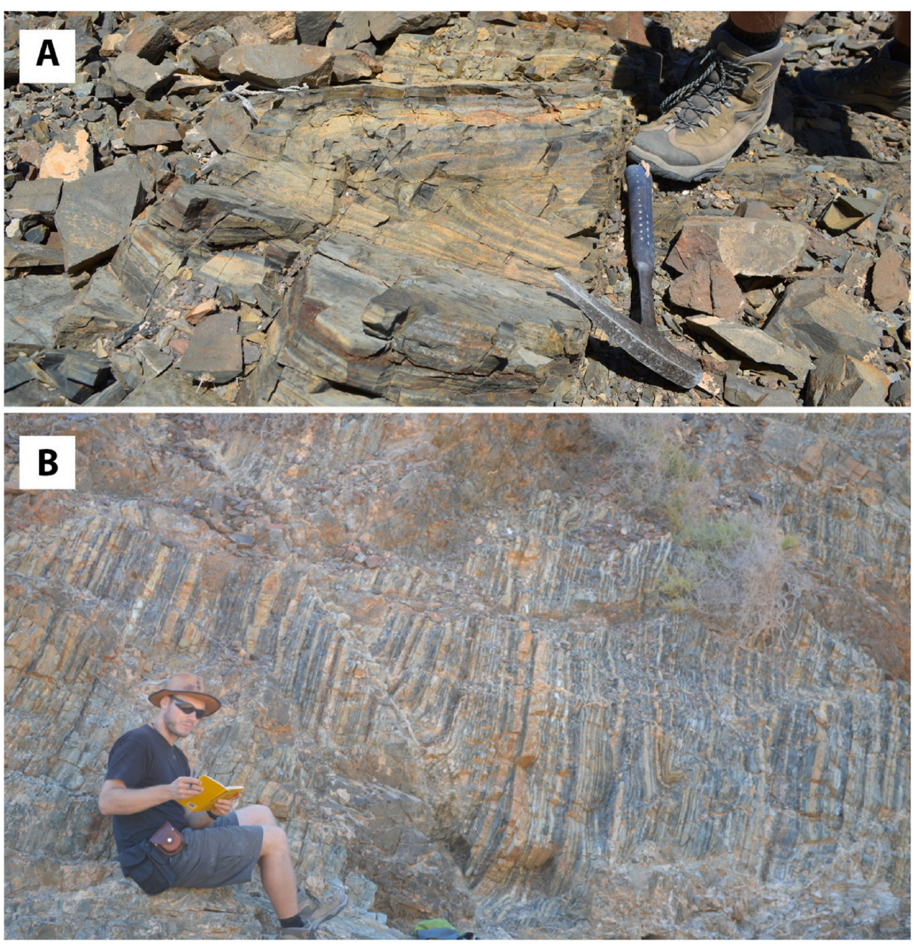

Fig. 11. Field examples of isoclinal fold at Barranco de la Peña (A) and folds and associated fault at Barranco de los Sojames (B). See location on Fig. 4.

4. Discussion

4.1. New stratigraphic subdivision and interpretation of the Main Clastic Unit

The high-resolution logging presented in this study allows for a new stratigraphic subdivision and interpretation of the Main Clastic Unit (Fig. 6). We identify 12 subunits, which form 3 sequences. Sequence A consists of subunits 1–4 and represents a coarsening-up sequence. The total thickness is 183m with a net sand content increasing from 25 % in subunit 1–90 % in subunit 3 and 80 % in subunit 4. Sequence 1 records the progradation of a turbidite fan, with the distal lower fan deposits of subunit 1 progressively overlain by middle fan deposits formed in channel-levee complexes. The discovery of the ammonite Tirnovella sp. at the base of Sequence 2 constrains the age of Sequence 1 to the Berriasian.

Sequence 2 consists of units 5–8 and represents a second coarsening-up sequence. The total thickness is 265m and shows increasing sand content from 30 % in subunit 5–65 % in subunit 8. At the base of Sequence 2, subunit 5 consists of thinly bedded dark silts coarsening up to medium-coarse sands. The sedimentary facies of subunit 5 represent low-density turbidites deposited in the lower fan. The base of subunit 5 yielded the ammonite Tirnovella sp. allowing us to constrain the base of sequence 2 to the late Berriasian.

Sequence 3 consists of subunits 9–12 and represents a progressive change in sedimentation. The total thickness of Sequence 3 is estimated to be 255m, with a broadly aggradational character. Sand content ranges from 40 % at the base and decreases to 20 % in sub-unit 11. In sub-unit 12, calcareous sandstones and limestones occur, marking the onset of a transition from clastic-dominated to carbonate-dominated sedimentation. Sequence 3 represents a migrating lobe complex at the base, interspersing sand-rich lobes with mud-rich inter-lobe complexes overlain by lower fan deposits in subunit 11 before the calcareous subunit 12 deposition. Our results record the first observations of increased carbonate content at the top of the Main Clastic Units. These calcareous deposits in subunit 12 suggest a gradual evolution from the Main Clastic Unit to the overlying Pelagic Limestone Unit.

We propose a new evolution of the MCU based on the identification of twelve subunits and three sequences. The basal sequence of the MCU records the onset of deep-water clastic sedimentation in the offshore Tarfaya Basin, with an increase in sediment supply leading to turbidite deposition. The overlying sequence B represents a continuation of the high deep-water sediment supply following a period of reduced sedimentation – either due to lobe avulsion or a drop in sediment supply to the shelf. Sequence C records a fining-up trend and gradual transition from clastic-dominated to carbonate-dominated deep-water sequences along the Tarfaya segment of the Atlantic margin during Aptian – Albian times.

4.2. Improved biostratigraphic age and regional correlation for the Main Clastic Unit (MCD)

Previous work on the MCD reported the discovery of a long-ranging Neocomites sp. ammonite (Renz et al., 1992), which in conjunction with lithostratigraphic correlations to DSDP site 370/416, led to the assignment of the base of the MCU to the Valanginian. Our discovery of the short-ranging Tirnovella sp. ammonite at the base of unit B, subunit 5, provides a new age for the MCU. The Tirnovella sp. ammonite is constrained here to the Late Berriasian, which shifts the age of the MCU down.

Based solely on the two ammonite discoveries, we can constrain the timing of deposition of the MCU and overlying Pelagic Limestone Unit to the following:

MCU Sequence A: pre-Late Berriasian.
MCU Sequence B: Late Berriasian to Hauterivian.
MCU Sequence C: Hauterivian - Albian.
Pelagic Limestone Unit: Albian - Cenomanian.

Comparison with offshore seismic and well data and onshore sections provides further insight into the age of the MCU. The basal sequence, sequence A, can be correlated with a post-Jurassic clastic wedge which drapes the Jurassic carbonate platform to the east and the Red Conglomerates Member exposed onshore at Oued Draa (Araña and Ortiz, 1986; this issue). These correlations help constrain the age of MCU sequence A to the Berriasian.

MCU sequence B begins with subunit 5, which contains the Tirnovella sp. ammonite and can be constrained to the late Berriasian. Subunit 6 contains the Valanginian to Hauterivian aged Neocomites sp. ammonite. These results provide a late Berriasian to pre-Albian age for sequence B of the MCU.

Onshore work (Araña and Ortiz, 1986; this issue) indicates a shift from Barremian fluvial sandstones to Aptian marls. This shift in onshore sedimentation, from clastic to carbonate dominated, is recorded offshore by MCU sequence C which this correlation to the Aptian can constrain. MCU Sequence C displays a fining-up trend and marks a gradational transition into the Pelagic Limestone Unit of the Albian age.

4.3. Regional correlation to onshore sections provides insight into the evolution of SRS across the Tarfaya Atlantic margin

These new data presented here indicate that Early Cretaceous systems corresponded to deep water sedimentation along the Moroccan Atlantic margin. Onshore sections preserve outcrop fluvial sands (Araña and Ortiz, 1986; this issue), with paleoflows directed towards the Atlantic margin. Offshore datasets encounter significant deltaic sequences offshore Tan-Tan and Boujdour (the Tan-Tan and Boujdour Deltas, e.g., Charton et al., 2021, Fig. 12), with a distal deep marine sequence preserved on Fuerteventura dominated by sandy turbidites.

During the early Berriasian (~125Ma), the deposition of sandy turbidites occurred within an overall coarsening-up package. The increase in clastic deposition during this time interval could be related to sea-level fall or the observed increase in uplift recorded within the Anti-Atlas and Reguibat Shield (Charton et al., 2021). The increase in the uplift in the hinterland would increase sediment supply to the Atlantic margin, feeding the Tan-Tan and Boujdour deltas and deep-marine systems.

The long-lived nature of this event is marked by the presence of a second, significant coarsening-up sequence, beginning in the late Berriasian as marked by the ammonite Tirnovella sp., found in this study. The ammonite at the base of the sequence indicates that the onset was no later than late Berriasian. The shift from one progradational cycle to another could reflect a change in sediment supply or just avulsion and migration of the active lobe within a more significant turbidite fan. Our interpretation is that the coarsening-up sequences reflect a long-lived forced regression linked to the hinterland uplift, and the shift between sand-rich and mud-rich deep-water facies reflects autogenic processes within the deep-marine fan. The transition at the top of sequence three from clastic-dominated to carbonate-dominated sedimentation helps constrain the upper age of the sequence to Aptian-Albian times as a progressive switch to carbonate-dominated sedimentation across the margin at this time. Numerous factors could have caused this, likely a relative increase in sea level and a decrease in exhumation rates observed in the rift hinterland during the Aptian – Albian (Charton et al., 2021). The margin-wide sea-level fall and a decrease in hinterland activity reduced sediment supply and increased accommodation space on the shelf, reducing clastic delivery to deep water. These long-term trends lead to a gradual transition from the clastic-dominated lower Cretaceous sequence to a carbonate-dominated middle Cretaceous (Aptian-Albian) sequence, recorded by the field transition from the Main Clastic Unit to the Pelagic Limestone Unit.

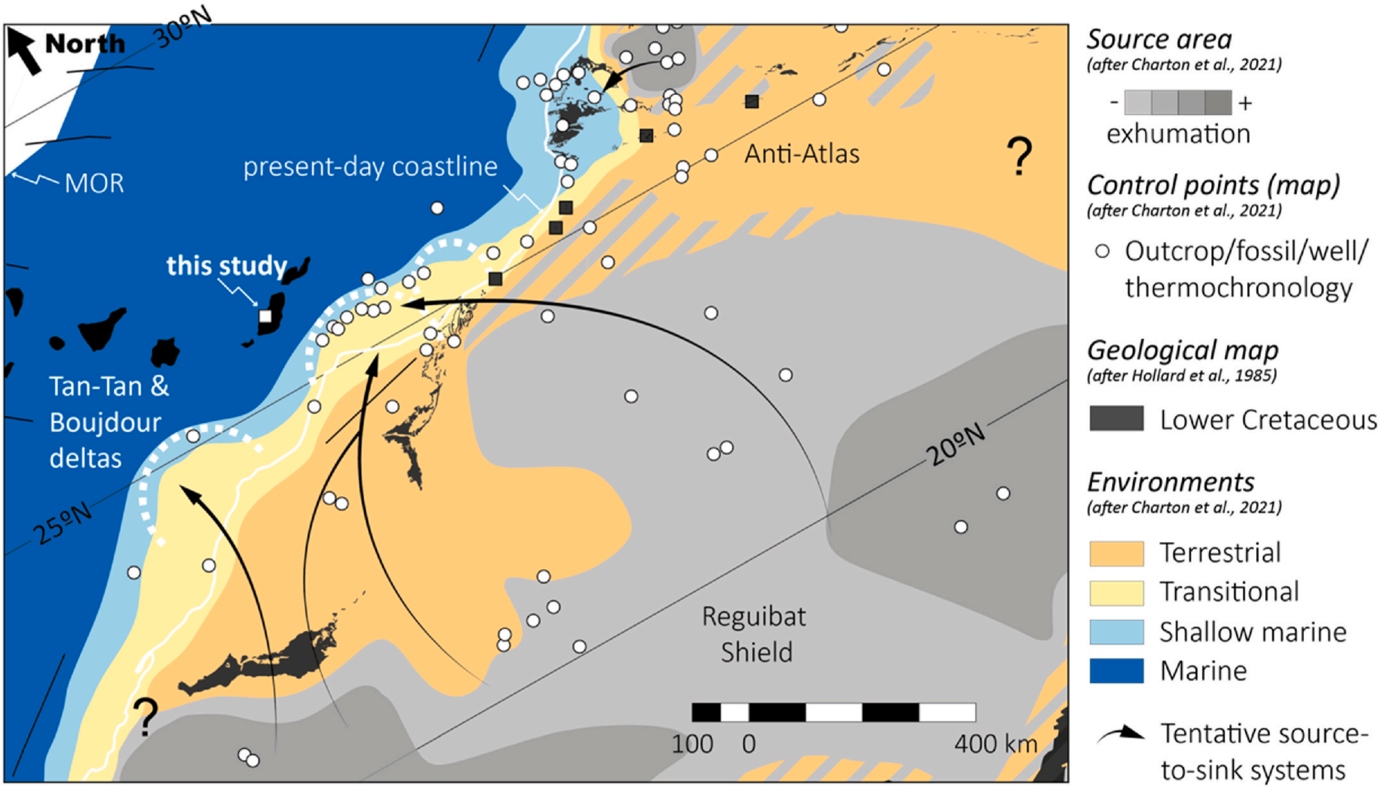

Fig. 12. Source-and-Sink map for the Early Cretaceous (145-125Ma) depicting the location of the sedimentary source areas, modified from Charton et al. (2021).

5. Conclusions

The Mesozoic turbiditic succession of Fuerteventura has been re-logged, with the main focus on the lower Cretaceous Main Clastic Unit of Steiner et al. (1998). An updated, more detailed stratigraphic log is presented. A new ammonite discovery and correlation with onshore sections allows further constraint of the age of main sedimentary cycles and transition between the Mixed Clastic Unit, Main Clastic Unit and Pelagic Limestone Unit.

The abundant evidence from the lithologies, sedimentary structures, bioturbation and stacking patterns, suggest sedimentation took place in a deep marine fan/lobe environment initially dominated by terrigenous sediment, deposited dominantly by turbidity currents.

The early Berriasian period has higher proportion of sand deposited throughout the succession. Over 200 m of turbidites were logged, that exhibit a large-scale coarsening-upward trend, culminating in a large channel fill, about 50 m thick. This is interpreted to record the progradation of a lobe complex, related to a sedimentary wedge observed on seismic and developed to the east, at the slope of the Jurassic carbonate platform and with alluvial fans recorded onshore in outcrop. An ammonite (Tirnovella sp.) of late Berriasian age occurring above the last sand-dominated interval has been used to date the termination of this pulse of terrigenous sediment.

A second big-scale progradational coarsening-upward cycle is 265 m thick and has a lower sand content. Its base is dated as late Berriasian by the ammonite found in this study. The upper age can be established as pre-Albian based on correlation of large-scale trends with onshore successions.

The upper part of the section becomes increasingly carbonate-prone, with sedimentation of calciturbidites and occasional limestone beds among the clastic turbidites. This is interpreted to be related with a relative sea-level increase in the area during Aptian that triggered carbonate production on the shelf. These carbonates were resedimented by turbiditic currents in distal lobe complexes.

Although the entire succession seems continuous, small tectonic isoclinal folds produce local duplication of parts of the succession. Further mapping is needed in other to assess the effect of these structures on the total thickness of the sequence.

CRediT authorship contribution statement

Angel Arantegui: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

Anguita, F., Hernan, F., 1975. A propagating fracture model versus a hot spot origin for the Canary Islands. Earth Planet Sci. Lett. 27, 11–19. https://doi.org/10.1016/0012-821X(75)90155-7.

Anguita, F., Hernán, F., 2000. The Canary Islands origin: a unifying model. J. Volcanol. Geoth. Res. 103, 1–26. https://doi.org/10.1016/S0377-0273(00)00195-5.

Araña, V., Ortiz, R., 1986. Marco geodinámico del volcanismo canario. An. Física (serie B) 82, 202–231.

Arantegui, A., Jerret, R., Lovell-Kennedy, J., Bulot, L., Charton, R., Redfern, J., 2024. Sedimentology and stratigraphy of lower Cretaceous fluvial to shallow marine deposits on the central Atlantic passive margin: The Aaiun-Tarfaya Basin, Morocco. J. Afri. Earth Sci. this volume.

Arnott, R.W.C., 2010. Deep marine sediments and sedimentary systems. In: James, N.P., Dalryrmple, R.W. (Eds.), Facies Models 4. Geological Association of Canada, pp. 295–322.

Bouma, A.H., 1962. Sedimentology of Some Flysch Deposits : a Graphic Approach to Facies Interpretation. Elsevier, Amsterdam.

Carracedo, J.C., Day, S., Guillou, H., Rodríguez Badiola, E., Canas, J.A., Pérez Torrado, F. J., 1998. Hotspot volcanism close to a passive Continental margin: the Canary Islands. Geol. Mag. 135, 591–604. https://doi.org/10.1017/S0016756898001447.

Charton, R., Bertotti, G., Arnould, A.D., Storms, J.E., Redfern, J., 2021. Low-temperature thermochronology as a control on vertical movements for semi-quantitative source-to-sink analysis: a case study for the Permian to Neogene of Morocco and surroundings. Basin Res. 33 (2), 1337–1383. https://doi.org/10.1111/bre.12517.

Fúster, J.M., 1975. Las Islas Canarias: un ejemplo de evolucion espacial y temporal del vulcanismo oceanico. Estud. Geol. 31, 439–463.

Hartung, G., 1857. Die geologischen Verhältnisse der Inseln Lanzarote und Fuerteventura. Neue Denkschriften der Allg. Schweizerischen Gesellschaft für die Gesammten Naturwissenschaften 15, 1–168.

Hinz, K., Dostmann, H., Fritsch, J., 1982. The Continental margin of Morocco: seismic sequences, structural elements and geological development. In: von Rad, U., Hinz, K., Sarnthein, M., Seibold, E. (Eds.), Geology of the Northwest African Continental Margin. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 34–60. https://doi.org/10.1007/978-3-642-68409-8.

Holik, J.S., Rabinowitz, P.D., Austin, J.A., 1991. Effects of canary hotspot volcanism on structure of Oceanic crust off Morocco. J. Geophys. Res. 96, 12039–12067. https://doi.org/10.1029/91JB00709.

Howell, D.G., Normark, W.R., 1982. Sedimentology of submarine fans. AAPG mem. 31 sandstone depos. Environ. Times 365–404.

Le Bas, M.J., Rex, D.C., Stillman, C.J., 1986. The early magmatic chronology of fuerteventura, Canary Islands. Geol. Mag. 123, 287–298. https://doi.org/10.1017/S0016756800034762.

Lowe, D.R., 1982. Sediment gravity flows: II. Depositional models with special reference to the deposits of high-density turbidity currents. J. Sediment. Petrol. 52, 279–297.

Martinis, B., Visintin, V., 1966. Données géologiques sur le bassin sédimentaire côtier de Tarfaya (Maroc méridional). In: Reyre, D. (Ed.), Bassin Sedimentaires Du Littoral Africain. Union Internationale des sciences géologiques, Paris, pp. 13–26.

Morgan, W.J., 1971. Convection plumes in the lower mantle. Nature 230, 42–43.

Prelat, A., Hodgson, D.M., Flint, S.S., 2009. Evolution, architecture and hierarchy of distributary deep-water deposits: a high-resolution outcrop investigation from the Permian karoo basin, South Africa. Sedimentology 56, 2132–2154. https://doi.org/10.1111/j.1365-3091.2009.01073.x.

Ramsay, J.G., 1967. Folding and fracturing of rocks. Folding and Fracturing of Rocks. McGraw-Hill, New York. https://doi.org/10.1126/science.160.3826.410.

Ranke, U., von Rad, U., Wissmann, G., 1982. Stratigraphy, facies and tectonic development of the on and offshore aaiun-tarfaya basin - a review. In: von Rad, U., Hinz, K., Sarnthein, M., Seibold, E. (Eds.), Geology of the Northwest African Continental Margin. Springer-Verlag, pp. 86–105.

Renz, O., Bernoulli, D., Hottinger, L., 1992. Cretaceous ammonites from fuerteventura, Canary Islands. Geol. Mag. 129, 763–769.

Roemer, F.A., 1836. Die Versteinerungen des norddeutschen Oolithen-gebirges. Hahn.

Robertson, A.H.F., Bernoulli, D., 1982. Stratigraphy, facies and significance of late Mesozoic and early tertiary sedimentary rocks of fuerteventura (Canary islands) and Maio (cape verde islands). In: von Rad, U., Hinz, K., Sarnthein, M., Seibold, E. (Eds.), Geology of the Northwest African Continental Margin. Springer Verlag Berlin Heidelberg, New York, pp. 498–525.

Robertson, A.H.F., Stillman, C.J., 1979. Late Mesozoic sedimentary rocks of fuerteventura, Canary Islands: implications for West African Continental margin evolution. J. Geol. Soc. London 136, 47–60. https://doi.org/10.1144/gsjgs.136.1.0047.

Rothe, P., 1968. Mesozoische Flysch-Ablagerungen auf der Kanareninsel Fuerteventura. Geol. Rundsch. 58, 314–332. https://doi.org/10.1007/BF01820611.

Steiner, C., Hobson, A., Favre, P., Stampfli, G.M., Hernandez, J., 1998. Mesozoic sequence of fuerteventura (canary islands): witness of early Jurassic sea-floor spreading in the central Atlantic. Geol. Soc. Am. Bull. 110, 1304–1317. https://doi.org/10.1130/0016-7606(1998)110<1304.

Stillman, C.J., Bennell-Baker, M.J., Smewing, J.D., Fúster, J.M., Muñoz, M., Sagredo, J., 1975. Basal complex of fuerteventura (Canary islands) is an Oceanic intrusive complex with rift-system affinities. Nature. https://doi.org/10.1038/257469a0.

Uhlig, V., 1906. Review of “La Faune jurassique de Mazapil avec un appendice sur les fossiles du crétacique inférieur” by C. Burckhardt. (Boletín del Instituto geológico de México, No. 23, 1906, 43 plates). Neues Jahrbuch für Mineralogie. Geologie und Paläontologie 2, 469–471.

von Fritsch, K., 1868. Reisebilder von den Canarischen Inseln. Petermanns Geogr. Mitt. 5, 1–44.

Wenke, A.A.O., 2015. Sequence Stratigraphy and Basin Analysis of the Meso- to Cenozoic Tarfaya- Laâyoune Basins, on- and Offshore Morocco. Ruprecht-Karls-Universität Heidelberg.