The Cretaceous Continental Intercalaire in central Algeria: subsurface evidence for a fluvial to aeolian transition and implications for the onset of aridity on the Saharan Platform

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Abstract

The Lower Cretaceous Continental Intercalaire of North Africa is a terrestrial to shallow marine continental wedge deposited along the southern shoreline of the Neotethys Ocean. Today it has a wide distribution across the northern Sahara where it has enormous socio-economic importance as a major freshwater aquifer. During the Early Cretaceous major north-south trending basement structures were reactivated in response to renewed Atlantic rifting and in Algeria, faults along the El Biod-Hassi Messaourd Ridge appear to have been particularly important in controlling thickness patterns of the Lower Cretaceous Continental Intercalaire. Subsurface data from the Krechba gas field in Central Algeria shows that the Lower Cretaceous stratigraphy is subdivided into two clear parts. The lower part (here termed the In Salah Formation) is a 200 m thick succession of alluvial deposits with large meandering channels, clearly shown in 3D seismic, and waterlogged flood basins indicated by lignites and gleyed, pedogenic mudstones. The overlying Krechba Formation is a 500 m thick succession of quartz-dominated sands and sandstones whose microstructure indicates an aeolian origin, confirming earlier observations from outcrop. These interbed with brick red, highly oxidised mudstones representing deposition in temporary lakes or lagoons under an arid climate. The switch from fluvial to aeolian sedimentation at Krechba on the Saharan Platform occurred in the late Aptian and Albian and is thus synchronous to a comparable change observed by previous authors in Lower Cretaceous non-marine deposits of NE Spain. This was probably driven by a combination of sea-level fall and the northward shift of global arid belts into western Neotethys caused by oceanic rifting between Africa and South America.

Keywords

Continental Intercalaire; Lower Cretaceous; Saharan Platform; El Biod-Hassi Messaourd; Krechba; In Salah; Timimoun Basin

1 Introduction

The Early Cretaceous was a dynamic interval in the Mesozoic with the ongoing breakup of Gondwana and the connection of the North and South Atlantic leading to a major reorganisation of global climatic belts (Hallam, 1985; Hu et al., 2012; Scotese, 2009). A general trend of global warming throughout the Early Cretaceous was punctuated by many short-lived temperature excursions related to elevated levels of greenhouse gases from magmatic activity (Hu et al., 2012). This culminated in the Cenomanian-Turonian Thermal Maximum when global sea-level reached an all-time highstand for the Phanerozoic, flooding many continental margins (Hallam, 1985). Prior to the late Cenomanian marine transgression, many of these continental margins had been sites of terrestrial and paralic sedimentation which provide an important record of changing non-marine environments, faunas and floras during the Early Cretaceous (Anderson et al., 2007).

The Lower Cretaceous of North Africa is a particularly extensive example of an Early Cretaceous terrestrial to shallow marine continental-margin wedge that was subsequently flooded during the Cenomanian transgression. The predominantly siliciclastic Lower Cretaceous deposits, which are often referred to as the Continental Intercalaire and Nubian Sandstone, extend from Morocco to Egypt across Saharan Africa and were deposited along the southern shoreline of the Neotethyan Ocean (Guiraud et al., 2005). Early interest in the Lower Cretaceous Continental Intercalaire of North Africa was driven by the presence of dinosaur faunas (Kilian, 1931; Lapparent, 1960) whose evolution chart the breakup of Gondwana and the progressive isolation of the African continent (Anderson et al., 2007; Benton et al., 2000). The Lower Cretaceous Continental Intercalaire of North Africa is also of enormous socio-economic importance as one of the world's largest groundwater systems in one of the most arid regions (Edmunds et al., 2003; Guendouz and Michelot, 2006). The over-exploitation and protection of "fossil" groundwaters following expansive drilling programmes (Moulla et al., 2012) is one of a number of reasons why our understanding of the stratigraphy of these vast Lower Cretaceous coastal-plain deposits needs to be improved.

Relative to its areal extent, the amount of published literature on the Lower Cretaceous Continental Intercalaire and related deposits in North Africa is remarkably small (Busson and Cornée, 1991). This partly reflects the relative inaccessibility of Lower Cretaceous outcrop, much of which lies in remote locations within the Sahara Desert. This applies particularly to the large areas of Cretaceous outcrop which occur in central Algeria (Fig. 1), where substantial field studies have not been undertaken since the work of Le Franc (1974) and Toutin (1975). The logistical difficulties in undertaking fieldwork in regions such as Central Algeria increases the importance of stratigraphic information that can be gleaned from other sources such as water borehole records or the many hydrocarbon fields which occur across the region (Askri et al., 1995; OSS, 2004).

The primary aim of this paper is to present new information on the Lower Cretaceous Continental Intercalaire from the Krechba gas field in the Timimoun Basin of central Algeria (Fig. 1). This gas field has had a high profile in recent years because of pioneering industrial-scale carbon capture and storage (CCS) work, in which context it is commonly referred to using the licence area designation, In Salah (Ringrose et al., 2013). Cretaceous strata form a relatively thick (900 m) cover resting unconformably on Carboniferous rocks which have been the primary interest for CCS work (Ringrose et al., 2013). In this paper we aim to show how subsurface data such as borehole geophysics, cuttings and 3D seismic which were captured primarily to understand deep Palaeozoic reservoirs can greatly improve our understanding of the stratigraphy and depositional environments of the Lower Cretaceous cover. When combined with relatively sparse, but important, published outcrop work, these data may provide the first evidence for the development of a major aeolian erg (or sand sea) in the Lower Cretaceous of North Africa. This has implications for understanding how fluctuating sea-levels and changing global climate belts in the Early Cretaceous influenced regional depositional patterns around the western periphery of the Neotethyan Ocean.

2 Geological setting

2.1 Lower Cretaceous stratigraphy of North Africa

During the Cretaceous, North Africa was located on the southern passive margin of Neotethys and a thick wedge of terrestrial to shallow marine sandstones, mudstones, evaporites and carbonates accumulated on a north-dipping platform (Fig. 2) (Guiraud et al., 2005). The Cretaceous stratigraphy of Algeria, and adjacent areas of Tunisia, Libya and Morocco, generally divides into two parts (Fig. 2). The Early Cretaceous (Berriasian to Albian) is a predominantly non-marine or marginal marine siliciclastic succession while the Late Cretaceous (Cenomanian to Maastrichtian) is dominated by marine mudstones, evaporites and carbonates which were deposited following the major Cenomanian global sea-level rise which inundated extensive areas of the northern African continent (Busson 1998). Marine-influence persisted in North Africa until the Eocene when the progressive growth of the Atlas Mountains in response to the Alpine collision of Africa and Europe isolated the region as a continental basin (Outtani et al., 1995).

Lower Cretaceous non-marine siliciclastic deposits in North Africa have long been referred to the Continental Intercalaire in Algeria and adjacent parts of the western Sahara, or the Nubian Sandstone in eastern parts of the Sahara (Lefranc and Guiraud, 1990). However, such terms need to be treated with caution as they are very loosely defined and are often used to describe any deposit of largely terrestrial aspect that was deposited between the Namurian (Carboniferous) and Cenomanian (Late Cretaceous) marine transgressions (Kilian, 1931; Kogbe and Burollet, 1990; Lefranc and Guiraud, 1990). In Algeria and the western Sahara there has been a trend, particularly in hydrogeological literature, of restricting the term Continental Intercalaire to two major sandy tongues within the Lower Cretaceous which are often informally referred to as the Barremian and Albian sandstones (Fig. 3) (OSS, 2004; UNESCO, 1972). This usage is adopted here, but for clarity the term Continental Intercalaire is prefixed by Lower Cretaceous. While these sands may be largely Barremian to Albian age in northern parts of Algeria (Askri et al., 1995) it is probable that in southern locations close to the Hoggar Massif (Fig. 4) sands of the Continental Intercalaire extend to the base of the Cretaceous (Fig. 3) (Lefranc and Guiraud, 1990). In the northern half of Algeria the Barremian and Albian tongues of the Continental Intercalaire are split by the 'Aptian Bar' or 'Intercalation argilo-carbonatée', a succession of muddy carbonates typically around 30 m thick which represent a significant pre-Cenomanian marine incursion onto the Saharan Platform (Askri et al., 1995). There is good evidence for marine influence throughout the Lower Cretaceous stratigraphy of the Saharan Platform, with the recognition of alternating of fluvial, tidal and lagoonal deposits in areas of Tunisia and Libya where there have been a number of recent detailed studies (Anderson et al., 2007; Wood et al., 2014).

A unified, well-defined and consistently applied lithostratigraphic nomenclature for the Lower Cretaceous of Algeria does not currently exist and much work combines informal terms, such as Continental Intercalaire, terminology which mixes chronostratigraphy and lithostratigraphy (e.g. Albian Sandstone), and varied combinations of terms imported from Morocco, Tunisia and Libya (Askri et al., 1995). Due to the confused nomenclature it has been necessary to introduce new lithostratigraphic terms for the Lower Cretaceous stratigraphy at Krechba which are described in following sections.

2.2 Early Cretaceous tectonics in North Africa

The Early Cretaceous was an important tectonic period for North Africa with a new stage of active rifting along the Atlantic margin to the west and in the Neotethys, or Alp Tethys, to the north (Stampfli et al., 2002). Tectonic stress from marine rifting was transmitted deep into the Saharan Platform resulting in the extensional or strike-slip reactivation of long-lived, crustal lineaments many of which are visible in, and propagate northwards, from the Hoggar Massif (Coward and Ries, 2003; Smith et al., 2006) (Fig. 4).

The major N-S trending Amguid and Essaouidi Mellene were particularly important with extension or transtension generating subsiding basins in the vast continental plain that lay to the east of the West African Craton and north of the Hoggar (Coward and Ries, 2003) (Fig. 2). In the Lower Cretaceous successions of Tunisia and Libya, tectonic unconformities have been recognised in the Late Aptian and the Middle Albian. The Late Aptian, or Austrian unconformity, is placed at the end of the first phase of Cretaceous rifting (Guiraud et al., 2005). The Late Cretaceous was characterised by uniform regional subsidence and minor tectonic compressional activity with onlap of Cenomanian and Turonian marine deposits onto long-lived highs across North Africa. Into the Santonian, a compressional episode caused folding and inversion of the former extensional basins along the North African margin and initialised the growth of the Saharan Atlas Mountains.

2.3 Distribution and thickness of the Lower Cretaceous Continental Intercalaire

The Lower Cretaceous Continental Intercalaire covers a large part of the Western Sahara Desert between the South Atlas Front and the Hoggar Massif (Fig. 4). This area corresponds to the Saharan Platform, a tectonic domain of relatively weakly-deformed Mesozoic and Cenozoic deposits resting unconformably on sub-Hercynian basement (Askri et al., 1995; Guiraud et al., 2005). Across the Saharan Platform the Lower Cretaceous Continental Intercalaire extends in outcrop and in subcrop as a gently undulating blanket of relatively consistent thickness over 600,000 km^2 (Castany, 1981). To the north of the South Atlas Front, the Continental Intercalaire, together with marine strata of equivalent Lower Cretaceous age, are folded and thrusted within the Atlas orogenic belt (Outtani et al., 1995).

The main outcrop of the Lower Cretaceous Continental Intercalaire is located just to the north of the Hoggar Massif, a vast expanse of exposed Precambrian basement (Fig. 4). Here an arcuate belt of Lower Cretaceous outcrop occurs around the flanks of the Tademait and Tinghert, a rocky plateau formed from Upper Cretaceous and Lower Tertiary carbonates. Together with the M’zab and Jeffara escarpments, these elevated areas encircle the low-lying depression of the Oued Mya Basin, where the Continental Intercalaire subcrops beneath a thick (up to 1 km) cover of Late Cretaceous and Cenozoic deposits. A surface constructed from published well data (UNESCO, 1972) shows that the base of the Continental Intercalaire aquifer reaches a maximum depth of around 1500 m below sea level in the El Oued Mya Basin, with Lower Cretaceous strata dipping into this central basin from the south, west and east (Fig. 5). The Continental Intercalaire at the Krechba gas field lies in a relatively shallow structural position relative to the El Oued Basin, in a southerly position close to the present eroded margin of the Cretaceous deposits. The Continental Intercalaire also occurs in the area occupied by the Great Western Erg to the north of Krechba, but here the bedrock is concealed beneath a cover of Quaternary and Holocene alluvial fan and aeolian dune deposits (Fig. 4). This area is bounded to the west by the Ougarta Range, where deformed Palaeozoic rocks are exposed at surface. The El Biod-Hassi Messaourd structural high forms an eastern boundary to the El Oued Basin. This high extends northward from the Hoggar Massif and is part of a major Pan-African fault system (5°E Shear Zone) that was repeatedly reactivated as normal or stike-slip faults during the Phanerozoic, particularly in the Mid Palaeozoic, Late Palaeozoic (Hercynian) and Mid Mesozoic tectonic phases (Coward and Ries, 2003; Guiraud et al., 2005).

The El Biod-Hassi Messaourd High appears to have had an important control on the thickness distribution of the Lower Cretaceous Continental Intercalaire. A thickness map constructed from published UNESCO (1972) borehole data shows that this predominantly sandy interval is 500-800 m in the Oued Mya Basin, but east of the El Biod-Hassi Messaourd High thins to typically less than 400 m thick, with some local thickening into the Berkine (Ghadames) Basin (Fig. 6). This thickness pattern is similar to that seen in the Upper Triassic when the north-south trending Pan-African lineaments were reactivated as normal faults creating two main sub-basins either side of the El Biod-Hassi Messaourd high (Eschard and Hamel, 2003). The Krechba gas field overlies the Palaeozoic Timimoun Basin (Fig. 6). Reactivation of faults to the west of the Allal High may have created a local depocentre during Early Cretaceous extension, but there is insufficient well control at present to be certain.

3 Lower Cretaceous stratigraphy at the Krechba gas field

3.1 Location, geological setting and data availability

The Krechba gas field is located 200 km east of Timimoun and 215 km north of In Salah on the Tademait, a bare rocky plateau which reaches an elevation of around 600 metres above sea level (Fig. 4). The plateau is formed from Late Cretaceous carbonates, mudstones and evaporites which form a series of step-like terraces (Fig. 7A). The Krechba gas field is located on the minor secondary escarpment formed by the Dalle Turonienne Limestone which dips at an extremely low angle (<0.5 degrees) toward the SE. The nearest outcrop of the Continental Intercalaire to the Krechba site is located 60 km to the NW on the low-relief flanks of the Tademait plateau where much of the bedrock is covered by Quaternary and Holocene deposits of the Great Western Erg (Fig. 7B). At Krechba, Lower Cretaceous strata rest unconformably on the thick (950 m) succession of Carboniferous (Visean) mudstones which core the synclinal Timimoun Basin. The Visean mudstones form the caprock to underlying Tournaisian sandstone gas reservoirs which, in addition to being an important source of hydrocarbons, are notable for their part in recent pioneering onshore CO2 capture and storage work (Ringrose et al., 2013). Northwards toward the Oued Mya Basin a wedge of Triassic and Jurassic strata is present between the base of the Cretaceous and the Hercynian unconformity (Logan and Duddy, 1998).

The primary data used in this study are geophysical logs, borehole cuttings and 3D seismic. Much of the subsurface data used in this study are available because of the carbon capture and storage work at Krechba, where injection boreholes had to penetrate the Cretaceous cover to reach the underlying reservoirs (Ringrose et al., 2013). The well data are distributed across the 20 km wide Krechba site (Fig. 8). A block of 3D seismic data was available which, although difficult to interpret at shallow (<500 m) levels, provided remarkable insight into fluvial depositional systems in the lowest parts of the Cretaceous.

The Cretaceous stratigraphy starts with a thin anhydrite bed which occurs immediately above the Hercynian unconformity and forms a conspicuous marker on gamma-ray logs (Fig. 9). Between the Hercynian Unconformity and the base of the Cenomanian mudstones, which define the top of the Continental Intercalaire, are around 700 m of sandstones, poorly consolidated sands and mudstones. Sands and sandstones account for approximately 80 percent of the interval, with most of the mudstone concentrated in the lowermost 150 m of the Cretaceous stratigraphy. Before considering this interval further it is important to discuss previous work on the Lower Cretaceous stratigraphy of the Tademait region because correlation to outcrop, where non-marine vertebrate fossils are found, provides the principal means of dating the borehole successions.

3.2 Published Cretaceous stratigraphy of Tademait Plateau

Published information on the Cretaceous of central Algeria is sparse with the most significant contribution coming from work undertaken to produce the 1:500,000 scale geological map of Timimoun which includes the Krechba gas field (Lefranc, 1974). This map introduced a new stratigraphic scheme for the Lower Cretaceous of the region, although the only readily available supporting documentation is provided by brief discussion in Lefranc and Guiraud (1990), with additional information, particularly on the vertebrate fossils and palaeoecology, in Busson and Cornée (1991). Fig. 10 shows the lithostratigraphical scheme of the Timimoun geological map in which the predominantly sandy and non-marine Cretaceous strata below Cenomanian transgressive mudstones are subdivided into ten units. Note that this interval does not equate to the Continental Intercalaire as used by Le Franc and Guiraud (1990), who apply the term in the sense of Kilian (1937) to include all non-marine formations between the Carboniferous (Namurian) and the Cretaceous Cenomanian marine transgression. Continental Intercalaire strata of Lower Cretaceous age are specifically termed the Djoua Series.

On the Timimoun geological map the lowermost Cretaceous strata resting unconformably on the Carboniferous are the Toubchirine Sands, which are assigned a Neocomian age. These are overlain by the Rheilar Clay, Ouadjda Sands and El Feiza Clay which are Lower Barremian. According to the scaled generalised vertical section on the Timimoun map these strata account for the lowermost 244 m of the Lower Cretaceous Continental Intercalaire. Details on the lithologies are sparse. Busson and Cornée (1991) describe this interval as both sandy and argillaceous at the base, coarsening upwards into sandstones and conglomerates at the top. It contains numerous vertebrate fossil debris (particularly dinosaurs) and silicified wood. The overlying Barremian Oumrad gravels are 98 m thick and include the Argile d'El Feiza clay at the base. Lefranc and Guiraud (1990) include an additional unit the 'Tinoumeur Clay' at this level in the stratigraphy. The gravels contain fragments of silicified wood, fish and reptile bones and around the flanks of the Tademait Plateau are an important aquifer into which water trapping galleries (foggaras) are preferentially excavated (Lefranc and Guiraud, 1990).

The remainder of the Continental Intercalaire is made from the sands and sandstones of the Barremian to Albian Méguidéne and Samáni sands which are a total of 307 m thick. Busson and Cornée (1991) note that Toutin (1975) observed an abundance of well-rounded, frosted quartz grains indicating a significant input of wind-blown sand, although much of the primary aeolian deposits may have been reworked by fluvial processes. The sands showed common cross-bedding and in particular an abundance of convolute or slumped lamination. Crocodiles, fish and freshwater bivalves (*Desertella foureaui*) were found in some of the muddier units within this interval. The upper parts of the Samani sands (the 'Sable lité de Samani') are finer-grained and become argillaceous below the transgressive Cenomanian El Goléa clays.

Lefranc and Guiraud (1990) tentatively correlate a 20 m thick calcareous sandstone in the Timimoun region, the Hassi el-Homeur Sandstone, located 122 m below the top of the Continental Intercalaire with the marine carbonates of the Aptian Bar. The Aptian Bar is a well-defined marker unit of dolomitic limestones within the Continental Intercalaire further north in the Oued Mya Basin (Askri et al., 1995).

3.3 Surface to subsurface stratigraphic correlation

The generalised vertical section on the Timimoun geological map (Lefranc 1974) indicates a total thickness of sub-Cenomanian Cretaceous of 649 m which compares reasonably closely to the mean thickness of this interval (702 m) at the Krechba gas field. As discussed below, the general character of the stratigraphy can also be readily recognised in the borehole stratigraphy at Krechba, as might be expected given that the gas field is located around 60 km from the nearest outcrop, a small distance relative to the vast sedimentary basin. However, there are a number of reasons why it is not possible to accurately and objectively transfer the terms shown on the Timimoun map to the boreholes at Krechba including the relatively fine-scale, and potentially localised, nature of Lefranc's (1974) subdivisions, the lack of a lithostratigraphic hierarchy of groups, formations and members and the absence of readily-available and detailed documentation. For the purposes of discussion, two new lithostratigraphic terms are introduced at Krechba (the In Salah and Krechba formations) which recognise a fundamental two-fold subdivision of the sub-Cenomanian, Lower Cretaceous stratigraphy. While the proliferation of lithostratigraphical terms is never desirable, the introduction of two new terms prevents the misuse of the relatively sparsely-documented terms established at outcrop and highlights the clear and well-defined two-fold subdivision of the Lower Cretaceous at Krechba. Many of the terms for individual sandstone and mudstone units (e.g. Rheilar Clay, Ouadjda Sands etc) used by Lefranc (1974) probably represent members with the two formations that are described below.

3.4 In Salah Formation

Description

The In Salah Formation describes the lowermost 200 m of the Lower Cretaceous stratigraphy. At Krechba the base of the formation is marked by a thin anhydrite bed overlying the Hercynian Unconformity which forms a conspicuous low gamma-ray spike (Fig. 9). Above this is an interval that comprises approximately equal proportions of mudstone and sandstone. Borehole cutting returns show that sandstones are dominated by quartz grains that are predominantly fine-grained, subangular to subrounded and brown, reddish brown or translucent in colour (Fig. 11A). Mudstones are micaeous and highly variable in colour including red, grey, green and brown (Fig. 11B). Lignite and pyrite are present, particularly toward the base of the formation, and some of the mudstones show possible small-scale root structures.

Geophysical logs show that the mudstones and sandstones are arranged into coarsening-upward cycles which produce funnel-shaped profiles on gamma-ray curves, with mudstones of high gamma-ray value at the base and sandstones of low gamma-ray value at the top (Fig. 9). It is probable that immediate gamma-ray values represent admixtures, or thinly interbedded (below the resolution of the logging tool), sandstone and mudstone. The coarsening-upward cycles range from 20 to 40 m thick with 5 to 8 cycles making up the 200 m thick In Salah Formation. The proportion and thickness of sandstone making up each cycle increases systematically upwards in each borehole, from sandstones that are 5 m or less at the base of the formation, to sandstones that are up to 25 m thick at the top of the formation (Fig. 12).

Thicker sandstones toward the top of the formation appear to have sharp, abrupt contacts with the underlying mudstones, suggesting that they could be channels with scoured bases. Upward-fining within some of the sandstone bodies is suggested by the development of bell-shaped gamma-ray profiles, which often results from the lateral migration of point bars within meandering channels. The presence of meandering channels is indicated by seismic analysis using a processed coherency cube of the 3D seismic data. Enhancing lateral discontinuities reveals many examples of high-sinuousity channels, ranging from 80 to several hundred metres wide with meander amplitudes varying from hundreds of metres (smaller channels) to several kilometres (Fig. 13). Seismic amplitudes within the channels are highly variable along their length, suggesting both varying thickness and the nature of the fill, probably being sand filled in one place, and mud filled elsewhere.

In terms of the published stratigraphy it is probable that the 200 m thick In Salah Formation is equivalent to the combined 243 m thickness of the Toubchirine Sand, Ouadjda Sand and Oumrad Gravel and their intervening clay members (Fig. 9). This would suggest a Neocomian to early Aptian age for the Krechba Formation. The upward transition from a mudstone-rich base to a sandy and gravelly top, which is clearly shown in gamma-ray logs at Krechba, is not described in published literature (Lefranc, 1974; Lefranc and Guiraud, 1990). This may indicate a more proximal position for the Toubchirine Sands, along the western flanks of the Tademait Plateau, or simply problems with the lower part of the stratigraphy being obscured by Quaternary and Holocene cover at outcrop (Lefranc and Guiraud, 1990). In this respect the borehole data may provide a much higher stratigraphic resolution than outcrop.

Interpretation

The presence of large meandering rivers channels, grey mudstones and lignite indicates that the In Salah Formation was deposited in a relatively wet lowland basin. Red, green and grey multicoloured clays probably indicate the development of palaeosols in areas that were subject to alternating intervals of gleying and oxidation (Newell, 2014). The high sinuosity of the channels suggests deposition on a very low-gradient surface and this is consistent with the general palaeogeographic setting of a coastal plain to paralic setting on the southern margin of the Tethys Ocean (Guiraud et al., 2005). Channels of multiple sizes visible on time-sliced 3D seismic may indicate the development of distributary channels or crevasse splays emanating from major meandering trunk channels. Thick coarsening-upward cycles or parasequences are the primary log motif of this formation and indicate the cyclic progradation of sandy fluvial deposystems into topographic lows. The parasequences are arranged into a progradational set indicating the overall basinwards advance of sandy channel systems over the duration of the In Salah Formation. It is uncertain at present whether the topographic lows into which the river channels, and their associated sandy mouth bars and levees, advanced were wholly freshwater swamps or lakes, or were interdistributary embayments or estuaries with some marine influence. Terrestrial dinosaurs and snakes, together with freshwater crocodiles, fish, turtles and molluscs tend to predominate in the Lower to Middle Cretaceous of Algeria, although fish, whose habitat can be marine, have also been reported (Busson and Cornée, 1991).

3.5 Krechba Formation

Description

The Krechba Formation is around 490 m thick and is dominated by sandstone (or more usually weakly-consolidated sand) with typically around 5 to 15 percent mudstone. The base of the formation can be readily identified on gamma-ray logs by a negative shift of around 5-10 gamma ray API (American Petroleum Institute) units (Fig. 9). There is also a change in the style of the log profile. While the In Salah Formation is characterised by funnel-shaped (coarsening-upward) motifs, the Krechba Formation has a uniform, blocky profile. Intervals of low gamma-ray value (sandstone) may extend over 100 m of stratigraphic thickness, but much thinner intervals of sandstone also occur. Intervening mudstones have higher gamma-ray values and range up to a maximum of 45 m thick, but are typically 15 m or less. Transitions between sandstones and mudstones are abrupt relative to those seen in the underlying In Salah Formation. Mudstones are distributed throughout the formation but in most wells there is tendency for thicker mudstones to concentrate toward the central part of the formation. Caliper logs show considerable borehole enlargement in the upper half of the formation suggesting the predominance of weakly-cemented sands (Fig. 9).

Cuttings over the 490 m thick interval of the Krechba Formation are remarkably uniform and of a very different character to the fluvial channel and floodbasin deposits of the underlying In Salah Formation. Sands and sandstones are composed predominantly of loose quartz grains typically around 0.5 mm in diameter (medium to coarse range), but fine-grained particles and occasional quartzite rock fragments of up to 2.5 mm (granules) are also present (Fig. 11C). The loose and uncemented character of the quartz sands precludes the determination of depositional sorting parameters because grains from different laminae and beds will become mixed during cutting and transit to the surface, however many of the samples could be described as moderately or well sorted. Based on visual estimates, 90% or more of the quartz grains are well- or very-well rounded and have a characteristic dull or opaque (frosted) surface texture (Fig. 11C).

The microstructure of three quartz grains from a depth of 370 m (mid to upper Krechba Formation) in borehole KB19 was examined using a scanning electron microscope (SEM). The grains show strong rounding and in particular the development of bulbous grain edges (Fig. 14), defined as prominent, protruding and rounded grain edges in the shape of a parabolic curve (Mahaney, 2002; Rodríguez-López et al., 2006). Bulbous edges occur in association with dish-shaped concavities or elongated depressions and occasional percussion marks (Fig. 14). All three grains display dissolution textures, with etching following crystallographic orientations. There is evidence of secondary authigenic mineral precipitation with some surfaces patchily coated with discontinuous authigenic titanium oxide nanoparticles, typically 50-100 nm in size. Pits and crevices sheltered from abrasion show euhedral secondary authigenic quartz precipitation.

Mudstones from the Krechba Formation are brick red in colour and contain much silt-size quartz intermixed with clays and as thin laminae (Fig. 11D). There is no evidence for the presence of grey mudstones or lignites which are present in the In Salah Formation.

The interpretation of seismic data is hampered by the general upward decrease in data quality at shallower levels. Time slices of the seismic coherency cube generally show the presence of distributed, irregular geobodies of high amplitude which probably delineate sandstone or mudstone bodies. There is certainly no evidence from the seismic data for the development of the large-scale meandering channels which are typical of the In Salah Formation.

Relative to the published stratigraphy of the Timimoun geological map (Lefranc, 1974), it is highly likely that the 490 m thick sand-dominated Krechba Formation is equivalent the Meguidene Sands and Samani Sands, a 310 m thick interval of sandstone between the Oumrad gravels and the Cenomanian El Golea Clay. The Meguidene Sands are dated as upper Barremian to Aptian while the vertebrate-fossil bearing Samani Sands are dated as Albian (Busson and Cornée, 1991; Lefranc and Guiraud, 1990). The two units are separated by a 20 m thick unnamed calcareous sandstone, which is tentatively correlated with the Aptian Bar, a transgressive carbonate in the Oued Mya Basin to the north (Askri et al., 1995). There is no clear evidence at Krechba for the development of this unit, with caliper logs indicating that sands and sandstones in the lower half of the In Salah are probably better cemented than the top where there is extensive borehole enlargement (Fig. 9). It is possible that a laterally-correlative belt of thicker mudstones which occurs toward the middle of the Krechba Formation (Fig. 12) represents an inland correlative of the Aptian Bar.

Interpretation

The Krechba Formation is dominated by clean quartz sands, which on gamma-ray logs form remarkably uniform, blocky intervals of low value, punctuated by red mudstones. Several lines of evidence suggest that the bulk of the sands and sandstones within the Krechba Formation have an aeolian origin including, (1) the rounding and surface morphology of quartz grains, (2) the lack of observed fluvial channels in 3D seismic, (3) the blocky gamma-ray response, (4) an association with red (highly oxidised) mudstones which lack lignite, and (5) observations from adjacent outcrop around the Tademait Plateau that aeolian facies occur in the upper part of the Continental Intercalaire (Toutin 1975). Rounding of quartz grains is a characteristic feature of wind-blown sands and experiments show that even limited saltation can achieve edge abrasion and rounding of particles (Rodríguez-López et al., 2006; Whalley et al., 1987). In particular the development of bulbous edge morphology (Fig. 14) is considered highly diagnostic of aeolian environments (Costa et al., 2013; Vos et al., 2014). This style of rounding of the edges and protrusions is attributed to the rotation of saltating grains and is typically shown by grains are generally coarser than 150 μm, as finer material is carried in suspension (Mahaney, 2002). Bulbous edges often occur in association with dish-shaped concavities or elongated depressions whose formation is attributed to high-energy aeolian transport where direct impacts between saltating or creeping grains occur (Vos et al., 2014). Most of the rounded quartz grains have a dull, opaque (frosted) surface appearance and this has long been described from quartz grains in deserts where it is related to the scattering or diffusion of light due to the presence of closely spaced surface irregularities (Folk, 1978). These include irregularities such as scratches and percussion cracks caused by violent impacts and abrasion during transport, together with a regular and orientated chemical etching where solution follows the crystallographic orientation (Kuenen and Perdok, 1962; Margolis and Keinsley, 1971). Etch pits are generally linked to diagenetic processes and in particular to contact with alkaline fluids such as seawater, particularly where this is concentrated by evaporative processes (Vos et al., 2014). The presence of such fluids is consistent with the arid, coastal setting of the Saharan Platform in the mid- to late Cretaceous.

It is possible that quartz grains showing the signature of aeolian transport can be reworked or recycled by fluvial and marine processes. In the current absence of downhole image logs, detailed description of small-scale sedimentary structures from outcrop are required to determine the types of aeolian bedform that were present and the extent to which these were reworked by other processes. At present outcrop observations are limited to those of Toutin (1975) from a location 65 km northwest of the Krechba gas field. Toutin (1975) observed that in the upper part of the Continental Intercalaire (above the Oumrad Gravels) around half the sediment was composed of well-rounded and frosted grains of aeolian origin. However, the presence of large-scale cross-bedding and extensive convolute lamination was noted and it was thought that this might indicate extensive reworking of an aeolian dune hinterland by fluvial processes. The extent of the reworking is uncertain at present. At Krechba, grain surfaces do not show clear evidence for overprint by subaqueous processes (Vos et al., 2014), which can occur relatively rapidly (Folk, 1978). Neither do the gamma-ray signatures nor 3D seismic provide evidence for fluvial channels which are clearly seen in the In Salah Formation. Inundation of dune fields by floodwaters could account for the common occurrence of convolute lamination (Toutin 1975) and this has been described from many coastal erg settings where water ingress causes the destabilisation and deformation of aeolian dune sands (Rodriguez-Lopez et al. 2008).

The highly-oxidised brick-red mudstones of the Krechba Formation are very different from the grey, lignitic mudstones of the fluvial In Salah Formation. On the basis of poorly-resolved 3D seismic data these appear to form irregular patches which may be several kilometres in width. It is probable that these mudstones were deposited from suspension in temporary water bodies which may have been lakes or lagoons in topographic lows between dune fields. Floodwaters could have been overland freshwater flows or, given the coastal plain setting, from marine storm surges. At outcrop mudstones within the correlative Samani Sands contain vertebrate remains including a large crocodile skull and the freshwater bivalve *Desertella foureaui* (Busson and Cornée, 1991).

4 Discussion

The Lower Cretaceous Continental Intercalaire of North Africa provides an important record of Early Cretaceous terrestrial environments along the southern periphery of the western Neotethyan Ocean (Anderson et al., 2007; Russell and Paesler, 2003). In recent years the bulk of research has been undertaken on the Lower Cretaceous successions of Tunisia and Libya, which are generally fluvio-marine in character, relatively thin and punctuated by major unconformities (Aloui et al., 2012; Anderson et al., 2007; Fanti et al., 2012; Lazzez et al., 2008; Wood et al., 2014). This study is one of very few to have investigated the Continental Intercalaire on the Saharan Platform to the west of the El Biod-Hassi Messaoud structural, across which Lower Cretaceous strata thicken markedly into the Oued Mya and Timmoun basins.

Subsurface evidence from geophysical logs, cuttings and 3D seismic from the Krechba gas field show that the pre-Cenomanian stratigraphy has a clear two-fold subdivision into a lower 200 m thick fluvial succession overlain by a 500 m unit dominated by sands of aeolian origin. The lowermost fluvial deposit, here termed the In Salah Formation, forms a coarsening-upward succession that culminates in thick gravelly and sandy channel fills. 3D seismic shows the development of major meandering channels up to several hundred metres in width and provides a remarkable visualisation of an Early Cretaceous coastal plain on the Saharan Platform. The presence of grey mudstones and lignites suggests the development of water-logged floodbasins or lakes, while grey red and purple mottled mudstones are usually indicative of fluctuating pedogenic redox processes under a warm and humid climate (Newell, 2014).

Well-to-well correlation across a 20 km transect suggests the fluvial to aeolian change was abrupt and is a relatively planar surface. This may represent a composite wind deflation and sand-drift surface developed in response to a regional lowering of the groundwater level and a switch toward a relatively arid climate. The primary limiting factor on the accumulation of thick aeolian deposits is the availability of an abundant supply of dry, loose sand (Pye and Tsoar, 2009). The timing of the shift is constrained by correlation to vertebrate-bearing successions at outcrop (Lefranc, 1974) which indicates it occurs around the middle of the Aptian. Aeolian sedimentation continued until the Cenomanian marine transgression which capped the Continental Intercalaire with evaporitic muds and shallow marine carbonates. Episodic flooding of the aeolian dune field, by marine and possibly fluvial processes, may account for the reported abundance of convolute lamination within the aeolian sands at outcrop (Toutin, 1975).

Aside from the brief notes of Toutin (1975), the possibility of a major aeolian erg in the Lower Cretaceous of Algeria has not been considered in any detail. It has considerable practical importance in estimating the volume of the groundwater reserves in the Continental Intercalaire because aeolian sandstones typically have a high porosity in addition to a high permeability. The extent of the aeolian deposits beyond Krechba and the Timimoun Basin needs to be established but it could be extensive. Accumulations of silt-size quartz, which are thought to have been transported by aeolian processes, have been briefly described from the Lower Cretaceous Continental Intercalaire of the Belezma Hills of NE Algeria (Bureau and Douillet, 1972).

The character and timing of the fluvial to aeolian switch described here is similar to one that has recently been described from the mid Cretaceous of NE Spain (Rodríguez-López et al., 2008). During the Early Cretaceous, Spain was located north of the narrow Neotethyan or Alp-Tethys (Stampfli et al., 2002) marine rift basin that separated Africa from Europe (Fig. 15). Here Rodríguez-López et al. (2006, 2008) describe a major Late Aptian to Albian aeolian erg system with a marine erg margin which is around 300 m thick and extends over 4600 $km^2$of the Iberian Range of NE Spain. Remarkably this was the first Cretaceous erg system to be reported from Europe and, before the significance of the outcrop in the Iberian Range was recognised, its occurrence was predicted by the presence of aeolian grains within coeval marine deposits (Rodríguez-López et al., 2006; Rodríguez-López et al., 2008). The late Early

Cretaceous stratigraphy is similar to that seen at Krechba, with a thick aggradational aeolian system represented by the Utrillas Group of Late Aptian and Albian age resting on a sharp deflation/sand-drift surface developed on coal-bearing, alluvial strata of the Aptian Escucha Formation (Barrón et al., 2015; Rodríguez-López et al., 2008) (Fig. 16). Rodriguez-Lopez et al. (2006) relate the occurrence and timing of the Iberian erg to a phase of global cooling and sea-level lowstand in the mid Cretaceous, together with the establishment of the northern hot arid belt. The mid Cretaceous was a time of marked perturbations in the Cretaceous δ13C isotopic record (Föllmi et al., 2006; Herrle et al., 2015) with a positive δ13C shift and a climatic cold snap in the late Aptian possibly related to the sequestration of carbon in newly formed oceanic basins such as the South Atlantic, created as the African continent separated from South America (McAnena et al., 2013) (Fig. 16). The connection of the South and North Atlantic was also important in causing the breakdown of the intracontinental arid zone which had previously occupied central Gondwana (Scotese, 2009). This was replaced by an equatorial humid belt which forced aridity from central Africa into the former tropical humid zones of the Saharan Platform and adjacent areas. The combination of greater aridity and lowered sea levels, possibly increasing sand availability on exposed shelves, may have been conducive to the formation of aeolian ergs around the periphery of western Neotethys.

The Iberian Range was probably located near the northern limit of the northern hot arid belt and the dune fields appear to have developed under the influence of westerly winds (Rodríguez-López et al., 2006). Krechba located further south on the Saharian Platform was likely to have been under the influence of NE tradewinds, but palaeowind directions require confirmation from outcrop studies or orientated borehole image logs. Regional rifting of the Saharan Platform and the development of north-south orientated basins during the Early Cretaceous would have played an important part in creating sand traps which arrested the transport of wind-blown sand and allowed the accumulation of thick aggradational aeolian sand deposits.

5 Conclusions

- The Lower Cretaceous Continental Intercalaire of North Africa is a terrestrial to shallow marine continental wedge deposited along the southern shoreline of the Neotethys Ocean. Today it has a wide distribution across the northern Sahara where it has enormous socio-economic importance as a major freshwater aquifer.
- During the Early Cretaceous major north-south trending basement structures were reactivated, probably as normal faults, in response to renewed Atlantic rifting. In Algeria and adjacent regions, the faults along the El Biod-Hassi Messaourd Ridge appear to have been particularly important in controlling thickness patterns of the Lower Cretaceous Continental Intercalaire.
- Subsurface data from the Krechba gas field show that the Lower Cretaceous stratigraphy is subdivided into two clear parts. The lower part (here termed the In Salah Formation) is a 200 m thick succession of alluvial deposits with large meandering channels, spectacularly shown in 3D seismic, and waterlogged flood basins indicated by lignites and gleyed, pedogenic mudstones. The overlying Krechba Formation is a 500 m thick succession of quartz-dominated sands and sandstones whose microstructure indicates an aeolian origin, confirming earlier observations from outcrop (Toutin, 1975). These interbed with brick red, highly oxidised mudstones representing deposition in temporary lakes or lagoons under an arid climate.
- The switch from fluvial to aeolian sedimentation at Krechba on the Saharan Platform occurred in the late Aptian and Albian and is thus synchronous to a similar change observed in Lower Cretaceous non-marine deposits of NE Spain. The geographic separation of the two areas suggests that the switch from fluvial sedimentation under relatively humid conditions to aeolian sedimentation under arid conditions was caused by external drivers, most probably a combination of global cooling and a temporary fall in sea-level and the northward shift of arid belts caused by oceanic rifting and the connection of the south and North Atlantic.

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8 Figure Captions

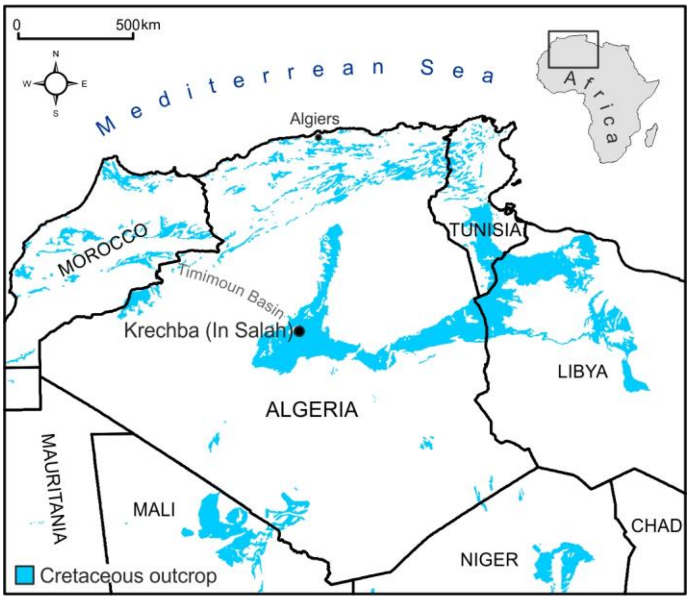

Fig. 1. Location of the Krechba (In Salah) gas field in central Algeria. Blue areas show Cretaceous outcrop in North Africa (Persits et al., 1997).

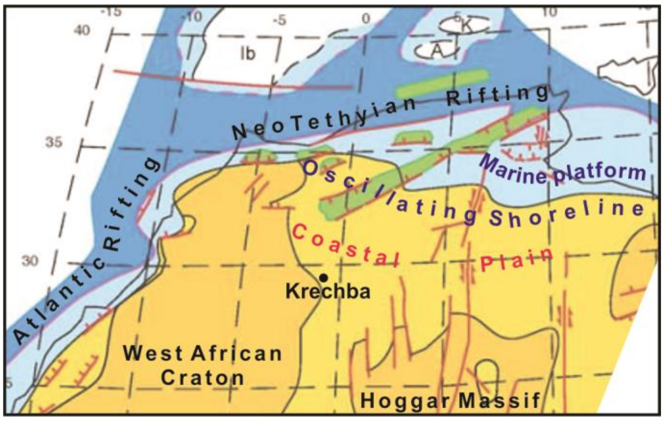

Fig. 2. Early Cretaceous (Late Berriasian-Early Aptian) palaeogeography of North Africa showing the position of Krechba on a coastal plain south of the rifted NeoTethyian rifted marine margin. A shoreline is shown but this was highly dynamic (modified from Guiraud et al., (2005)).

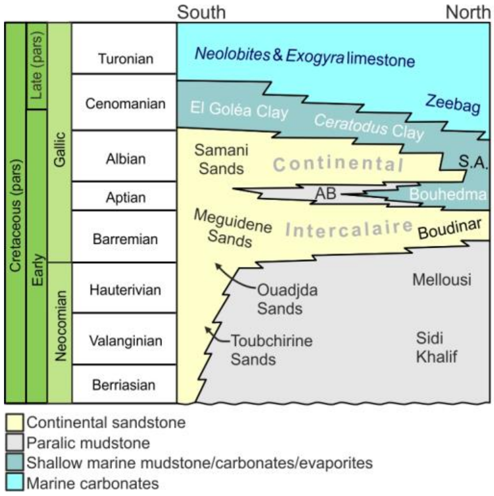

Fig. 3. Schematic Early Cretaceous stratigraphy of Algeria from a southern, landward, position toward the marine north. The lithostratigraphical terms shown are from (Lefranc, 1974) and (Outtani et al., 1995). (S.A. = Sidi Aich Formation; A.B. = Aptian Bar).

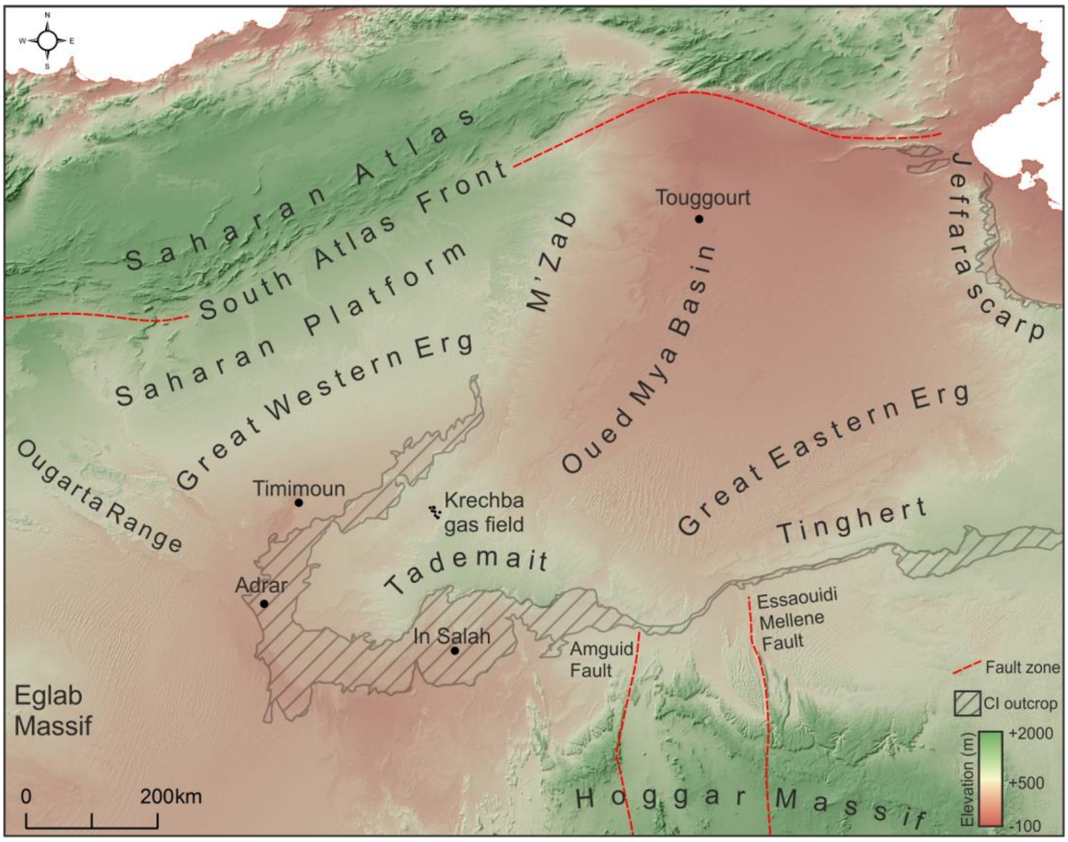

Fig. 4. Location of the Krechba gas field relative to some major physiographic and geological features of Saharan North Africa. The Krechba field sits on the Tademait Plateau which is formed from Upper

Cretaceous carbonates and flanked by an arcuate outcrop of Lower Cretaceous Continental Intercalaire (shown as grey diagonal hatching). The Precambrian Hoggar Massif forms a southern boundary to the Cretaceous deposits and is cut by major north-south structural lineaments. The South Atlas Front forms a boundary between the relatively undeformed Cretaceous strata of the Saharan Platform and the folded and thrusted Cretaceous of the Saharan Atlas.

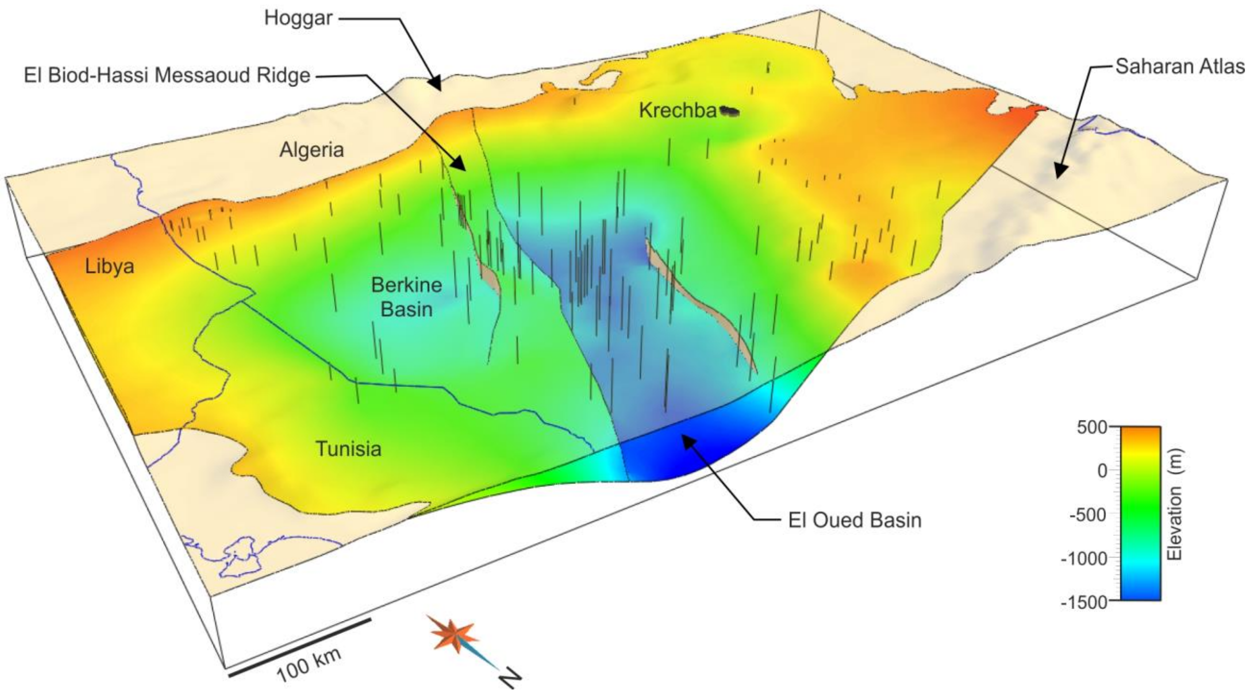

Fig. 5. Perspective view (toward the southwest) on the base of the Continental Intercalaire (here defined as the base Barremian sandstone) across the relatively undeformed Saharan Platform of central Algeria and adjacent areas of Tunisia and Libya. The base of the formation sags into a central trough formed by the El Oued Basin, which is bounded to the east by the El Biod-Hassi Messaoud structural high trending northward from the Hoggar Massif. Black vertical lines indicate well control points which are sourced from UNESCO (1972). Terrain is shown as transparent beige. Elevation is in metres above or below sea level.

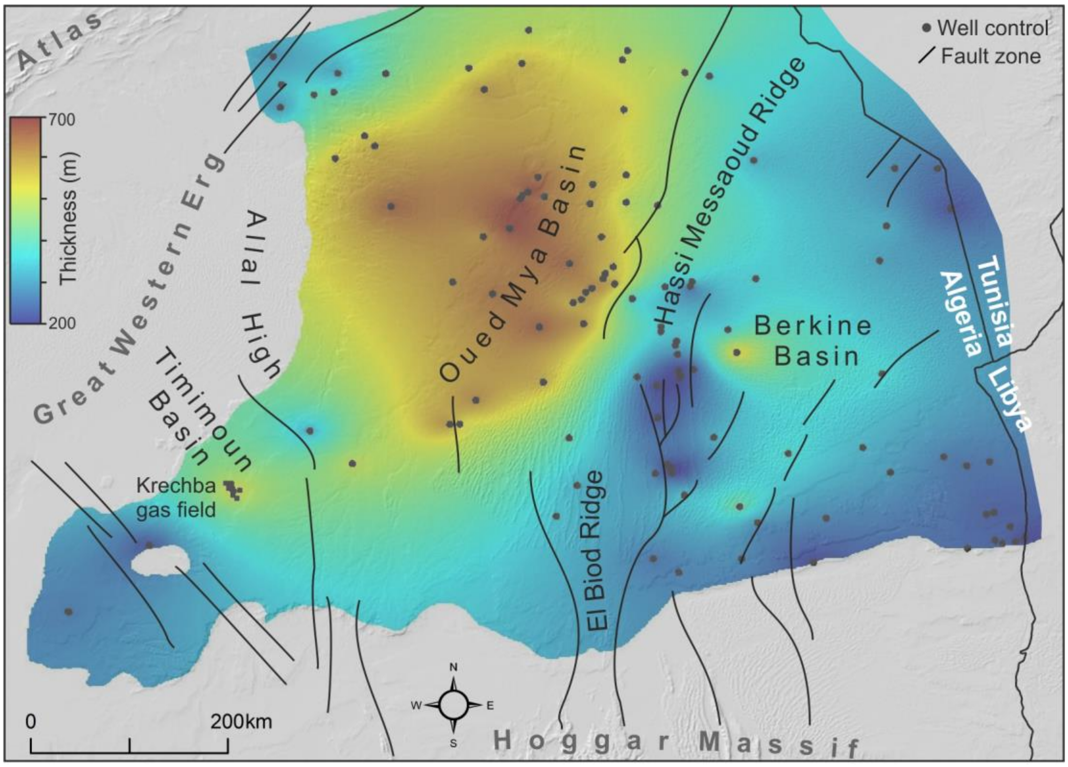

Fig. 6. Thickness map of the Continental Intercalaire (here defined as base Barremian to base Cenomanian sandstones). Black dots indicate borehole control points which are sourced from UNESCO (1972). The generalised location of major basement faults, and selected structural highs and basins are shown.

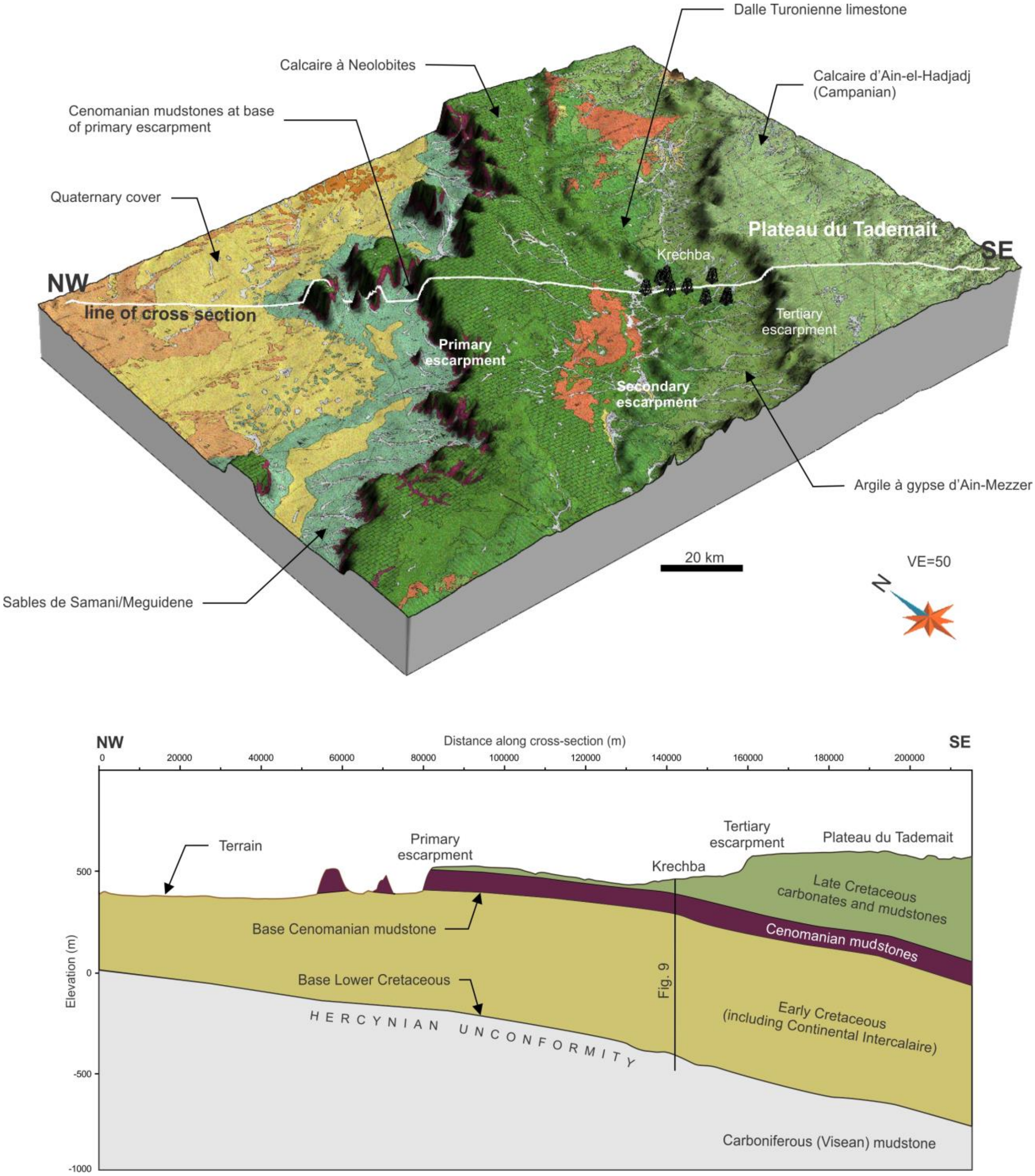

Fig. 7. (A) Block diagram combining a terrain model (based on SRTM (Farr et al., 2007)) and mapped surface geology (Lefranc, 1974) showing how boreholes at the Krechba gas field sit on a stepped topography of southeast-dipping Late Cretaceous carbonates. The Continental Intercalaire crops in low-lying terrain around the flanks of the Tademait Plateau some 60 km to the northwest, (B) Cross-section (position shown as a white line in Fig. 7A) showing Lower Cretaceous strata, including the Continental

Intercalaire, resting unconformably on Carboniferous (Visean) mudstones and sealed beneath Cenomanian mudstones. The position of the borehole shown in Fig. 9 is shown. Note the disparity in the vertical and horizontal scales which greatly exaggerates the southeast dip.

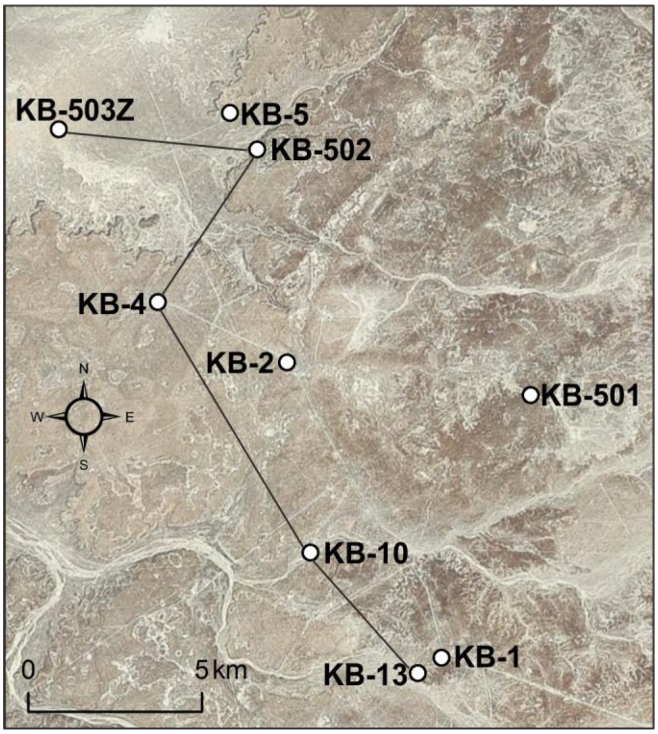

Fig. 8. Map showing the location of selected boreholes at the Krechba gas field. The reference borehole KB-502 (Fig. 9) is located at 29°09’52’’ N and 02°11’45’’ E. The black line shows the location of the well correlation panel (Fig. 12).

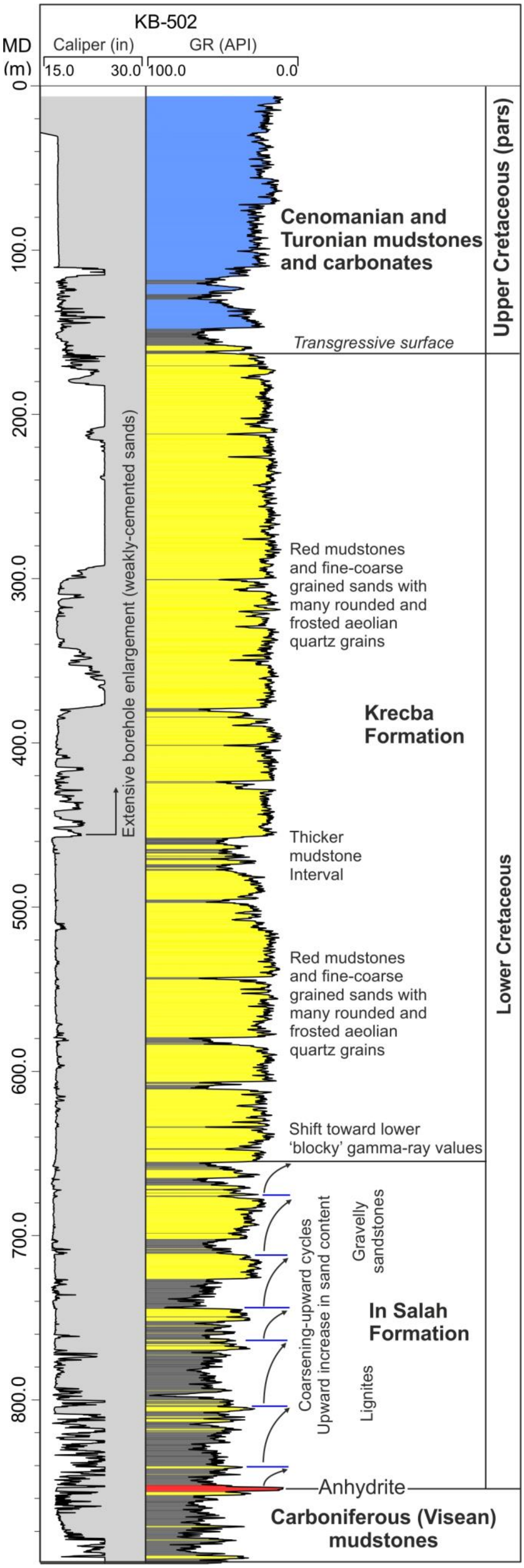
KB-502
MD (m)
Caliper (in)
15.0
30.0
GR (API)
100.0
0.0
0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
Cenomanian and Turonian mudstones and carbonates
Upper Cretaceous (pars)
Transgressive surface
Extensive borehole enlargement (weakly-cemented sands)
Red mudstones and fine-coarse grained sands with many rounded and frosted aeolian quartz grains
Krecba Formation
Thicker mudstone Interval
Red mudstones and fine-coarse grained sands with many rounded and frosted aeolian quartz grains
Lower Cretaceous
Shift toward lower 'blocky' gamma-ray values
Coarsening-upward cycles
Upward increase in sand content
Gravelly sandstones
In Salah Formation
Lignites
Anhydrite
Carboniferous (Visean) mudstones

Fig. 9. The general stratigraphy of Cretaceous strata at the Krechba gas field illustrated using well KB-502 (see Fig. 8 for location). A caliper log (inches) is shown in the left track and a gamma ray log (API units) is shown in the right track. Downhole depth is shown in metres. The gamma log is shaded into generalised lithologies (based on borehole cuttings returns and gamma-ray cut-off values) using red for anhydrite, grey for mudstone, yellow for sand/sandstone and blue for carbonates and muddy carbonates. The caliper log shows considerable enlargement of the borehole in the upper part of the Lower Cretaceous stratigraphy, probably as a result of the removal of weakly or uncemented sands. Log annotation shows the two fold subdivision of the Lower Cretaceous into the In Salah Formation and Krechba Formation which is introduced in this paper.

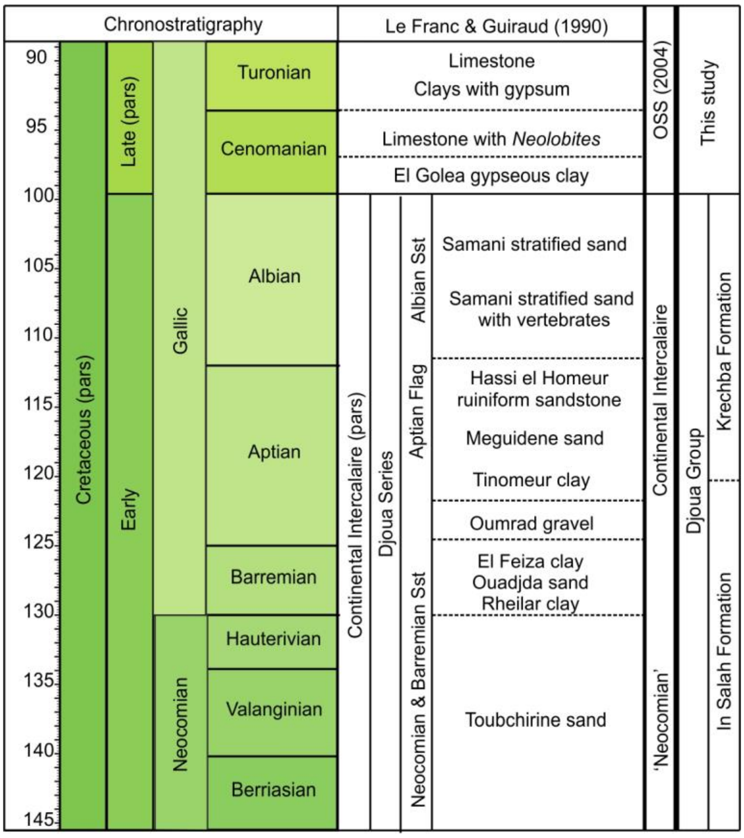

Fig. 10. Chart showing the subdivision and chronstratigraphy of the Early Cretaceous that is used on the Timimoun geological map (Lefranc, 1974; Lefranc and Guiraud, 1990) which includes the area covered by the Krechba gas field (see Fig. 7). The most likely correlation of the In Salah and Krechba formations introduced in this study is shown together with the extent of the Continental Intercalaire (Barremanian

to Albian) that is used in many regional hydrogeological studies of the aquifer (OSS, 2004). Note that Le Franc and Guirad (1990) do not adopt this use of the term but use it to include underlying Mesozoic and Palaeozoic units of general continental facies.

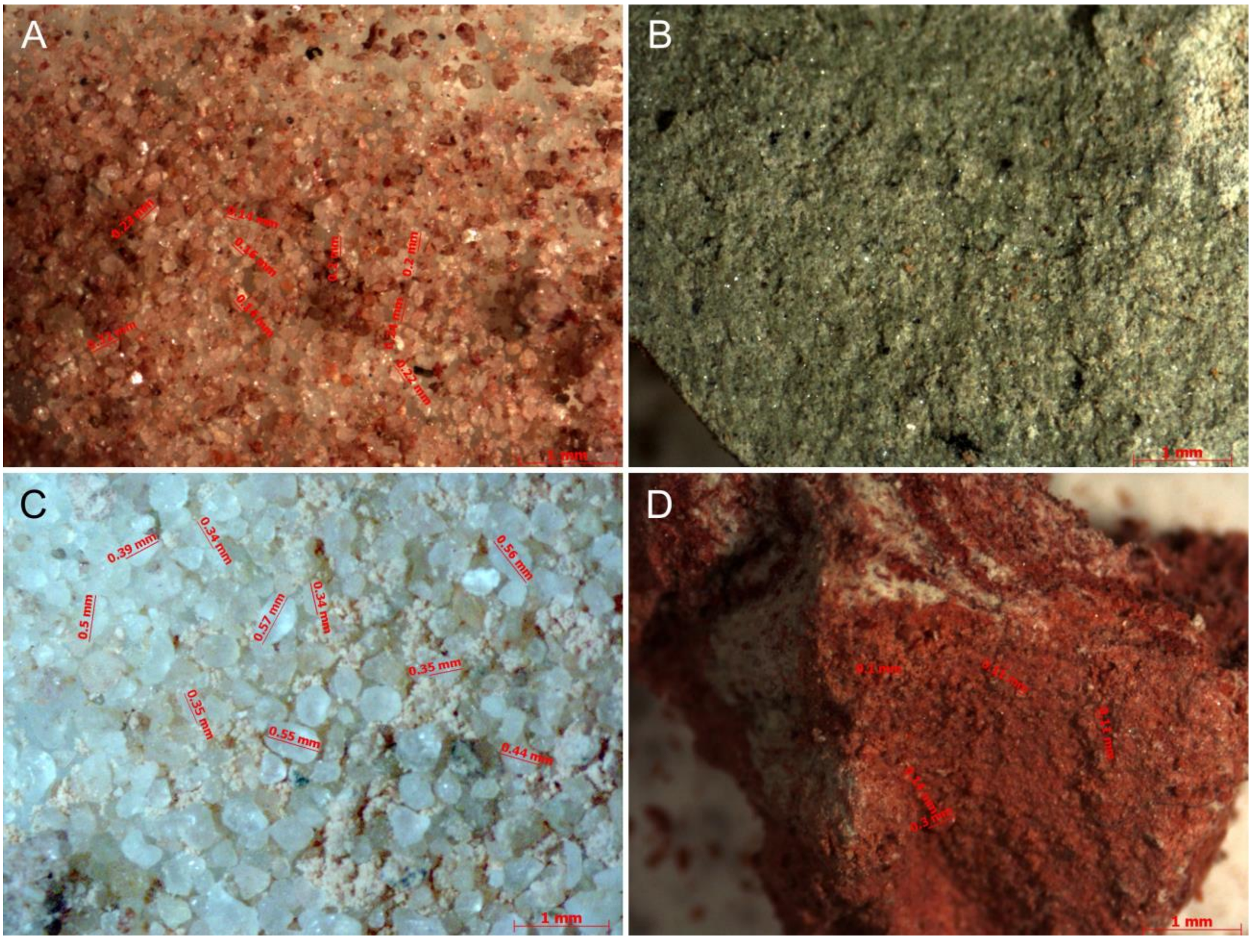

Fig. 11. Borehole cuttings returns from well KB-502 (Fig. 9) that are representative of the two Lower Cretaceous formations recognised in this study. (A) Loose, fine-grained, commonly subangular, quartz grains (sample depth=700 m) and (B) grey micaeous mudstone (sample depth=720 m) from the In Salah Formation. (C) Loose, translucent, very well rounded and frosted medium- to coarse-quartz grains (sample depth=420 m) and (D) brick red mustones with grey silt-size quartz (sample depth=480 m) from the Krechba Formation.

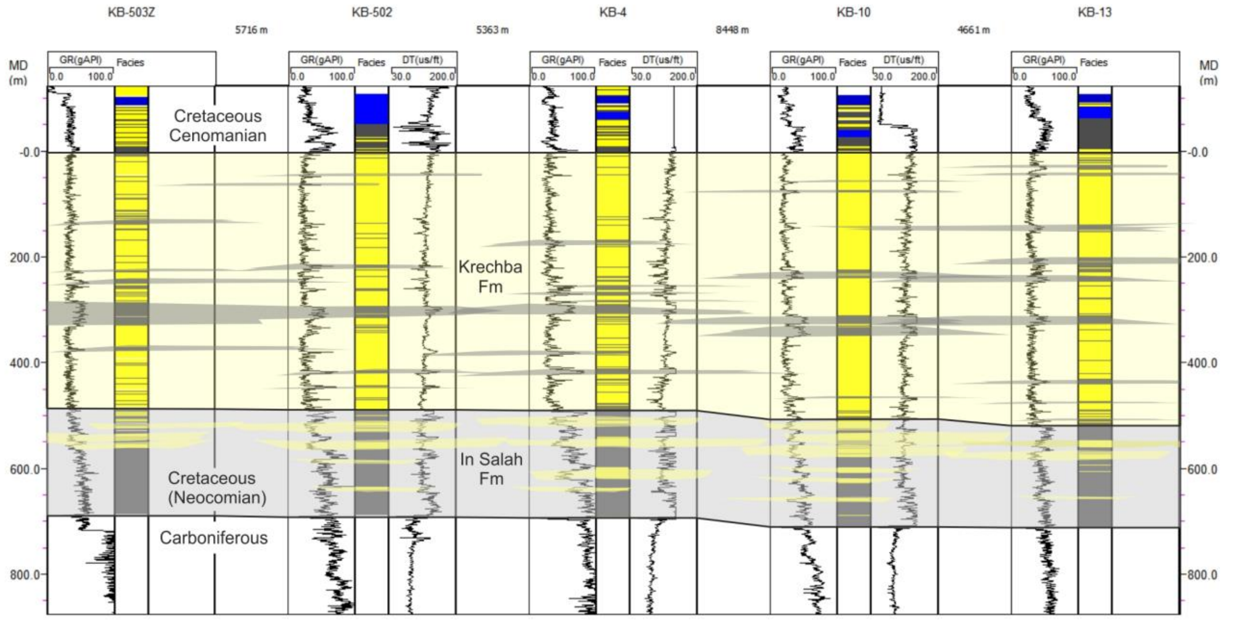

Fig. 12. Well correlation panel (see Fig. 8 for location) showing the consistency in the thickness and geophysical log character of the In Salah and Krechba formations across an approximately 20 km north-south transect of the Krechba gas field. Lateral extrapolations of the major mudstone (grey) and sandstone (yellow) intervals within each well (width is constrained to some extent by 3D seismic) are used to give an impression (or conceptual model) of the likely stratigraphic architecture of the two formations. Note increasing thickness and amalgamation of channel sandstone bodies toward the top of the In Salah Formation and the possibility of a relatively continuous belt of mudstone toward the middle of the Krechba Formation.

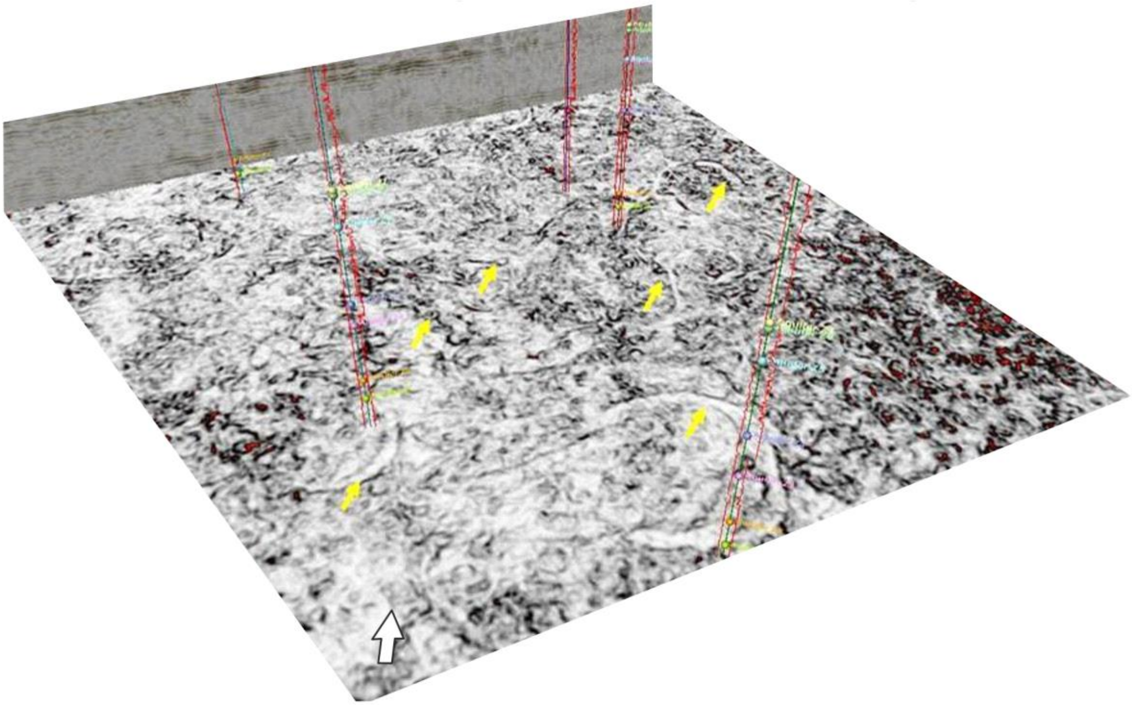

Fig. 13. Time slice of the 3D seismic coherency cube in the central part of the In Salah Formation showing an abundance of meandering channels (arrowed) of various dimensions.

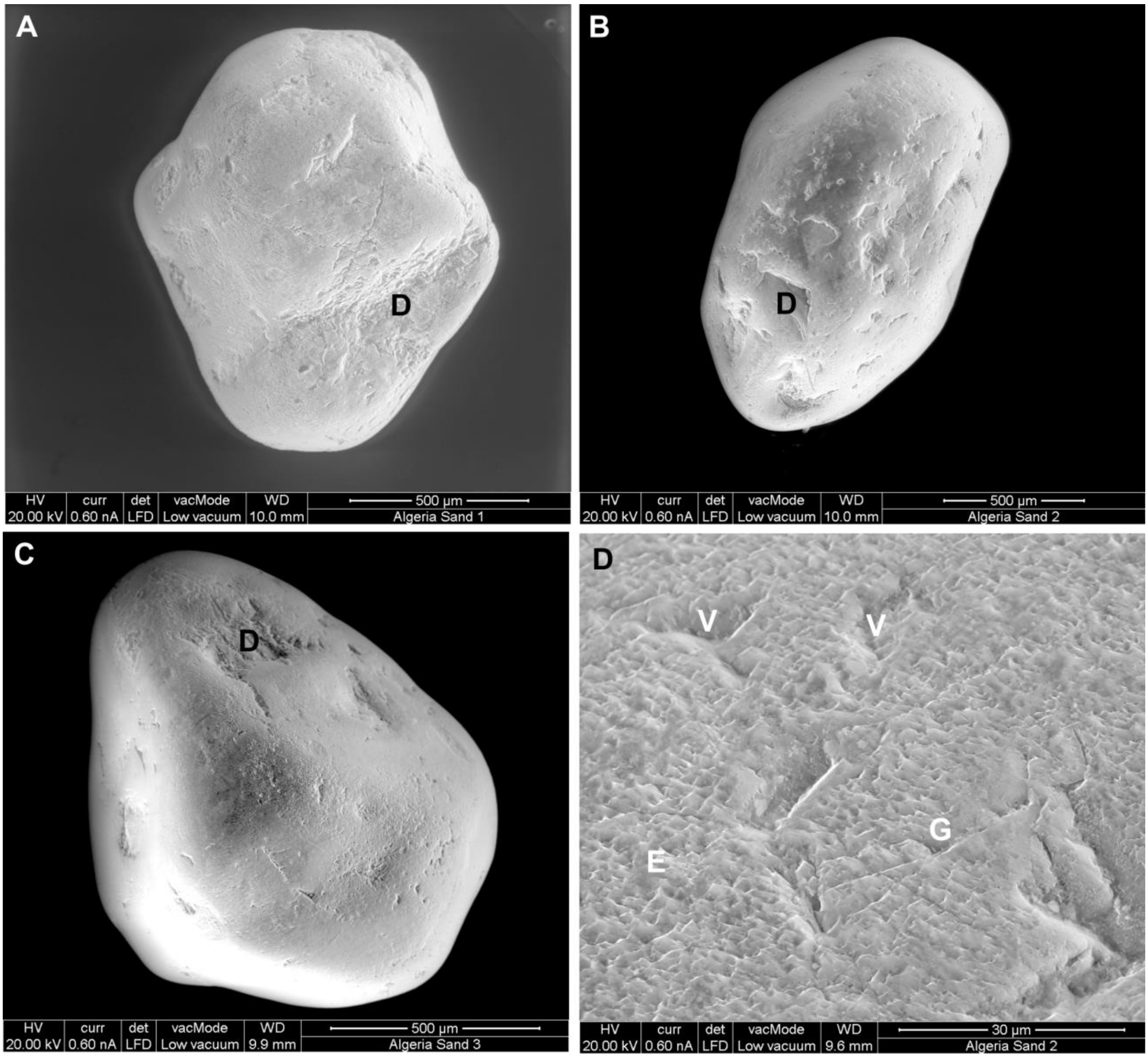

Fig. 14. SEM images of quartz sand grains from the Krechba Formation, (a-c) Quartz grains showing strong rounding with low relief, bulbous edges and equidimensional or elongate depressions (D), (d) Grain surface exhibiting several V-shaped impact marks (V), grooves (G) and extensive dissolution etching (E) along crystallographic orientations.

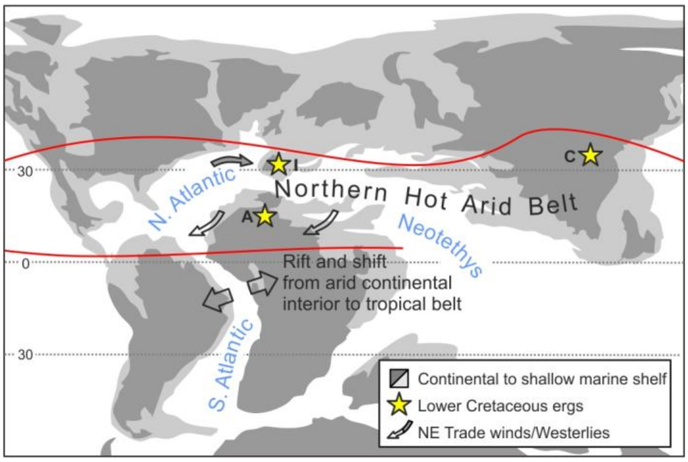

Fig. 15. Middle Cretaceous palaeogeography (generalised from Blakey (2011)) showing the position of the northern hot arid belt and major wind directions around western Neotethys (modified from Rodríguez-López et al. (2008)). Yellow stars show the approximate location of Krechba in Algeria (A) relative to major aeolian ergs of comparable age in the Iberian Range of NE Spain (I) and China (C).

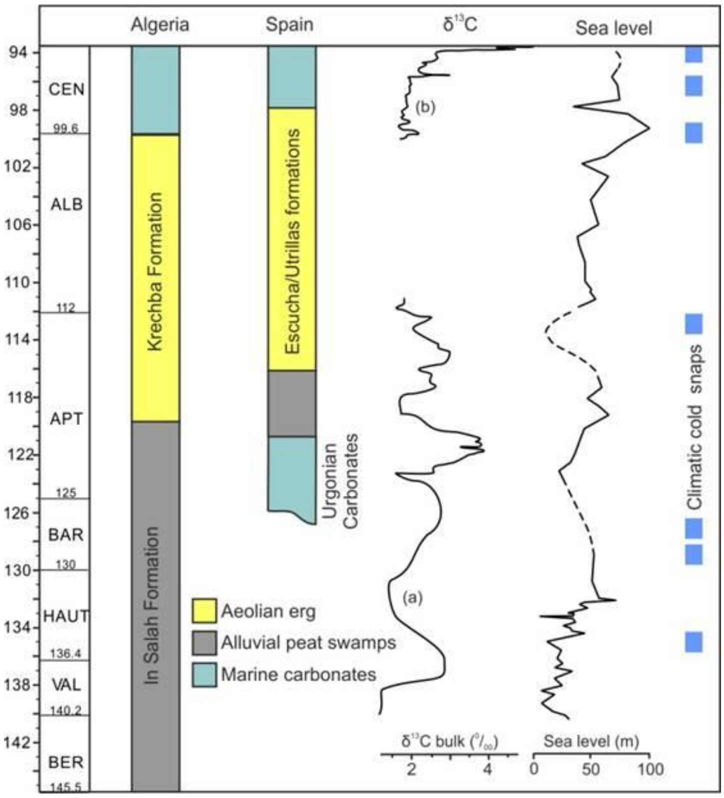

Fig. 16. Generalised Early Cretaceous stratigraphy at Krechba in Algeria compared with the upper part of the Early Cretaceous in the Iberian Range of NE Spain (Rodríguez-López et al., 2008). Both successions

feature the transition from coal-bearing alluvial swamps to a major coastal erg system in the Aptian and Albian (correlation to time-scale should be regarded as very approximate). Timescale and curves (modified from Hu et al., (2012)) showing d13C of bulk rocks (a=(Föllmi et al., 2006) b=(Herrle et al., 2015), (c) global sea level relative to present (Sahagian et al., 1996) and (d) late Aptian to early Albian cold snap (McAnena et al., 2013). Development of aeolian ergs may be related to climate cooling and a global fall in sea-level together with shifts in the arid-zone caused by the linkage of the South and North Atlantic (Rodríguez-López et al., 2006).