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Coastal salina evaporites of the Triassic-Liassic boundary in the Iberian Peninsula: the Alacón borehole

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ABSTRACT

The evaporite unit (the Lécera Formation), which was formed at the Triassic–Liassic boundary in the Aragonian Branch of the Iberian Chain, was studied at the 01 Alacón borehole (Alacón village, Teruel province), where it is mainly constituted by a thick (>300 m) succession of predominant sulphates (anhydrite, secondary gypsum and carbonate) overlain by brecciated carbonates. In the evaporite succession, a number of lithofacies were recognized, which can be grouped into an "ideal cycle", from base to top: (C1) massive to banded carbonate mudstone, (C2) alternation of carbonate and anhydrite laminae, (A1) alternation of anhydrite and carbonate bands, (A2) clastic intercalations in the alternation of anhydrite and carbonate bands, (A3) laminated to banded anhydrite, (A4) bedded pseudomorphs, (A5) interstitial pseudomorphs, and (A6) massive to nodular anhydrite. Fine-grained gypsum (anhydrite laminae and bands), bedded selenitic gypsum (bedded pseudomorphs), interstitial selenitic gypsum (interstitial pseudomorphs), and graded-nodular anhydrite (a particular fabric of nodular anhydrite) were the most outstanding depositional lithofacies. The evaporite succession exhibits a marked cyclicity: in the lower part the individual cycles are more similar to the ideal cycle and reflect deeper water settings, whereas in the upper part they correspond to shallower water settings. The evaporite sedimentation mainly occurred in a subsiding coastal basin of the salina or lagoon type. In this setting, the subaqueous precipitation of the carbonate and gypsum lithofacies was followed, in each cycle, by the interstitial growth of anhydrite in exposed conditions. As a whole, the evaporite succession reflects an infilling process. The conversion into anhydrite of the selenitic gypsum -probably also of the rest of depositional gypsum lithofacies-started under synsedimentary conditions and followed during shallow to moderate burial diagenesis.

KEYWORDS **Evaporites. Anhydrite. Salina. Triassic-Liassic boundary. Iberian Chain.**

INTRODUCTION

Evaporite deposits are common at the Triassic–Liassic boundary in the Iberian Peninsula. These deposits overlie the carbonates of the Imón Formation (of Rhaetian age; Goy and Yébenes, 1977; Arnal et al., 2002) and underlie the carbonates of the Cortes de Tajuña Formation (of Hettangian age; Goy et al., 1976) (Fig. 1).

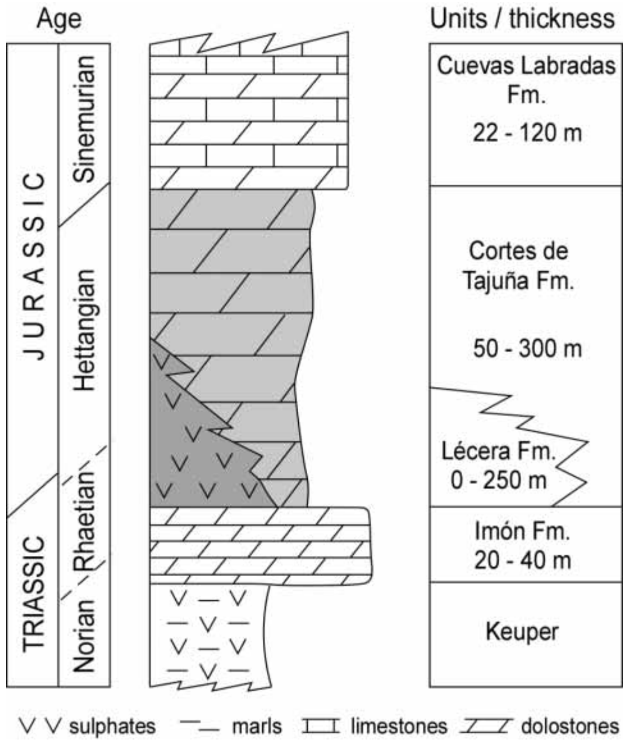

FIGURE 1 **Lithostratigraphic units of the Triassic-Liassic boundary in the Sierra de Arcos area (adapted from Bordonaba and Aurell, 2002, fig. 2).**

In outcrop, the evaporite deposits of the Triassic-Liassic boundary constitute a thick gypsiferous unit traditionally known as the "Rhaetian Gypsum". On the basis of borehole data, Castillo Herrador (1974) highlighted the importance of these transitional deposits, up to 800 m thick at the Carcelén borehole (Albacete province). This author assigned a Rhaetian-Hettangian age to these deposits and referred to them as the "Anhydrite Zone". Studying the available anhydrite samples of the Carcelén borehole, Ortí (1987) showed a predominance of nodular lithofacies. This author interpreted subsiding sabkhas as the depositional sites of these deposits, and termed them the "Carcelén Anhydrite". In some outcrops in Eastern Spain, Pérez López et al. (1996) confirmed a Rhaetian age for the lowermost part of the Carcelén Anhydrite. Utrilla et al. (1992) and Ortí et al. (1996) contributed geochemical data and demonstrated a marine supply for the sulphate in these evaporites.

The study of some outcrops in the Sierra de Arcos (the boundary between the Zaragoza and Teruel provinces), in the Iberian Chain, led Gómez and Goy (1998) to propose the new name "Lécera Carbonate, Anhydrite and Gypsum Formation" for this unit (Fig. 2). These authors noted the laminated to massive character of the gypsum rocks in this area. More recently, the study of both outcrops and drill samples in the same area allowed Bordonaba and Aurell (2002), and Bordonaba (2003) to characterize the laminated, massive and nodular facies for the gypsum and anhydrite rocks constituting the Lécera Formation. These authors interpreted a tidal flat complex (intertidal zone and sabkhas) for this evaporitic precipitation.

This paper offers new insights into the Ca-sulphate lithofacies at one of the boreholes recently drilled in the Sierra de Arcos in order to better understand the sedimentary environments in northeastern Iberia during the Triassic-Liassic boundary, and the diagenetic processes undergone by these evaporites.

MATERIALS AND METHODS

The exploratory 01 Alacón borehole, drilled by the *Confederación Hidrográfica del Ebro* (C.H.E.) in 2002 for hydrogeological purposes, is located at 2 km to the NE of the Alacón village (Teruel province), near the

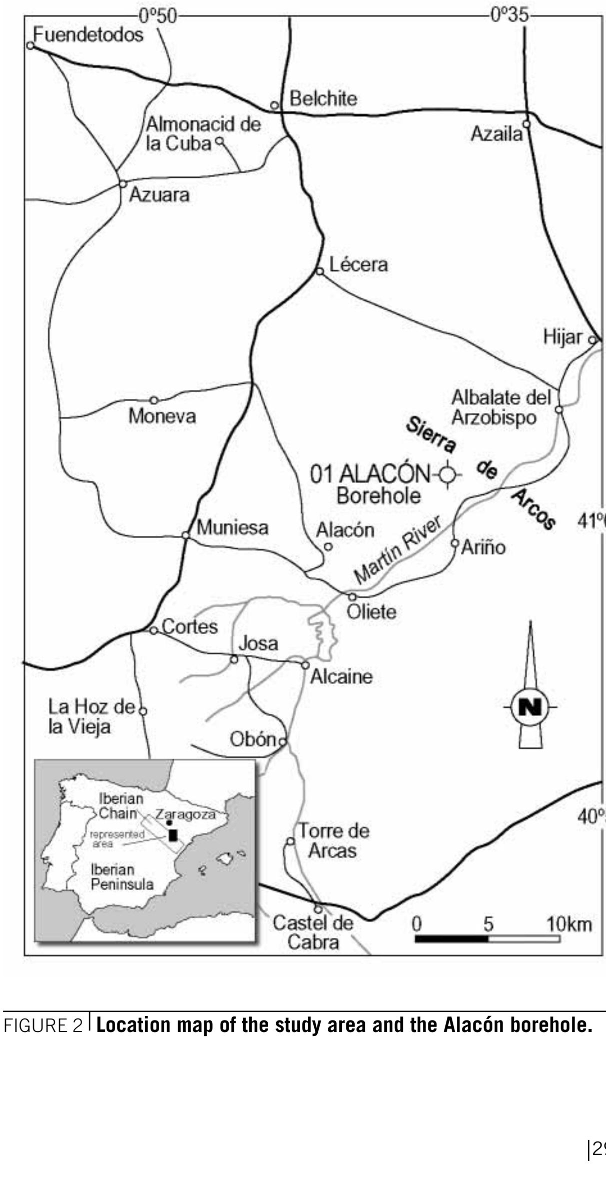

FIGURE 2 **Location map of the study area and the Alacón borehole.**

Muniesa-Lécera area (Fig. 2). This borehole records more than 800 m of Jurassic materials overlying the dolomitic layers of the Imón Formation at the base (Bordonaba, 2003). The deeper half of the borehole log (below 485 m) corresponds to the carbonate-sulphate assemblage of the Lécera Formation (Fig. 3). The carbonates of the Cortes de Tajuña Formation and other younger Jurassic units overlie this assemblage (between 485 m deep and the surface).

At the Alacón borehole, the Lécera Formation can be subdivided into a lower and an upper part. About 250 m of predominant anhydrite rock with subordinate carbonate is present in the thick, lower part (between 815 and 564 m deep). In contrast, the thin upper part is composed of predominant carbonate rock and interlayered gypsum beds (between 564 and 485 m deep).

For this study, 135 samples of sulphate and carbonate rocks of the Alacón borehole succession were selected in the depth interval ranging between 815 and 454 m. These samples have lengths between few centimetres and 90 cm, averaging 35 cm, and diameters of 36 mm and 47 mm. A number of these samples were cut vertically into two parts; one part was polished and the other was destined for powdered fractions for XR diffraction analysis and thin sections. The study is mainly focused on the sulphate lithofacies. Additional mineralogical and geochemical data of the carbonates present at this borehole are found in Bordonoba (2003).

FACIES ANALYSIS

The facies of the samples present at the Alacón borehole can be classified into three groups: carbonate, anhydrite and gypsum lithofacies. We use the following bedding terms throughout the paper: fine laminae (<1 mm thick); laminae (1 mm to 1 cm thick); bands (1 cm to 1 dm thick); and beds (>1 dm thick). Anhydrite is fine-grained and composed of prismatic (laths) textures and granular (equant crystals) textures. Carbonate usually has a micritic texture and a dolomitic mineralogy (dolomicrite).

Carbonate lithofacies

C1- Massive to banded carbonate mudstone

Massive mudstone and laminated to banded mudstone are the most common carbonate lithofacies (Fig. 4A). In general, burrowing is absent and no organic remains are embedded within these carbonate mudstones. Limited amount of anhydrite is present as fine laminae, small nodules and replacive porphyroblasts -equant crystals of about 1 mm in length-, either isolated or grouped along the bedding planes (Fig. 4B).

C2- Alternation of carbonate and anhydrite laminae

This is an irregular alternation of carbonate laminae and anhydrite laminae, where the thickness of each lamina oscillates from <1 mm to few mm, being less than 1 cm, in general. The lamination can be even or deformed

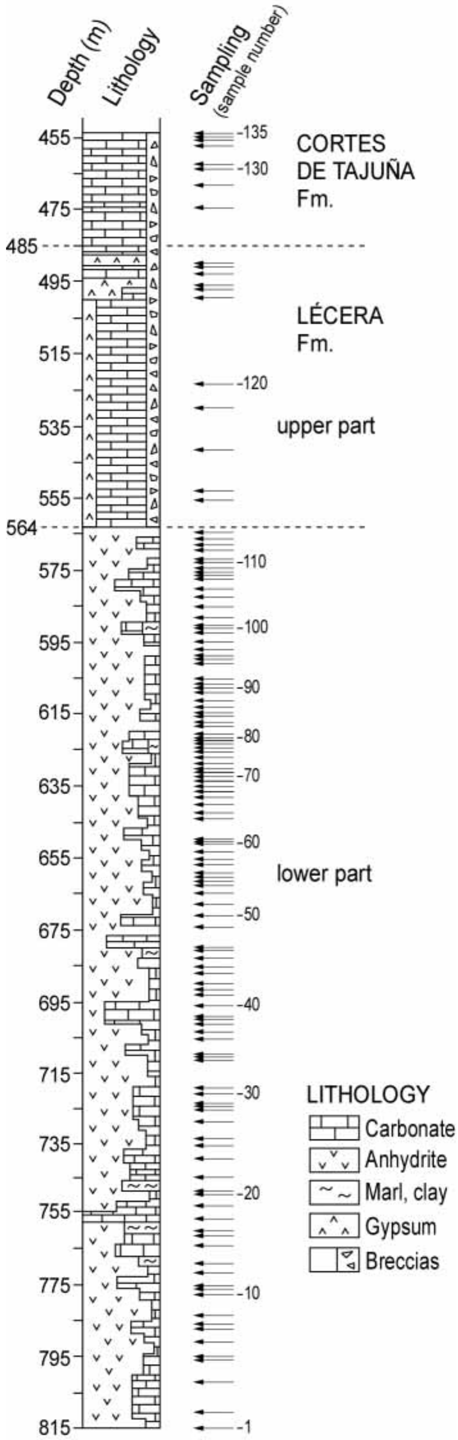

FIGURE 3 | **Simplified lithologic log of the Lécera Formation at the Alacón borehole, and sampling carried out for this work.**

to several degrees, and small ripples are present locally (Fig. 4C). The relative proportion between carbonate and anhydrite is variable, although carbonate usually predominates. Petrographically, the presence of anhydrite pseudomorphs after fine-grained gypsum crystals is common. Very few samples at the base of the borehole succession display clayey, dark laminae within this alternation; these laminae appear to be rich in organic matter.

Interpretation of the carbonate lithofacies

The massive to banded carbonate mudstone (C1), where burrowing is absent and the anhydrite content is very low, can be assigned to sedimentation in restricted lagoons. Two interpretations can be proposed for the alternation of carbonate and anhydrite laminae (C2): a) intertidal facies. The very few samples characterized by dark laminae at the base of the succession resemble the algal mats present in the intertidal belts of the evaporitic environments. However, diagnostic features characterizing this setting, such as crenulation or domatic morphology in the lamination and remains of microbial filaments were not clearly recognized; b) subtidal facies. In the rest of the samples, many of the deformational features affecting this alternation can be attributed to compaction of a soft (unlithified) sediment formed in a shallow, subtidal setting. In this setting, the original alternation of carbonate laminae and fine-grained gypsum laminae suggests fluctuating conditions of precipitation.

Anhydrite lithofacies

A1- Alternation of anhydrite and carbonate bands

This is an irregular alternation of anhydrite bands and carbonate bands, where the anhydrite bands predominate (Fig. 5A). The individual thickness of these bands oscillates between one and some cm, and rarely exceeds 10 cm. The carbonate band, made up of massive to poorly laminated mudstone, is commonly thinner than the anhydrite band. Planar bedding is rare and, more frequently, bedding is irregular, diffuse or deformed. Gradations between this lithofacies and the alternation of carbonate and anhydrite laminae (C2) were observed.

A2- Clastic intercalations within the alternation of anhydrite and carbonate bands

Locally, the A1 alternation shows clast-supported intercalations of anhydritic particles with sizes ranging between 1 mm and 1 cm, which resemble clastic accumulations (Fig. 5B). On closer inspection, many anhydritic particles are pseudomorphs after precursor crystals, whereas others correspond to small fragments of broken

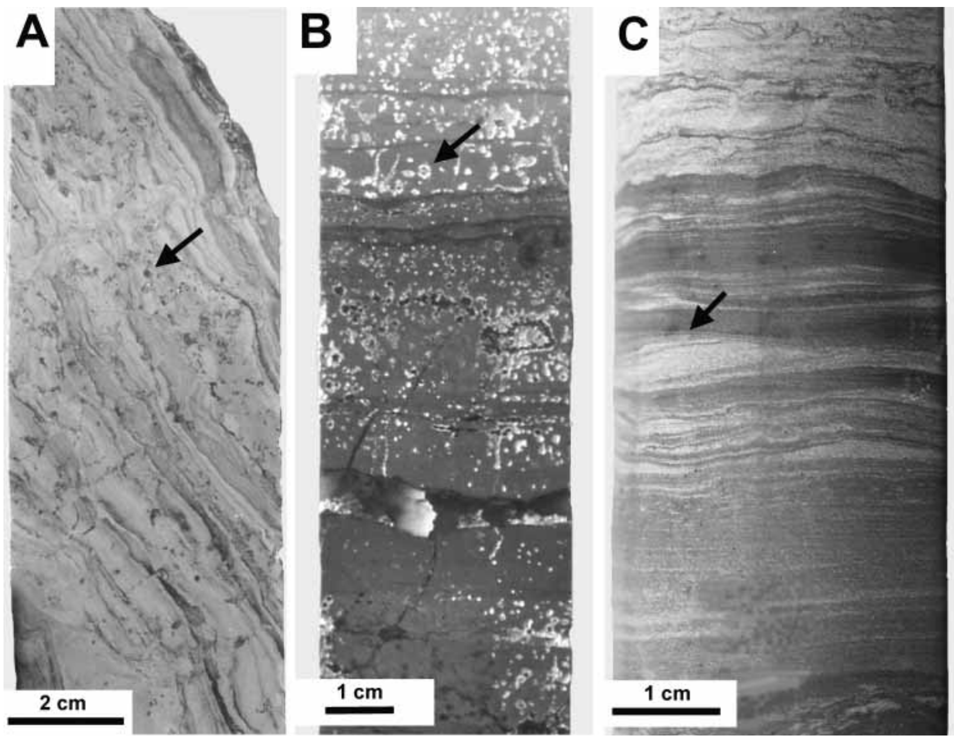

FIGURE 4 | **Carbonate lithofacies. A) Laminated carbonate mudstone. Some laminae are slightly deformed and broken. Dark points correspond to millimetre-sized porphyroblasts of replacive anhydrite (arrow); sample at 468 m depth. B) Massive to banded carbonate mudstone. Abundant anhydrite porphyroblasts (light points; arrow) can be observed; sample at 756.30 m depth. C) Alternation of carbonate laminae (dark) and anhydrite laminae (light). Some ripples (arrow) are present; sample at 749.2 m depth.**

laminae and bands (intraclasts). These intercalations have a thickness of few centimetres (<10 cm, in general), contain carbonate matrix surrounding the pseudomorphs, and exhibit irregular or erosive bases.

A3- Laminated to banded anhydrite

This lithofacies is made up of laminae and bands of anhydrite, with scarce carbonate matrix. The individual bands attain a thickness of a few centimetres (Fig. 5C). Locally, small particles resembling intraclasts or micronodules were observed. Under the microscope, many of these particles were identified as pseudomorphs after small gypsum crystals.

A4- Bedded pseudomorphs

This lithofacies consists of banded to bedded, vertically elongate anhydrite individuals (palisade fabric), suggesting a pseudomorphic origin after precursor evaporite crystals. The pseudomorphs are 1 to 6 cm long and 0,5 to 2 cm wide, and vestiges of twinning were not observed in them (Fig. 6A). Locally the pseudomorphs display truncated tops (Fig. 6B). The carbonate matrix is scarce and preferentially accumulated along the bedding planes. Bending or other deformation structures in the pseudomorphs are frequent, as are sutured boundaries between adjacent individuals; locally, the marked deformation suggests a plastic behaviour of the pseudomorphs (Figs. 6B and 6C). In this lithofacies, a number of upward gradations were observed: (a) from the palisade fabric to other arrangements (oblique to bedding, subhorizontal, random); (b) from the crystal pseudomorphs to nodular morphologies; and (c) from bedded to interstitial pseudomorphs (see below).

A5- Interstitial pseudomorphs

At first sight, this lithofacies appears to be a massive accumulation of anhydritic "clasts" embedded within abundant carbonate matrix (Fig. 7). On closer inspection, however, the clast-like anhydrite masses are identified as pseudomorphs after evaporite crystals. The geometry of these pseudomorphs is less elongate and more equant and thicker than in the palisade fabric; the orientation is variable, from random to subhorizontal or oblique to bedding. The size of the pseudomorphs can decrease upward in some samples. Many of these pseudomorphs display a plastic deformation (Fig. 7A) and sutured boundaries

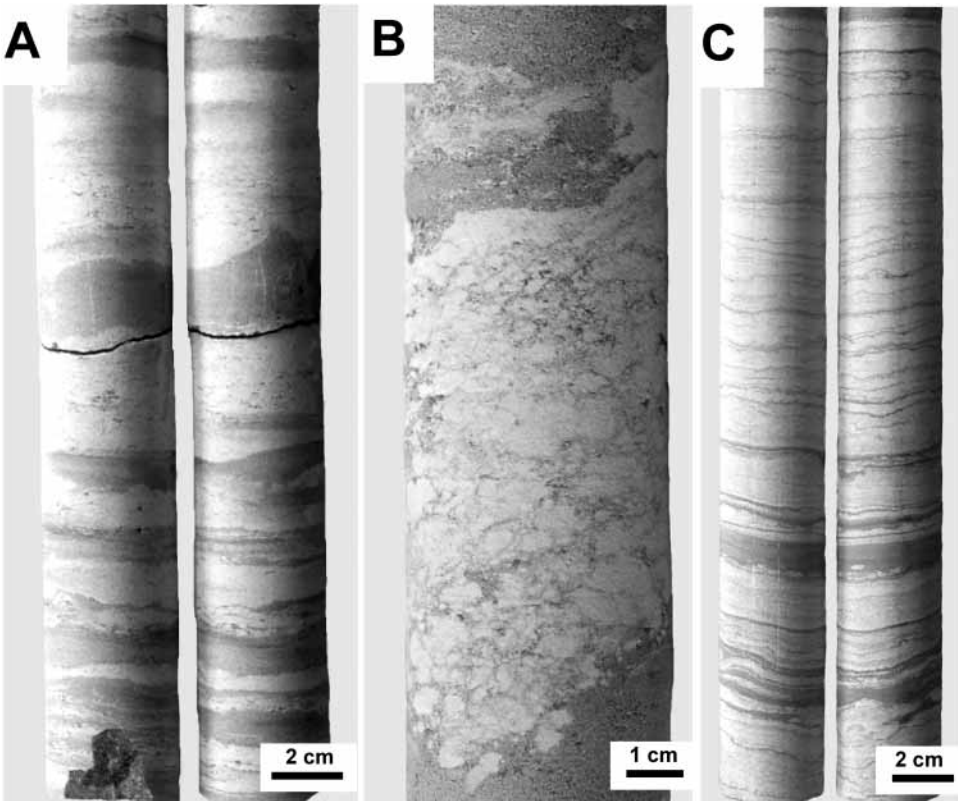

FIGURE 5 **Lithofacies of carbonate and anhydrite. A) Alternation of anhydrite (light) and carbonate (dark) bands; sample at 619.60 m depth. B) Detail of a clastic intercalation (currently anhydritic pseudomorphs or clasts) within the alternation of carbonate and anhydrite bands. Dark material at the top and the base of the intercalation is carbonate; sample at 579.6 m depth. C) Laminated to banded anhydrite (light). Dark material is carbonate laminae; sample at 724.75 m depth.**

(Fig. 7B). Upward gradation from the pseudomorphic morphology to nodular shapes is common in this lithofacies.

A6- Massive to nodular anhydrite

This general term is used here for a number of anhydrite lithofacies present in the samples, which exhibit mutual gradations between them. *Massive anhydrite*: this lithofacies consists of beds up to >1 m thick, where the anhydrite texture is microcrystalline and very pure. In detail, however, the presence of diffuse films of carbonate matrix suggests the existence of poorly-defined nodular to irregular masses, ranging from 1 to 10 cm in length (Fig. 8A). In many samples, this lithofacies grades upward to better defined nodular forms. *Nodular anhydrite*: this lithofacies is composed of nodules with variable morphologies, which occur either isolated or arranged in mosaic (chicken-wire) patterns. These mosaics, however, never develop a sutured geometry in the boundaries between the nodules. The diameter of the nodules oscillates from few millimetres to some centimetres, and the carbonate matrix is scarce. *Banded-nodular anhydrite*: bands, and also beds up to 15 cm thick composed of anhydrite nodules are found in some samples, where the carbonate matrix forms thin levels separating the nodular bands. The diameter of the nodules oscillates between 1 and 5 cm, and is rarely <1cm. The presence of enterolithic (contorted) layers of nodular anhydrite was not observed. *Graded-nodular anhydrite*: in this lithofacies, the size of the nodules decreases upward, from some centimetres at the base to <0,5 cm at the top, and the nodules are often slightly flattened (Figs. 8B and 8C). The thickness of the anhydrite levels displaying this lithofacies varies from 10 to 30 cm. An upward transition from massive anhydrite at the base to graded-nodular anhydrite at the top was observed in many samples.

Interpretation of the anhydrite lithofacies

In the A1 and A3 lithofacies, where anhydrite pseudomorphs after precursor gypsum can be observed petrographically and no vestiges of transport were found, the various types of anhydrite laminae and bands can be interpreted as precursor gypsum deposits composed of small-sized crystals. As in C2 lithofacies, the original alternation of gypsum and carbonate bands (lithofacies A1) suggests fluctuating conditions of precipitation on a shallow depositional floor.

The intercalations exhibiting a clastic appearance (lithofacies A2) –bearing pseudomorphs of small crystals and coarser-sized clasts– reflect the reworking of the original gypsum crystals and broken fragments of gypsum laminae and bands.

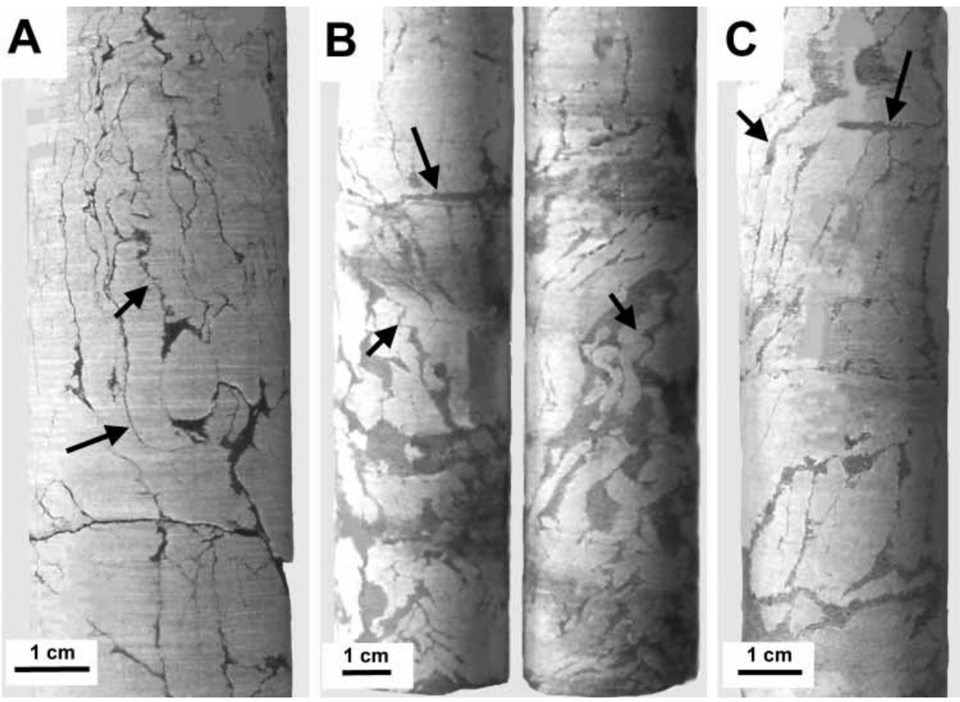

FIGURE 6 **Anhydrite lithofacies: bedded pseudomorphs. A) Bedded pseudomorphs (after selenitic gypsum) displaying a palisade fabric. Carbonate matrix (dark material) is scarce. Plastic deformation (long arrow) and sutured contacts between the pseudomorhs (short arrow) are seen; sample at 699.80 m depth. B) and C) Details of the bedded pseudomorphs. Carbonate matrix (dark material) is abundant locally. The deformation of the pseudomorphs (short arrows) is noticeable. Dissolution features at the top of some pseudomorphs (long arrow) can be observed; samples at 711 m depth.**

In the laminated to banded anhydrite lithofacies (A3), the micronodular texture of anhydrite present locally could be assigned, *a priori*, to interstitial precipitation in a supratidal (sabkha) setting. However, the banding appears to be too regular for such an interpretation. We assume that (1) the precursor fine-grained gypsum in the laminae and bands was formed subaqueously in a shallow, subtidal setting, and (2) the micronodular textures were formed during the subsequent diagenetic transformation of the gypsum crystals into anhydrite (see below).

The bedded pseudomorphs (lithofacies A4) presumably correspond to gypsum selenites. At present, such crystals are known to grow subaqueously with competitive fabrics on shallow depositional floors (Warren, 1982). The flat tops of the pseudomorphs correspond to erosion/dissolution features which formed during the dilution of the brine. A number of factors can account for the oblique, subhorizontal or random arrangements of the selenites: original growth fabrics, mechanical compaction, and some reworking. Similar details were described for the selenite fabrics in the Messinian evaporites in Spain (Ortí and Shearman, 1977).

The interstitial pseudomorphs (lithofacies A5), rich in carbonate matrix, with randomly or weakly oriented fabric suggest a non-competitive growth within the matrix and a very shallow-water setting. An interstitial growth under subaerial conditions cannot be disregarded for the selenites, although no evidence of exposure was found.

Some of the aforementioned massive to nodular anhydrite lithofacies (A6) were formed in exposed conditions as in the case of the recent anhydrite in the supratidal flats of the Persian Gulf (Shearman, 1966). However, the absence of enterolithic layers in the samples (a typical feature of the vadose-capillary zone), suggests that for some nodular growths other different settings cannot be ruled out. This could be the case of some upward gradations of (pseudomorphic) selenitic morphologies into nodular geometries (see below). On the other hand, a satisfactory explanation for the graded-nodular anhydrite lithofacies –a particular fabric which to our knowledge has not yet been described in the sabkha setting- cannot be offered. In this lithofacies there is no evidence of an origin by replacement of a precursor fabric of graded selenites. Presumably, this lithofacies was formed in the sabkha environment at the top of the phreatic zone under the control of a salinity gradient (an upward increase of concentration) in the brine.

Occurrence of gypsum and brecciated lithofacies

Gypsum

The gypsum rocks above a depth of 564 m at the Alacón borehole consist of secondary gypsum derived

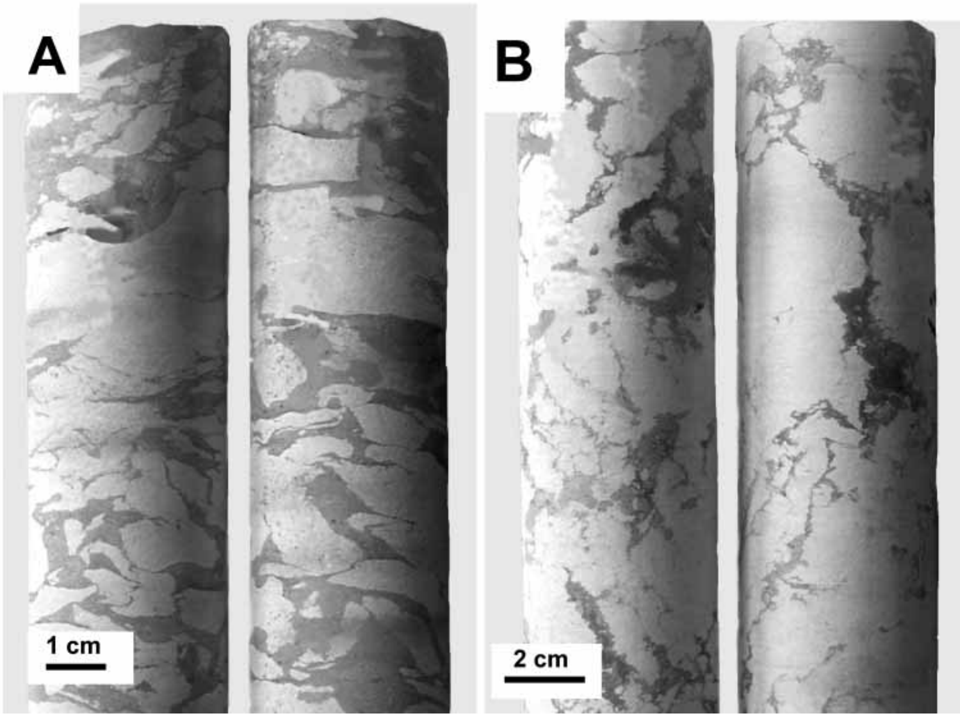

FIGURE 7| **Anhydrite lithofacies: interstitial pseudomorphs. A) Interstitial pseudomorphs (after selenitic gypsum) with abundant carbonate matrix (dark material). Plastic deformational features in the pseudomorphs can be seen; sample at 640.10 m depth. B) Interstitial pseudomorphs. Dark material is carbonate matrix. Sutured boundaries and plastic deformation in the pseudomorphs can be observed; sample at 598.40 m depth.**

from anhydrite hydration by the action of meteoric groundwater. It is very probable that this occurred in recent times. The most common lithofacies –inherited from the anhydrite– are laminated to banded gypsum, and massive to nodular gypsum. Pseudomorphic lithofacies were not observed.

Carbonate breccias

This lithofacies, which is present at the borehole above a depth of 560 m (Fig. 3), consists of brecciated, dolomitic masses up to some metres thick. Dolomitic clasts up to 10 cm in length are irregularly distributed in this lithofacies (Fig. 9A). Gradations between these breccias and undisturbed carbonate mudstones were observed (Fig. 9B). In some samples, the presence of secondary gypsum clasts was also recorded as well as fibrous gypsum veins cementing the dolomitic clasts. A late diagenetic origin because of anhydrite dissolution during the exhumation is proposed for this lithofacies.

Carbonate-anhydrite breccias

Below a depth of 560 m, the presence of thin levels made up of carbonate-anhydrite breccias intercalated into the other lithofacies is infrequent. In these scarce levels, the anhydrite clasts display a number of morphologies such as angular clasts, nodules, and pseudomorphs. The carbonate clasts may exhibit soft sediment deformation (Fig. 9C) suggesting unlithified sediment conditions at the time of brecciation. A synsedimentary origin because of early exposure and associated dissolution of gypsum/anhydrite is proposed for this lithofacies.

EVAPORITE CYCLICITY

In the interval studied at the Alacón borehole, a number of patterns of lithofacies arrangement were observed. These patterns clearly reflect the existence of cycles (Fig. 10A). Only one type of these cycles seem to represent a sabkha succession in a carbonate-sulphate tidal complex (Fig. 10Aa). The rest exhibit shallowing

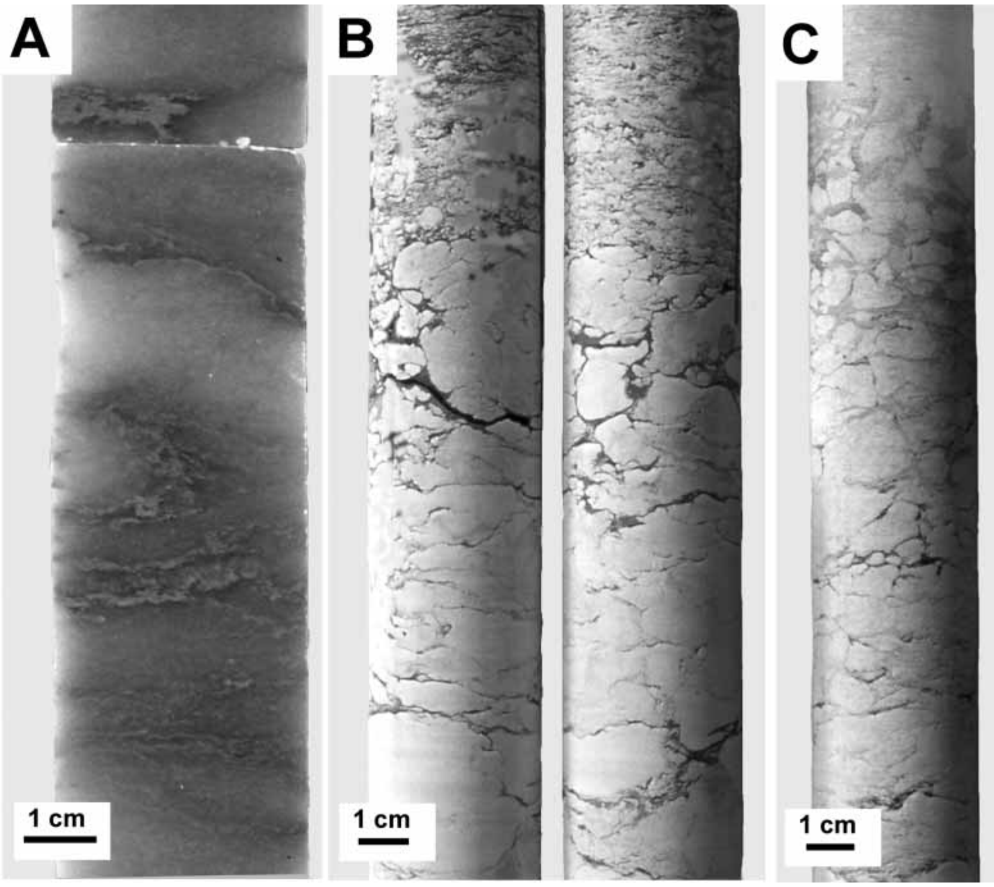

FIGURE 8 **Massive to nodular anhydrite lithofacies. A) Massive anhydrite. The distribution of the scarce carbonate matrix (dark material) suggests a diffuse, nodular structure. Polished speciment; sample at 692.8 m depth. B) Graded-nodular anhydrite. The size of the anhydrite nodules decreases upward. Some compaction features (flattened nodules) are present; sample at 795.1 m depth. C) Graded-nodular anhydrite. The size of the nodules decreases upward. Dark material at the top is carbonate; sample at 719.0 m depth.**

upward successions originally involving gypsum precipitated subaqueously: fine-grained gypsum (banded anhydrite) grading to nodular anhydrite (Fig. 10Ab); bedded selenites (bedded pseudomorphs) grading to nodular anhydrite (Fig. 10Ac); and interstitial selenites (interstitial pseudomorphs) grading to nodular anhydrite (Fig. 10Ad).

Taking these cycles together, an "ideal" cycle for the Lécera Formation at the Alacón borehole can be proposed, which would comprise up to eight lithofacies (Fig. 10B). We assume that this is a shallowing upward cycle. Along the lithologic log, the presence of 35 individual cycles, with an average thickness of about 7 m, was deduced (Fig. 11). Some of these cycles, however, are just irregular alternations and only contain two or three lithofacies. Other cycles are better developed and involve up to four or five lithofacies; these latter cycles would represent a closer approximation to the ideal cycle.

A distinction between a lower cyclic assemblage and an upper cyclic assemblage can be made (Fig. 11). The lower assemblage is composed of individual cycles (1 to 18) with a total thickness of 146 m and an average cycle thickness of 8.1 m. This assemblage is characterized by cycles beginning with carbonate lithofacies, followed by fine-grained gypsum and bedded selenites, and ending with massive to nodular anhydrite at the top. In general, the anhydrite tops are not very thick and may display graded-nodular lithofacies. Cycles 16 to 18 represent a gradual transition to the upper assemblage.

The upper cyclic assemblage is made up of individual cycles (19 to 35) with a total thickness of 102 m and an average cycle thickness of 6.0 m. This assemblage is characterized by cycles with few carbonate lithofacies, an absence of laminated to banded fine-grained gypsum, and by a predominance of interstitial selenites. In these cycles, the clastic intercalations in the alternation of anhydrite and carbonate bands (lithofacies A1) is also common. At the top of this assemblage, thick lithofacies of nodular anhydrite develop, especially in the uppermost cycles.

ANHYDRITIZATION PATTERN

The massive to nodular anhydrite forming the top of the cycles was interpreted as having been formed under synsedimentary, sabkha conditions. However, the conversion of the original gypsum lithofacies (fine-grained gypsum laminae and bands, clastic intercalations, and selenites) into anhydrite reflects more complex processes.

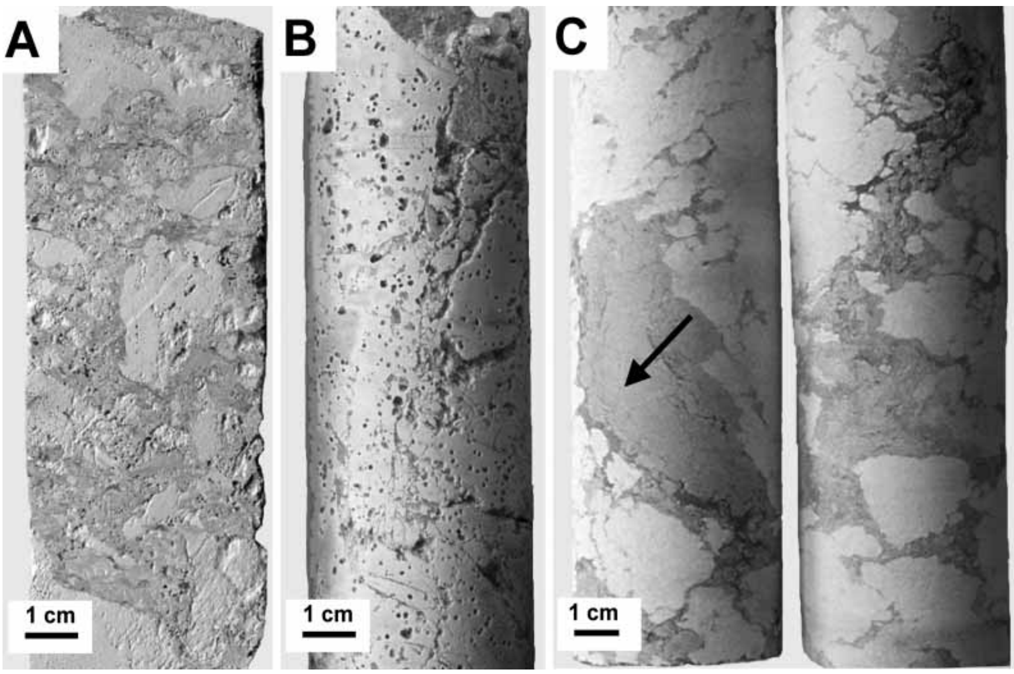

FIGURE 9 **Brecciated lithofacies. A) Carbonate breccia: dolomitic clasts are embedded in fine-grained, marly matrix; sample at 553 m depth. B) Incipient brecciation (right half) in massive (left half) carbonate mudstone. Dark points correspond to millimetre-sized porphyroblasts of secondary gypsum derived from the hydration of precursor anhydrite porphyroblasts; sample at 541.60 m depth. C) Carbonate-anhydrite breccia. Carbonate clasts (dark) show soft sediment deformation (arrow). Anhydrite clasts (light) derive partly from nodules (lower part) and partly from brecciated masses of interstitial pseudomorphs (left, upper part); sample at 593.30 m depth.**

Anhydritization from early diagenesis to moderate burial diagenesis

Two aspects of interpretative significance emerge from the observation of the pseudomorphic lithofacies (A4 and A5): (1) the plastic deformation of the selenites took place within a soft (unlithified) carbonate matrix (Figs. 6 and 7), and (2) the progressive, upward gradation from geometric (pseudomorphic) to nodular morphologies apparently occurred as a continuous process. As regards the first aspect, the plastic deformation of the pseudomorphs, especially in the palisade fabric, can be assigned to the gypsum-to-anhydrite conversion involving a decrease in volume, a plastic (unlithified) behaviour of the selenites when altered into fine-grained anhydrite, and a burial depth that would be sufficient to cause the marked deformation of the pseudomorphs by compaction. Despite the fact that the plastic behavior of the selenites during their alteration to anhydrite is compatible with early diagenesis, the marked deformation recorded in the pseudomorphs suggests shallow to moderate burial conditions of the deposit. As for the second aspect, it is highly likely that, during the conversion into anhydrite, the selenites also acted as a nucleus for progressive anhydrite precipitation with the result that some of the original shapes changed into nodular morphologies. It is worth noting that, in the upward morphological gradation (pseudomorphic to nodular), sharp boundaries or erosive contacts were not observed as expected if subaerial exposure at the top of each cycle had been the main factor of the anhydritization process. All these observations suggest that the anhydritization of selenites was a continuous process which started under synsedimentary conditions in contact with sabkha brines, and continued during shallow to moderate burial in contact with interstitial, pore brines (Fig. 12). It does not seem likely that such a transformation occurred during deep burial diagenesis; in this case, a homogeneous anhydritization pattern, without significant textural grading, would have resulted. It is possible that this anhydritization pattern discussed for selenites applies to the other gypsum lithofacies.

Anhydritization from moderate to deep burial diagenesis

A case of late (burial) diagenetic anhydrite is represented by the porphyroblasts embedded in the massive to banded carbonate mudstone (lithofacies C1), which are distributed throughout the studied interval of the borehole without any cyclic control. These porphyroblasts always replace the dolomicritic texture. Presumably, they were

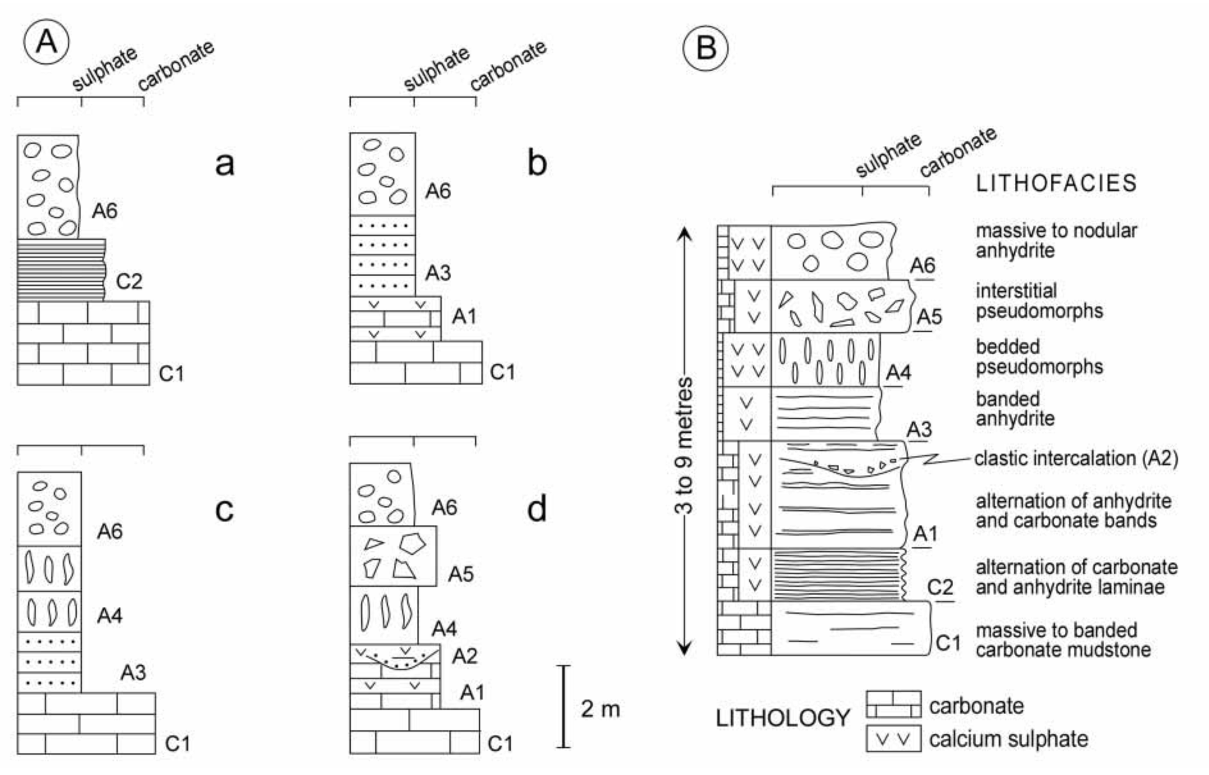

FIGURE 10 **Evaporitic cycles at the Alacón borehole. A) Individual cycles: a) sabkha cycle; b) fine-grained gypsum (laminated to banded anhydrite lithofacies) grading to nodular anhydrite; c) bedded selenites (bedded pseudomorphic lithofacies) grading to nodular anhydrite; d) interstitial selenites (interstitial pseudomorphic lithofacies) grading to nodular anhydrite. B) Evaporitic lithofacies succession of an ideal, shoaling upward, complete cycle.**

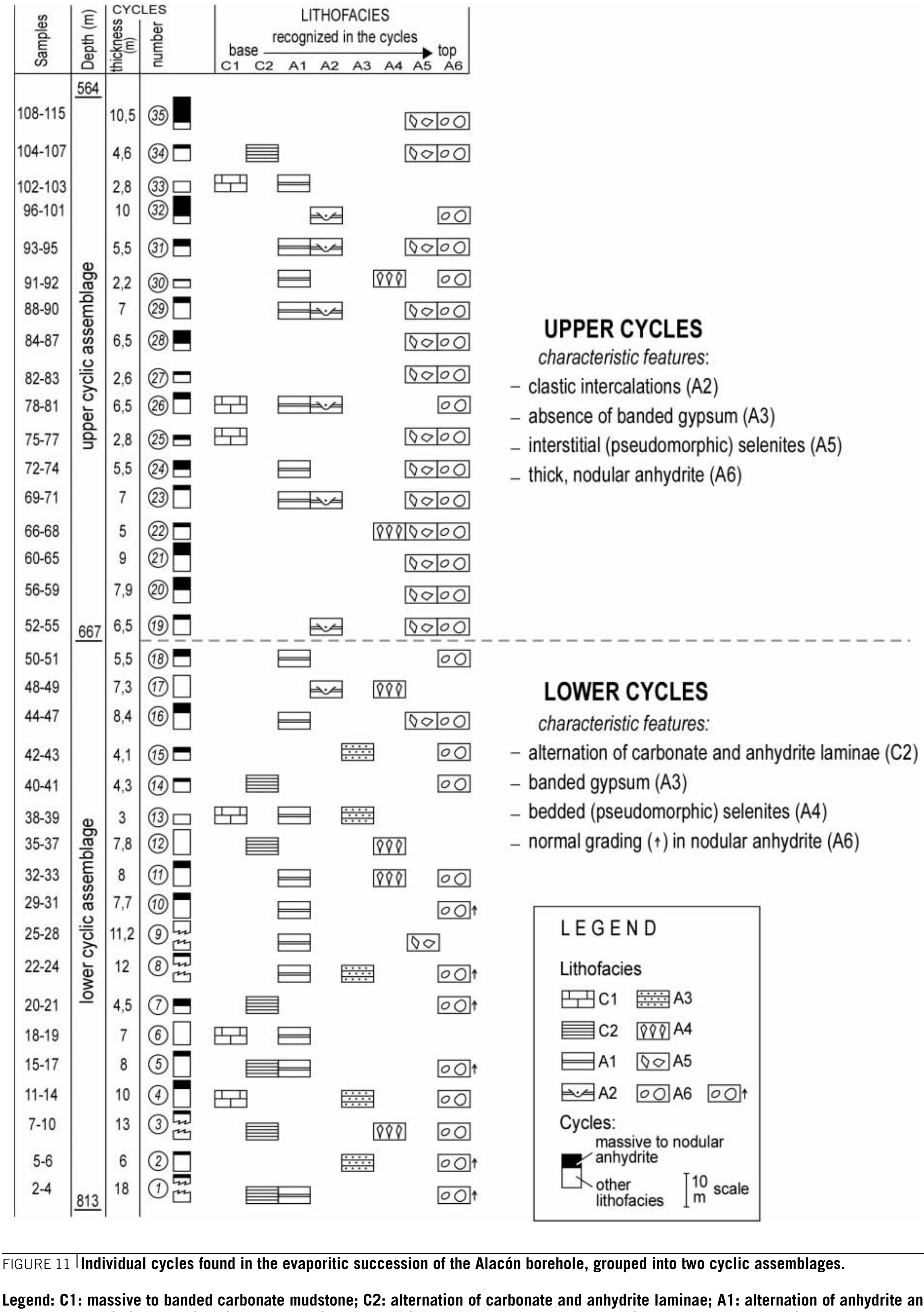

FIGURE 11 **Individual cycles found in the evaporitic succession of the Alacón borehole, grouped into two cyclic assemblages.**

Legend: C1: massive to banded carbonate mudstone; C2: alternation of carbonate and anhydrite laminae; A1: alternation of anhydrite and carbonate bands; A2: clastic intercalations in the alternation of anhydrite and carbonate bands; A3: laminated to banded anhydrite; A4: bedded pseudomorphs; A5: interstitial pseudomorphs; A6: massive to nodular anhydrite. In the "characteristic features" of the cycles, banded gypsum and bedded (pseudomorphic) selenites correspond to the interpretation of lithofacies A3 and A4, respectively.

formed from interstitial brines during moderate to deep burial diagenesis.

THE EVAPORITIC MODEL OF THE LÉCERA FORMATION

At the Alacón borehole, the most outstanding evaporite lithofacies which were interpreted as subaqueous deposits –laminated to banded fine-grained gypsum; bedded selenites– bear a strong resemblance to the gypsum facies currently characterizing the precipitation in the evaporative salinas (salt works) of the Mediterranean coast in Spain (Ortí et al., 1984). In these shallow settings, the fine-grained gypsum facies always precipitate at lower salinities than selenites. Moreover, the selenites are preferentially developed in the salinas where the hydrologic circuits are active throughout the year. In the other salinas, where the circuits are inactive in winter, the selenites are less developed or even absent, and mainly fine-grained gypsum facies are found.

Similarly, the evaporitic basin of the Lécera Formation in the Sierra de Arcos can be interpreted as a subsiding coastal basin of the salina or lagoon type, where the small size of the selenites (<10 cm, in general) suggests a shallow setting. Holocene, selenitic salinas have been described in South Australia (Warren, 1982), where the original water depth was up to 10 m, and the selenites can reach tens of decimetres.

At the Alacón borehole, the cyclic evolution from a salina (subaqueous) to a sabkha (subaerial) setting was probably controlled by relative sea level fluctuations.

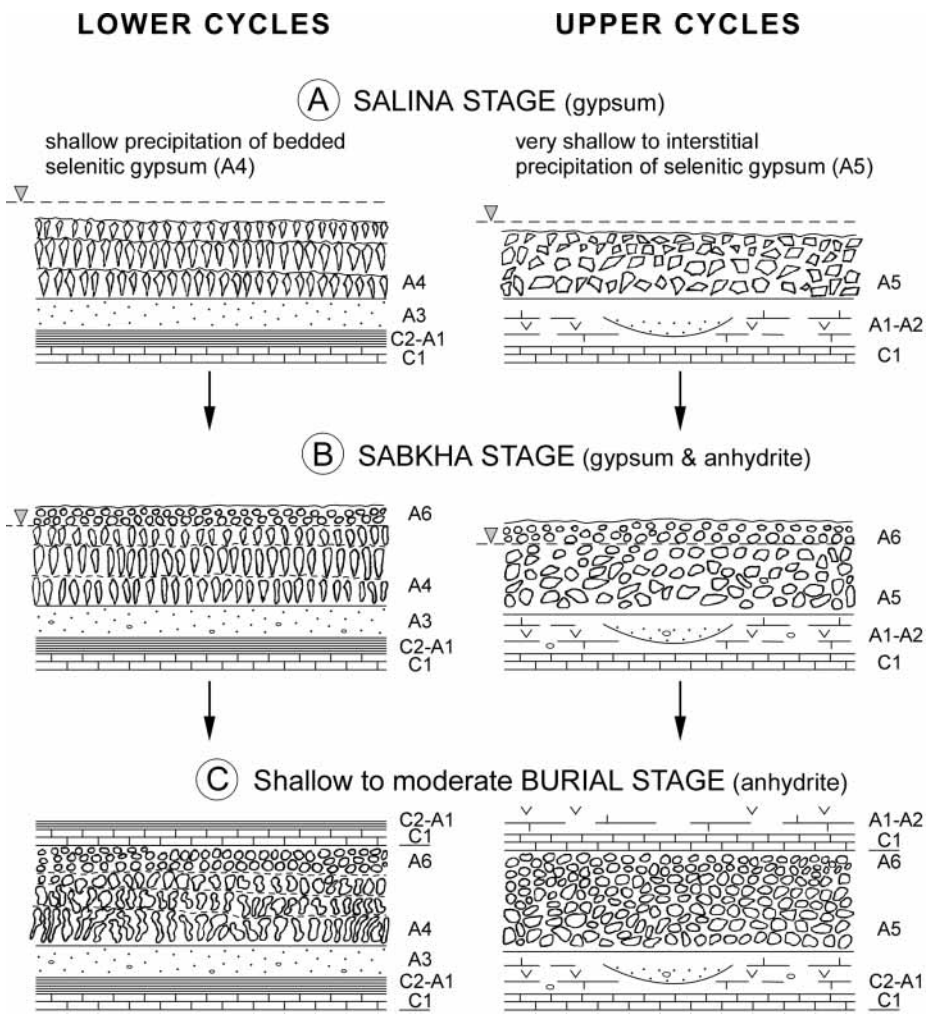

FIGURE 12 **Schematic representation of the evolution of the two (pseudomorphic) selenite lithofacies present at the Alacón borehole. Left half: bedded selenites in the cycles of the lower assemblage. Right half: interstitial selenites in the cycles of the upper assemblage. The evolution is presented as a continuous process accomplished along three successive stages: A) salina stage: subaqueous precipitaton of the bedded selenites. B) Sabkha stage (at the top of the cycle): nodular growth of anhydrite ("de novo") and initiation of the anhydritization and deformation of the underlying selenites. C) Shallow to moderate burial stage (few metres to one hundred metres of burial?): anhydritization and advanced deformation (by compaction) of the selenites. Lithofacies C1 to A6 as in Fig. 11.**

This cyclicity together with a marked subsidence favoured the accumulation of a 250 m thick deposit of predominant anhydrite in the Lécera Formation. At other boreholes in the Sierra de Arcos, the thickness of the horizon with predominant anhydrite reaches up to 300 m (Bordonaba, 2003).

The distinction between two different cyclic assemblages, lower and upper assemblages, in the evaporitic succession of the Alacón borehole allows us to better understand the evolution of the depositional coastal setting. In the lower part of the succession, where the cycles are thicker on average and exhibit more diversified lithofacies and competitive fabrics (bedded selenites), the salina setting was relatively deep. In this setting, the accumulation of carbonate matrix was limited and the laminae and bands of fine-grained gypsum preceded the accumulation of the bedded selenites. The presence, toward the base of this succession, of few intertidal lithofacies and sabkha cycles suggests that the subsiding salina only developed after a brief episode of carbonate-sulphate tidal flat complex.

By contrast, in the upper part of the succession a number of significant changes occurred: the cycles are thinner on average and exhibit few lithofacies; the presence of clastic intercalations is significant; the content of carbonate matrix is higher; the laminated to banded fine-grained gypsum lithofacies is lacking; the carbonate-rich, interstitial selenites predominate; and the nodular lithofacies at the top of the cycles are better developed. In this upper assemblage, the salina setting became progressively shallower, more contaminated by the host sediment, prone to episodes of erosion and exposure, and also deprived of the typical facies of this environment (laminated to banded gypsum; bedded selenites). This evolution ended with the infill of the salina and the expansion of the carbonates toward the top of the Lécera Formation.

OBSERVATIONS ON THE CARBONATE BRECCIATION

The origin of the carbonate breccias constituting the Cortes de Tajuña Formation has been the subject of debate in the literature of the Jurassic of the Iberian Chain. Regardless of the local existence of gravity-driven, sedimentary breccias (Giner, 1978, 1980), the brecciation process has often been assigned to the dissolution of evaporite beds and to the collapse of both the associated carbonate and the carbonate layers overlying the evaporite beds. The discussion, however, is mainly focused on timing of the brecciation process. Some authors consider the brecciation as late diagenetic and linked to deep burial (Morillo-Velarde and Meléndez, 1979) or to the exhumation of the Jurassic series (Gómez and Goy, 1998). Other authors, however, assume an early diagenetic origin linked to synsedimentary exposure (Bordonaba and Aurell, 2002; Bordonaba, 2003).

As stated above, the carbonate breccias at the Alacón borehole are only found above a depth of 564 m, where gypsum instead of anhydrite is present. These breccias usually contain secondary gypsum porphyroblasts derived from the hydration of the anhydrite porphyroblasts present in the carbonate lithofacies throughout the borehole interval studied. These anhydrite porphyroblasts, which were interpreted as having been formed during moderate to deep burial diagenesis, clearly preceded the brecciation process. On the other hand, the boundary between the top of the anhydrite rocks and the overlying carbonate breccias constitutes a regional aquifer of paramount importance in the Sierra de Arcos and its vicinity (Víctor Arquet, C.H.E.; pers. comm., 2002).

All these observations suggest that groundwater was a major factor in sulphate dissolution and associated carbonate brecciation in the region during the final exhumation of the lowermost Liassic carbonate series.

CONCLUSIONS

1) The evaporitic succession of the Lécera Formation at the Alacón borehole, up to 250 m thick, exhibits a number of individual cycles. An “ideal” cycle of this succession is made up of massive to banded carbonate lithofacies at the base, fine-grained gypsum and selenite lithofacies (the two currently preserved as anhydrite) in the central part, and nodular anhydrite at the top. This is a shallowing upward cycle that starts with subaqueous precipitation of carbonate and gypsum and ends with the subaerial growth of anhydrite.

2) The existence of a number of depositional cycles was deduced. In this cyclic succession, a lower assemblage can be differentiated from an upper one. In the lower assemblage, the cycles are thicker on average, exhibit more diversified lithofacies, reflect deeper settings, and are characterized by laminated to banded gypsum and bedded selenites. In the upper assemblage, the cycles are thinner on average, display less diversified lithofacies, reflect shallower settings, and are characterized by the deposition of carbonate-rich, interstitial selenites, and thick tops of massive to nodular anhydrite. As a whole, this cyclic succession records an infilling process.

3) The sedimentary environment where these cycles accumulated corresponds to a subsiding coastal salina or lagoon with a continuous supply of sea water. In this environment the water depth was progressively reduced.

4) At the top of each cycle, the selenitic gypsum lithofacies initiated a conversion into anhydrite under synsedimentary conditions in contact with sabkha brines. Subsequently, the process continued during shallow to moderate burial diagenesis in contact with interstitial (pore) brines. Probably, the other depositional gypsum lithofacies underwent a similar process of anhydritization.

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