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Depositional models of lacustrine evaporites in the SE margin of the Ebro Basin (Paleogene, NE Spain)

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ABSTRACT

An important evaporitic sedimentation occurred during the Paleogene (Eocene to lower Oligocene) in the Barberà sector of the southeastern margin of the Tertiary Ebro Basin. This sedimentation took place in shallow lacustrine environments and was controlled by a number of factors: 1) the tectonic structuration of the margin; 2) the high calcium sulphate content in the meteoric waters coming from the marginal reliefs; 3) the semiarid climate; and 4) the development of large alluvial fans along the basin margin, which also conditioned the location of the saline lakes. The evaporites are currently composed of secondary gypsum in surface and anhydrite at depth. There are, however, vestiges of the local presence of sodium sulphates. The evaporite units, with individual thicknesses ranging between 50 and 100 m, are intercalated within various lithostratigraphic formations and exhibit a paleogeographical pattern. The units located closer to the basin margin are characterized by a massive gypsum lithofacies (originally, bioturbated gypsum) bearing chert, and also by meganodular gypsum locally (originally, meganodules of anhydrite) in association with red lutites and clastic intercalations (gypsarenites, sandstones and conglomerates). Chert, which is only linked to the thickest gypsum layers, seems to be an early diagenetic, lacustrine product. Cyclicity in these proximal units indicates the progressive development of low-salinity, lacustrine bodies on red mud flats. At the top of some cycles, exposure episodes commonly resulted in dissolution, erosion, and the formation of edaphic features. In contrast, the units located in a more distal position with regard to the basin margin are formed by an alternation of banded-nodular gypsum and laminated gypsum layers in association with grey lutites and few clastic intercalations. These distal units formed in saline lakes with a higher ionic concentration. Exposure episodes in these lakes resulted in the formation of synsedimentary anhydrite and sabkha cycles. In some of these units, however, outer rims characterized by a lithofacies association similar to that of the proximal units occur (nodular gypsum, massive gypsum and chert nodules).

KEYWORDS **Evaporites. Gypsum. Saline lake models. Eocene. Oligocene.**

INTRODUCTION

During the Paleogene an important evaporitic lacustrine sedimentation occurred along the SE or Catalan margin of the Tertiary Ebro Basin (Ortí, 1990, 1997a, b). This margin involves the boundary zone between the basin fill and the Paleozoic and Mesozoic materials making up the Catalan Coastal Range. From the Ilerdian (lowermost Eocene) to the Stampian (lower Oligocene), a number of gypsum units interbedded with the siliciclastic and calcareous formations accumulated along this margin. In the sector under study, the historical relevance of some of these gypsum units as alabaster rocks ("Sarral alabaster") is worth noting since they have been traditionally used for ornamental purposes and sculpture in Catalonia.

The present paper is focused on the evaporitic sedimentation in the central part of the Catalan margin (Barberà sector, Tarragona province). Such an evaporitic sedimentation also occurred in adjacent areas, e.g. the Montsant sector, to the SW, and in the Anoia sector, to the NE (Fig. 1A). The diagenetic processes affecting the gypsum units make a precise characterization of the depositional facies difficult. A feature common to all these units, however, is that they exhibit secondary gypsum in outcrop. The main aim of this paper is to establish the sedimentary models of these evaporite units in the Barberà sector. We think that such models can be applied to the rest of the Catalan margin.

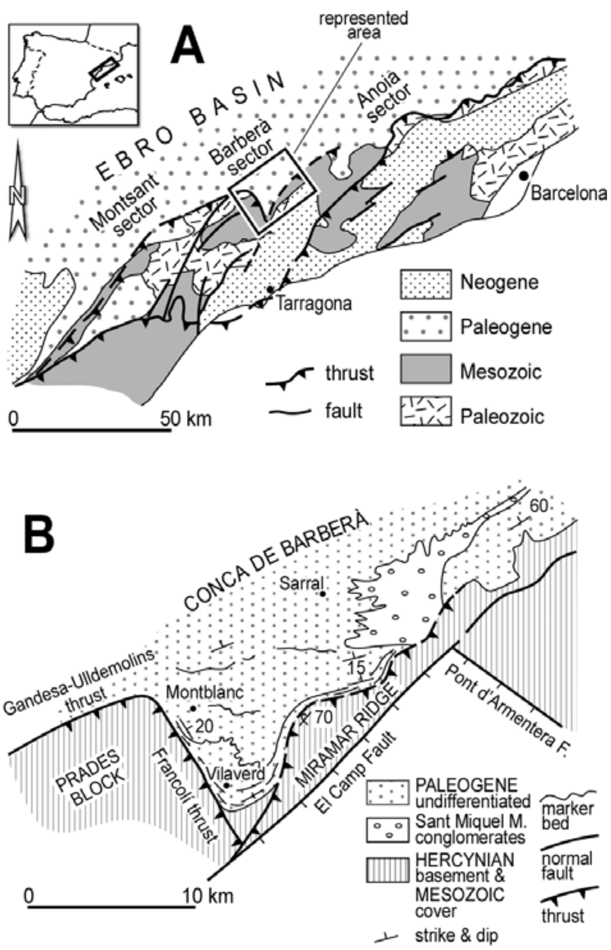

FIGURE 1 | **Geological location of the Barberà sector in the SE margin of the Tertiary Ebro Basin. A) Geological sketch of the central part of the Catalan Coastal Range (modified from Guimerà, 2004, fig. 7.11). B) Structural pattern of the Barberà sector (modified from Anadón et al., 1985, fig. 12).**

They could also help us to better understand the evaporite occurrences along the SW or Iberian margin of the Ebro Basin, in which also a number of gypsum units accumulated during the Miocene in lacustrine settings (Salvany, 1989; Salvany et al., 1994). From a wider perspective, the proposed evaporite lacustrine depositional models may apply to other ancient evaporitic records.

GEOLOGICAL AND STRATIGRAPHICAL SETTING

The Conca de Barberà region (the Barberà sector under study) is an erosive depression, elongated in a SW to NE direction, excavated in the Eocene and Oligocene sediments of the Ebro Basin (Fig. 1A). This sector of the Catalan margin is bounded to the SE by two well-differentiated parts of the Catalan Coastal Range: the Prades Block and the Miramar Ridge (Fig. 1B).

Sedimentation in the Catalan margin of the Ebro Basin was related to the tectonic evolution of the adjoining Catalan Coastal Range. During the Paleogene, the range was characterized by contractional structures (NNW-verging folds and thrusts), which were controlled by preexisting basement faults. These contractional structures acted as normal faults during the extensional evolution of the range in the Miocene (Anadón et al., 1985; Gómez and Guimerà, 1999; López-Blanco, 2002; Cabrera et al., 2004; Guimerà, 2004).

The Prades Block is a basement uplift of gently deformed Paleozoic and Mesozoic materials, which is bounded by three main structures (Fig. 1B): the Gandesa-Ulldemolins thrust, to the west, the El Camp normal fault, to the south, and the Francolí thrust, to the NE. The latter, a reverse fault oriented transversely to the Catalan Coastal Range, acted as a normal fault during the Mesozoic.

The Miramar Ridge is a basement uplift of Paleozoic and Mesozoic materials, which is bounded to the NW by a blind thrust (the Miramar thrust), with a SW to NE direction (Fig. 1B). This relief basically consists of a fold with a vergence to the NW. The uplift of the rigde caused the formation of progressive unconformities in the Paleogene conglomerate units of the margin. In the Barberà sector, the age of the deformation is upper Eocene-lowermost Oligocene.

The Francolí and the Miramar thrusts seem to have controlled the accumulation of a thick evaporitic sequence in the Barberà sector during the Eocene. The Triassic provenance of these sulphates by chemical recycling has been documented by Utrilla et al. (1991) and Utrilla et al. (1992).

The nomenclature of the Paleogene lithostratigraphic units in the sector under study has undergone two main stages. First, the names used by Colombo (1980, 1986) for members, formations and groups in the Montsant sector were applied to the Barberà sector, and second, the names used by Anadón (1978) in the Anoia sector were applied by Colldeforns et al. (1994a, b) to the Barberà sector also under the general term of the Barberà-Anoia sector (Fig. 2). The distribution of the lithostratigraphic units in the Barberà sector is shown in Fig. 3. The outcrops of the evaporite units under study are shown in Fig. 4.

EVAPORITE FACIES ANALYSIS

In the evaporite units of the Barberà sector, the terrigenous and gypsiferous facies are predominant, the

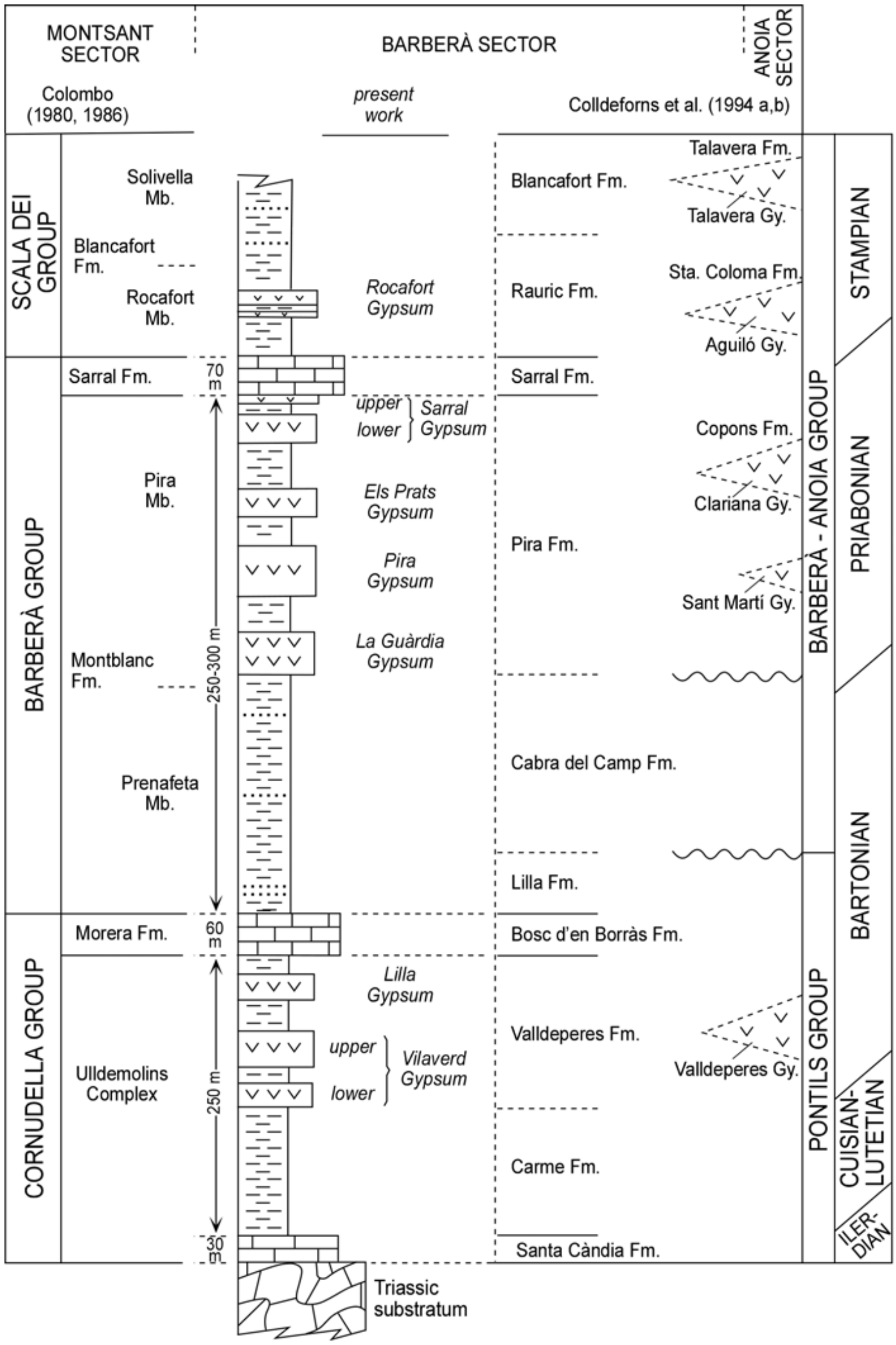

FIGURE 2 | **Stratigraphical sequence in the central part of the Barberà sector and comparison with the stratigraphic divisions proposed by Colombo (1980, 1986) in the Montsant sector and by Colldeforns et al. (1994a, b) in the Barberà-Anoia sector. The names used in this paper for the evaporite units are shown in the central part of the Figure.**

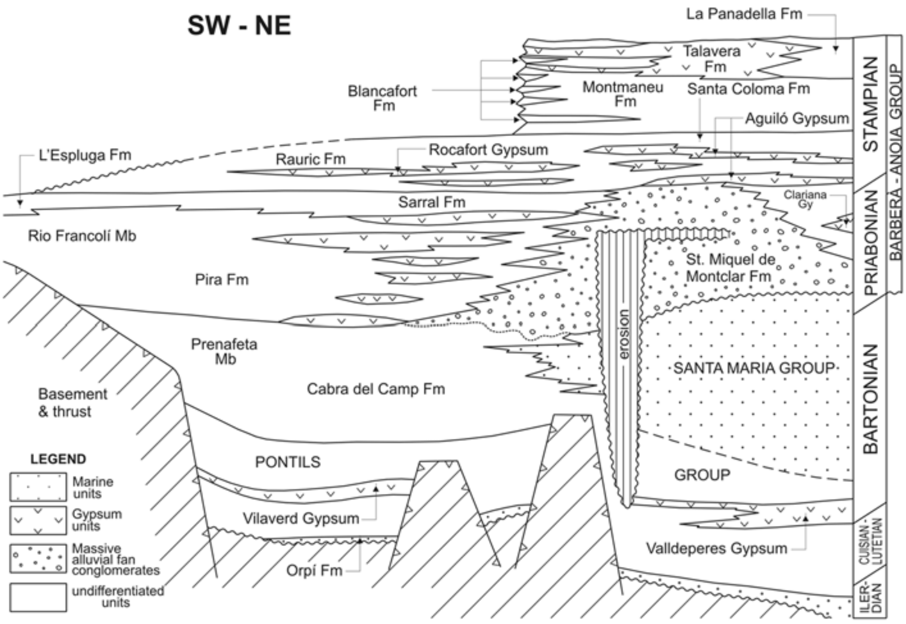

FIGURE 3 **Paleogene lithostratigraphic units in the Barberà sector and in the western part of the Anoia sector. Adapted from Colldeforns et al. (1994 a, b). The distribution of the evaporite units is highlighted as well as the marine facies (Santa Maria Group; Orpí Fm) and the coarse-clastic facies (Sant Miquel de Montclar Fm).**

calcareous and siliceous facies being subordinated. The terrigenous facies are composed of lutites, sandstones, and conglomerates. Red lutites are ubiquitous and commonly bear gypsum in variable degrees; locally, however, lutites are grey and grade into marls. The clay mineralogy of these lutites corresponds to illite, chlorite and the smectite group (Mg-smectite), with minor palygorskite (Inglès et al., 1991). Sandstones have variable compositions, from litharenites to quartz-arenites. Conglomerates have a clast-supported fabric and grade from calcareous to polymictic. Sandstones and conglomerates often have coarse-crystalline gypsiferous cement. The source area of all these terrigenous materials was the Catalan Coastal Range.

Carbonate facies associated with the evaporite units consist of pink to reddish mudstones with massive to nodular textures. Siliceous facies (chert) consist of nodules, stratiform horizons, and irregular masses. Chert nodules and stratiform horizons are commonly linked to gypsum layers, while irregular chert masses are preferentially associated with limestone layers. Chert nodules show different shapes with diameters ranging between 1 cm and some tens of cm, whereas the stratiform horizons have a thickness between 5 and 15 cm, and the irregular masses attain a few metres in size. Petrographically, all these chert types are made up of micro and megaquartz, and length-slow chalcedonic varieties, such as lutecite (Ortí et al., 1997); silica pseudomorphs after microlenticular gypsum are commonly observed.

Sulphate lithofacies: description and interpretation

The gypsum sediments in the Barberà sector have experienced a diagenetic cycle: deposition of primary gypsum; transformation of this gypsum into anhydrite during burial; and anhydrite hydration into secondary gypsum during final exhumation. As a result of this, the gypsiferous lithofacies are currently preserved as secondary gypsum, in which the alabastrine and porphyroblastic textures are predominant.

Gypsiferous lutites

This lithofacies consists of red lutites with variable amounts of interstitial gypsum. The latter is commonly present as micronodules (< 1 cm in diameter) or pseudomorphs after precursor lenticular (< 1

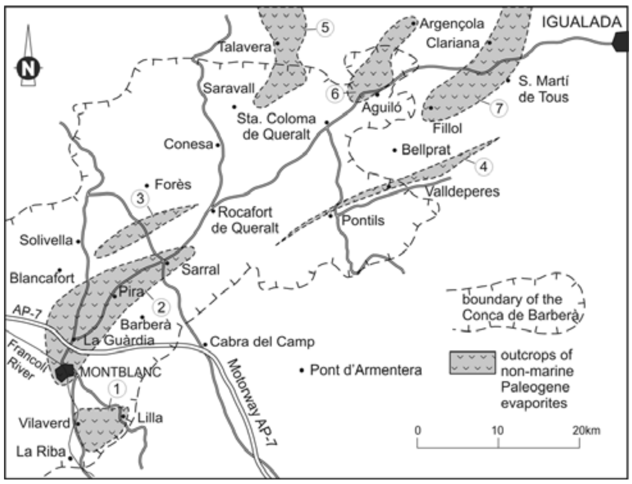

FIGURE 4 **Cartographic distribution of the main evaporite outcrops in the Barberà sector and the western part of the Anoia sector. Evaporite units: 1: Vilaverd Gypsum and Lilla Gypsum; 2: Pira Fm; 3: Rocafort Gypsum; 4: Valldeperes Gypsum; 5: Talavera Gypsum; 6: Aguiló Gypsum; 7: Clariana Gypsum and Sant Martí de Tous Gypsum.**

cm) and macrolenticular (1 to 10 cm or more) gypsum crystals.

Interstitial gypsum mainly reflects sulphate growths occurred within the lutites, either as gypsum crystals or as anhydrite nodules. Some of the micronodules could be due to the transformation of gypsum crystals into anhydrite during burial diagenesis. Other gypsum crystals could have been formed by the crystallization from calcium sulphate-saturated ground waters during the exhumation.

Gypsiferous lutites with vertical structures

Some red lutite layers exhibit vertical, tubular structures, ranging between few cm and 1 m in length. These tubes, with diameters between 1 and 2 cm, show the core filled with red lutite and the outer part composed of crystalline gypsum.

The tubes in this lithofacies resemble plant features, possibly roots or stems. Gypsum crystallization linked to these structures was probably related to the presence of sulphate-rich soils, which developed along the margins of saline lakes or in adjacent palustrine bodies affected by intense evaporation.

Cross-bedded gypsarenites

Gypsiferous layers displaying ripples and large scale cross-bedding are common in several evaporite formations in the study area. These layers reach a thickness up to few metres. Under the microscope the secondary gypsum content is very high, and it is accompanied by limited amounts of clastic particles (mainly quartz and rock fragments). This fact suggests that a large portion of the secondary gypsum replaces original clastic grains made up of gypsum (gypsarenite).

There is no evidence of mechanical transport of Triassic sulphates from the source area. Presumably, these gypsarenites derive from the synsedimentary erosion and resedimentation of other Paleogene gypsiferous units.

Laminated gypsum

This lithofacies is composed of gypsum laminae with an individual thickness between few mm and several cm. The layers making up this lithofacies generally reach thicknesses of few metres.

This lithofacies formed in shallow lacustrine bodies in which subaqueous sedimentation of primary gypsum laminae occurred.

Pseudomorphic (selenitic) gypsum

This lithofacies consists of thin (10 to 20 cm) gypsum layers constituted by domatic structures, with diameters between 15 and 30 cm and heigths between 10 and 15 cm. Domes, or clusters, are made up of a number of alabastrine secondary gypsum pseudomorphs after small, subvertical crystalline precursors.

This lithofacies corresponds to subaqueous gypsum crystals with competitive growths, i.e., a selenite lithofacies. At present, selenite crystals and domes commonly form in shallow salinas with stable brine bodies (Ortí et al., 1984).

Massive gypsum

This is the most common lithofacies in the gypsum layers. It is characterized by the absence of a well-defined sedimentary or diagenetic structure, although diffuse bedding and remains of a preexisting clotted texture are often present. Bioturbation structures preserved in carbonate, with diameters between few mm and up to several cm can be observed in some layers. Also, gastropod shells are found locally.

Presumably this lithofacies derives from the "massive bioturbated gysum lithofacies", which is well documented in the lacustrine formations made up of primary gypsum of the Tertiary basins in Spain, where it commonly includes bioclastic particles (Rodríguez-Aranda and Calvo, 1998; Ortí and Rosell, 2000). Burial transformation of this lithofacies into anhydrite and subsequent gypsification during exhumation, usually hinder a clear identification as precursor bioturbated gypsum, except where the burrows had been originally preserved in micritic carbonate. The massive bioturbated gypsum formed in shallow lakes, with the bottom sediments affected by the burrowing action of a number of organisms (Rodríguez-Aranda and Calvo, 1998; Ortí et al., 2003).

Nodular gypsum, banded-nodular gypsum

These two lithofacies correspond to nodules with diameters ranging between 1 and 10 cm, isolated or arranged in layers, respectively. Host sediment is commonly lutitic or carbonatic. Micronodules (diameters < 1 cm), however, are relatively common. Locally, also enterolithic layers (i.e. contorted-nodular layers parallel to bedding) are intercalated within the banded-nodular lithofacies.

Some of these lithofacies originated as anhydrite growths in the vadose-capillary zone of sabkha environments, in particular when the nodules are associated with enterolithic layers. Other nodules and micronodules, however, could have been formed during burial diagenesis; in this case, some of these may have a gypsum crystal precursor whereas others have directly replaced the gypsum sediment.

Meganodular gypsum

Meganodular gypsum consists of large nodules with diameters ranging between 50 cm and several metres, which are only found in the thickest gypsum layers (> 3 m, in general). The shapes of these meganodules are variable, from almost spherical to ovoid or irregular, and the boundaries between the meganodules can be more or less sutured. Many meganodules have a composite nodular fabric, either at the core or in the outer zone. The distribution of the meganodules in the gypsum layers oscillates from random to subhorizontal, and from oblique to the bedding to subvertical; in the latter case, a columnar appearance is observed. Meganodules are commonly composed of alabastrine secondary gypsum bearing porphyroblastic envelopes.

Meganodules are found in close association with large, irregular masses of alabastrine gypsum. Gradations between the meganodules and the irregular masses are observed. Contorted (enterolithic-like) gypsum layers with variable orientations, often subvertical, as well as lutite patches with fluid-like morphologies are common within the irregular masses and around the meganodules. Both the meganodules and the irregular masses replace any preexisting gypsum lithofacies and can destroy or deform any bedding and other sedimentary structures.

Several features in the meganodules, such as the large dimensions, the severe replacive character, and the fact that their tops are not eroded, suggest a process of pervasive anhydritization of any former lithofacies, in particular the bioturbated gypsum. This meganodular anhydritization could have originated at shallow or moderate burial (tens of metres?), before the lithification of the gypsum sediment.

EVAPORITE UNITS

The evaporite units present in the Barberà sector are mainly interbedded within the Valldeperes Fm, the Pira Fm, the Rauric Fm, the Santa Coloma Fm and the Talavera Fm. The names we use for the non-formal evaporite units are shown in Fig 2. The formal names of the lithostratigraphic units were taken from Colldeforns et al. (1994a, b). Layers in these evaporite units are gently tilted, between 5 and 20º to the NNW. Outcrops of these units are narrow and elongated in a SW–NE direction. The lithofacies present in these units have been described above.

At the end of this chapter a reference is made to the non-marine evaporite units in the Anoia sector (the Copons and Sant Genís formations), which develop close to the northeastern boundary of the Barberà sector.

Valldeperes Fm (Bartonian)

The assemblage of gypsiferous layers present in the Vilaverd depression is traditionally known as the Vilaverd Gypsum. This assemblage is composed of two units with well differentiated characteristics and depocenters: the Vilaverd Gypsum at the base and the Lilla Gypsum at the top (Fig. 5). Moreover, a lower and an upper subunit can be distinguished in the Vilaverd Gypsum.

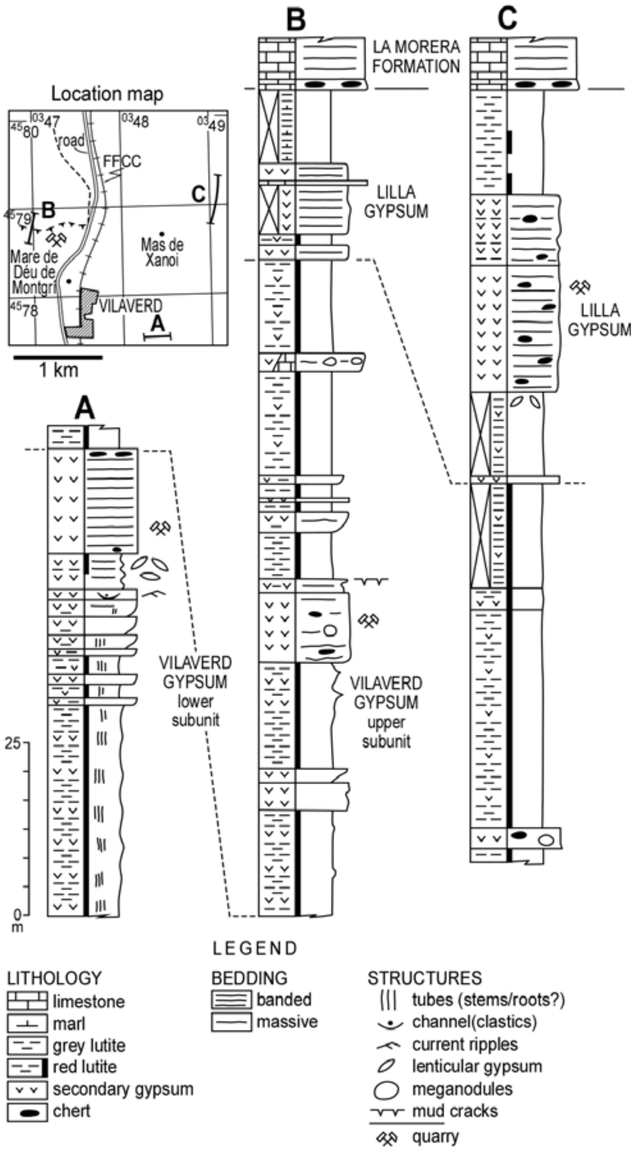

FIGURE 5 | **Correlation between some representative sections of the evaporite units integrating the Valldeperes Fm in the Vilaverd depression. A) Section to the SE of Vilaverd. B) Section in the quarry area to the N of Vilaverd. C) Section near the Mas de Xanoi, to the E of Vilaverd.**

Vilaverd Gypsum

The lower subunit in the Vilaverd Gypsum is well developed to the east of the Francolí River. Figure 5A shows a representative section, in which a clear cyclicity is developed. This subunit ends with a thick (up to 15 m) gypsum bed, in which abundant chert is present at the top. The gypsum beds are composed of clear to reddish, massive gypsum, without meganodules.

The upper subunit in the Vilaverd Gypsum crops out to the north of this village, in the area where a number of gypsum quarries are located. At this point, a complete section of this subunit can be studied, which ends with a cherty-calcareous key bed (Fig. 5B). In this section, the thickest (10 m) gypsum layer was the subject of intense exploitation; this layer is made up of massive gypsum bearing meganodules and chert.

Lilla Gypsum

The Lilla Gypsum is preferentially developed to the east of the Francolí River. A rather complete section of this unit was studied near the Mas de Xanoi site (Fig. 5C). At this point, the section reaches more than 40 m in thickness and can be subdivided into a gypsiferous lower part, up to 25 m thick, and a grey lutitic upper part, up to 15 m thick. The gypsiferous lower part is composed of massive gypsum very rich in chert, without meganodules. Overlying the lutitic upper part, the cherty-calcareous key layer is found; this layer, up to 2 m thick, is distributed throughout the Vilaverd depression.

Pira Fm (Priabonian)

In the Pira Fm, the following gypsum units were distinguished from base to top (Fig. 2): La Guàrdia Gypsum, Pira Gypsum, Els Prats Gypsum, and Sarral Gypsum. Maximum thickness of all these units together reaches about 200 m. Although some of the names of these units have been used in earlier papers (Julivert, 1954; Colombo, 1986), it is difficult to establish a precise equivalence with our terms. A map of the main gypsum layers in these units is shown in Fig. 6, and a correlation between some representative sections is shown in Fig. 7.

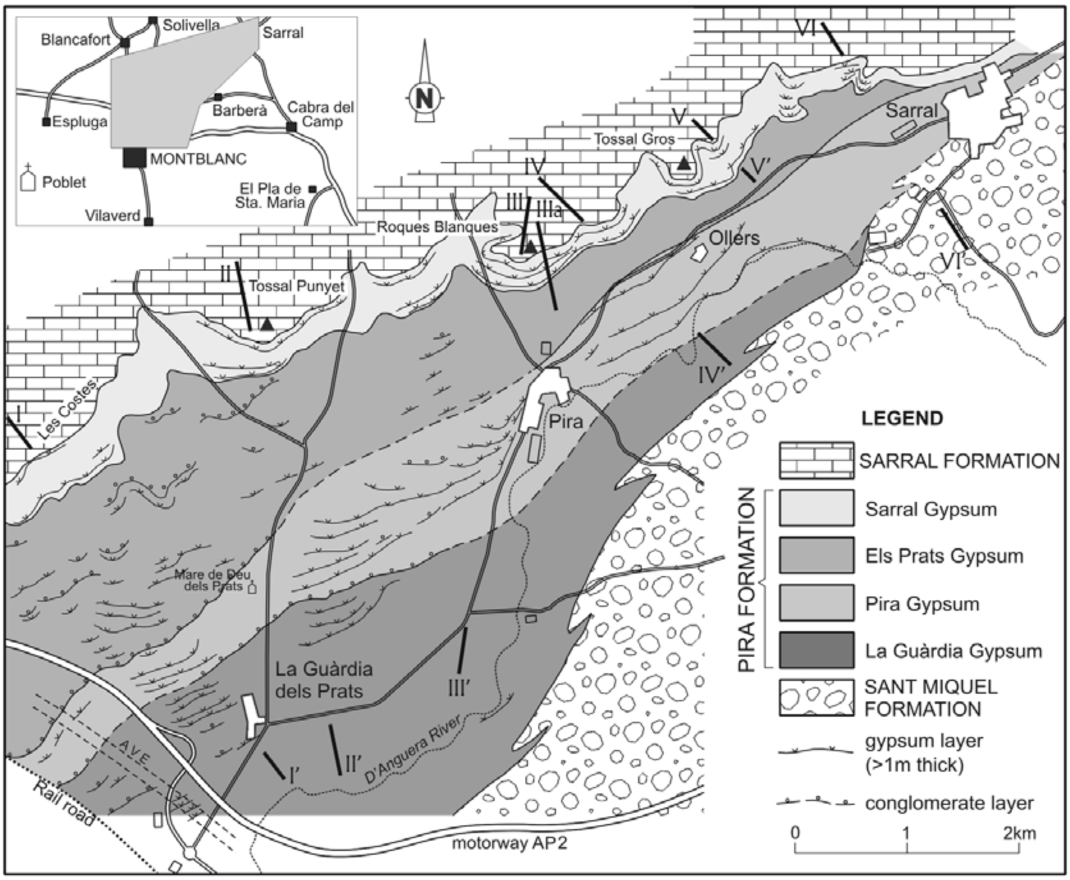

FIGURE 6 | **Map of the evaporite units composing the Pira Fm in the central part of the Barberà sector (between Montblanc and Sarral). The distribution of many gypsum layers thicker than 1 m as well as some significant conglomerate layers is shown. The extensive Quaternary cover in this area has been omitted. The interfingering between the evaporite units of the Pira Fm and the conglomerate facies of the Sant Miquel de Montclar Fm is approximate. The location of the sections in Fig. 7 (sections I to VI) is indicated.**

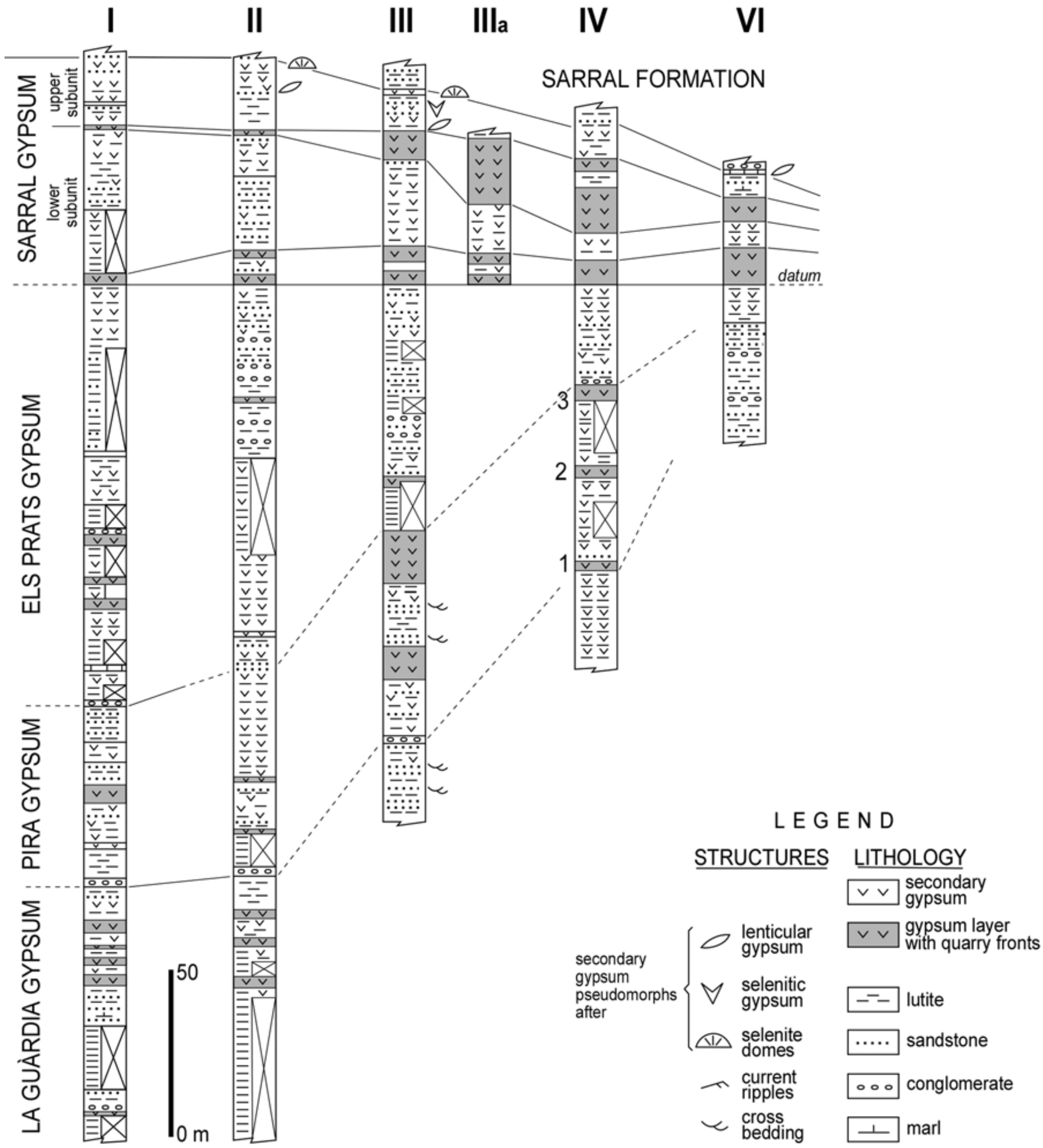

FIGURE 7 | **Correlation between some representative sections of the Pira Fm in the central part of the Barberà sector (see their location in Fig. 6). Only the main gypsum layers or groups of layers are shown. *Datum* is the base of the Sarral Gypsum. In Section IV, the three main gypsum layers making up the Pira Gypsum are numbered 1 to 3 (1: Anguera bed; 2: Ollers bed; 3: El Maçó bed)**

La Guàrdia Gypsum

This unit is limited to the zone between the village of Montblanc and the area to the NE of the village of La Guàrdia dels Prats. The upper part of this unit crops out to the north of this village, where it consists of gypsum layers, less than 4 m thick in general, which have been the subject of small exploitations. Outcrops of the lower part of this unit are rare, but there are vestiges of the existence of gypsum layers in it. Thus, the recent construction of the high speed train (AVE) has exposed several gypsum layers with a thickness of less than 3 m. Moreover, a thick (up to 7 m) gypsum layer crops out locally at the Anguera River (to the south of the Molí d'Amorós; Fig. 6). The top of this unit underlies a conglomerate layer that is 3 m thick (Figs. 6 and 7). The base, however, remains poorly defined.

Pira Gypsum

This unit is well developed between Montblanc and the village of Ollers. To the north of Montblanc, this unit includes at the base a conglomerate layer of about 3 m thick and its top underlies another conglomerate bed. In the zone between the Mare de Déu del Prats church and the village of Pira (Fig. 6), the unit displays a fan-like morphology, with a number of gypsum layers thickening to the SE. These layers have thicknesses ranging between 2 and 3 m and vestiges of gypsum exploitations are ubiquitous. The unit displays an inflexion and thins out toward the NE. Near Pira, it is composed of gypsum layers up to 5-10 m thick, which have been intensively exploited in quarries. Between Pira and Ollers, the unit is reduced to three main layers, with individual thicknesses of up to 4 m (Fig. 7), all of them showing exploitation vestiges. The main lithofacies in this unit is massive gypsum, and all the thick (> 2 or 3 m) gypsum layers bear chert nodules.

Els Prats Gypsum

This unit has a distribution limited to the zone between the north of Montblanc and Pira. This is a poorly defined unit, with gypsum layers thinner than 5 m, in general, interbedded within sandstones, conglomerates and red lutites. Small exploitations are located in these layers. Towards the SW, the unit intercalates carbonate beds. This unit shows a marked decrease in thickness from the SW, where it is very thick, to the NE, where it reduces and progressively loses the gypsum layers. Predominant lithofacies is massive gypsum, chert being abundant in the thickest layers.

Sarral Gypsum

This unit is the most continuous of the Pira Fm and extends between the zone to the north of Montblanc (Les Costes zone; Fig. 6) and the zone to the east of the village of Sarral. This unit can be subdivided into a lower and an upper subunit (Fig. 7). The lower subunit is the most important and is composed of two main gypsiferous levels. Both levels contain gypsum layers, with individual thicknesses between 3 and 10 m, in alternation with red lutites. Between Sarral and the zone to the north of Pira, this unit shows a number of gypsum quarries. Gypsum layers in this unit grade laterally both in facies and thickness. Thus, the two gypsiferous levels are stratigraphically very close to each other in the Sarral-Ollers zone. However, the upper level thins out toward the SW attaining a thickness of 1 m in the Les Costes zone, whereas the lower level thickens in the same direction and splits into two well defined layers. The most common lithofacies in this subunit is massive gypsum. However, meganodular gypsum becomes predominant in the thickest layers in association with nodular and stratiform chert.

The upper subunit, which has a poor gypsiferous character (Fig. 7), is mainly composed of grey lutites and marls. Interbedded within these materials, are some gypsum layers, with individual thicknesses less than 1 m, in general. The main lithofacies in this subunit are 1) alternations of nodular gypsum and laminated gypsum, and 2) pseudomorphic gypsum after selenitic domes and after lenticular and macrolenticular gypsum crystals. This subunit grades upward into the carbonates and sandstones of the Sarral Fm.

Rauric Fm (Stampian)

Rocafort Gypsum

This unit is intercalated within the Rauric Fm and has been traditionally considered as a lateral equivalent of the

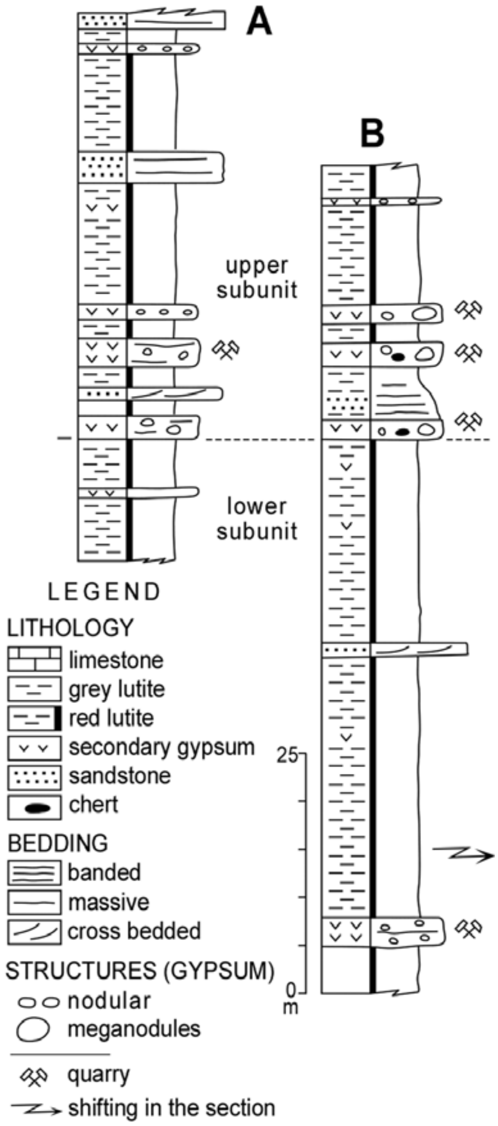

FIGURE 8 | **Correlation between two representative sections of the Rocafort Gypsum (Rauric Fm), to the SW of Rocafort de Queralt. Coordinates (UTM) of the base of Section A are: 03 51 85 1 and 45 92 67 2. Coordinates (UTM) of the base of the upper subunit in Section B are: 03 52 17 0 and 45 92 79 4.**

Aguiló Gypsum of the Santa Coloma Fm. In this paper, however, we consider the two units separately because of their different characteristics. The Rocafort Gypsum is limited to the zone between the villages of Solivella and Rocafort de Queralt.

A lower and an upper subunit can be distinguished in this unit (Fig. 8). The lower subunit is relatively thin and limited to one or two gypsum layers, with individual thicknesses of less than 3 m. Small quarries are located in these layers. The upper subunit is thicker and involves up to 4 gypsum layers with individual thicknesses of 3 m, which have been exploited locally. These gypsum layers alternate with lutite layers, averaging a total thickness of about 25 m. The predominant lithofacies in this unit is massive gypsum, with scattered meganodules and some chert nodules.

Santa Coloma Fm (Stampian)

Aguiló Gypsum

This unit is intercalated within the Santa Coloma Fm, and crops out between the villages of Aguiló and Santa Coloma de Queralt. Predominant lithofacies is an alternation of nodular and laminated gypsum, interlayered within grey lutites and marls. Chert is totally absent. The thickness of individual gypsum layers attains a few metres; the whole unit is up to 20-25 m thick.

Talavera Fm (Stampian)

Talavera Gypsum

Within the Talavera Fm, several gypsum levels are intercalated in alternation with grey lutites and marls. The predominant lithofacies is also an alternation of nodular gypsum and laminated gypsum, without chert. The whole unit attains a thickness of about 60 m. Based on the presence of an ancient spring of the sodium sulphate type near the village of Rubinat, it can be deduced that at least one of the gypsum levels of this unit could include sodium-bearing sulphate minerals (probably thenardite and glauberite) in subsurface.

Copons and Sant Genís formations (Priabonian; Anoia sector)

Although these formations are exclusively developed in the Anoia sector, their southwestern boundaries extend close to the Barberà sector and display interesting features for our study.

The Clariana Gypsum (a member of the Copons Fm) is mainly constituted by an alternation of nodular gypsum and laminated gypsum. However, in its southwestern margin (Fillol area) it grades to chert-bearing, nodular and meganodular gypsum lithofacies. Representative sections of this boundary zone are shown in Fig. 9.

The Sant Martí de Tous Gypsum (Sant Genís Fm) displays similar characteristics to the Clariana Gypsum. It is constituted by an alternation of laminated gypsum and nodular gypsum, but it changes to nodular gypsum bearing chert nodules in the southwestern margin (see below).

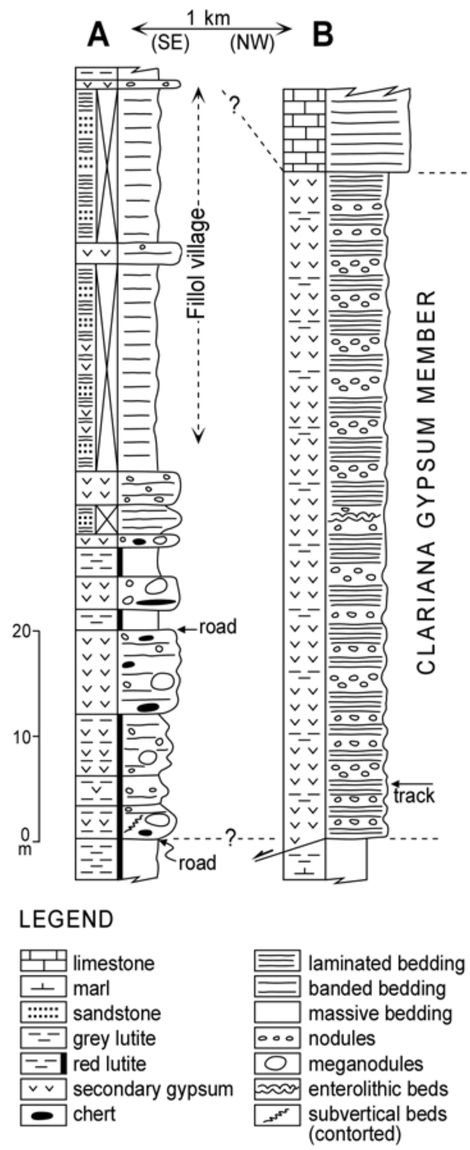

FIGURE 9 **Correlation between two sections in the southwestern margin (Fillol area) of the Clariana Gypsum, showing the change in the lithofacies associations. Coordinates (UTM) of the base of the sections are: Section A (Fillol): 03 72 63 9 and 46 00 83 6; Section B: 03 72 85 0 and 46 02 22 2.**

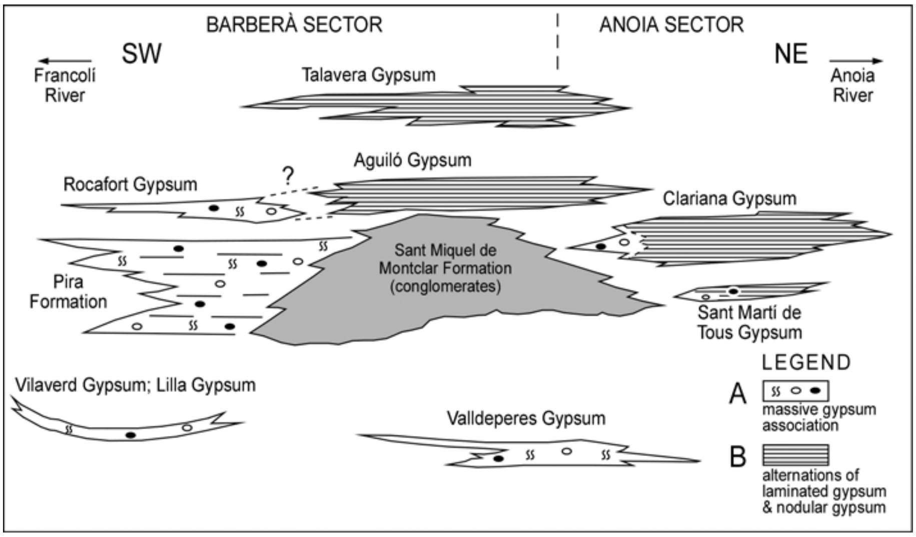

FIGURE 10 | **Schematic distribution of association A versus association B in the evaporite units of the Barberà and the Anoia sectors (in the latter, only the non-marine units are considered).**

EVAPORITE LITHOFACIES ASSOCIATIONS AND CYCLICITY

The distribution of the gypsum lithofacies in the various evaporite units of the Barberà sector shows two major lithofacies associations: A) massive gypsum with chert nodules, and locally also with gypsum meganodules; and B) alternation of banded-nodular gypsum and laminated gypsum layers devoid of both chert nodules and gypsum meganodules; enterolithic beds are commonly intercalated within the banded-nodular layers. Both lithofacies associations are known in many non-marine Tertiary evaporites in Spain (Ortí et al., 1989; Ortí, 1997a). Most commonly, the evaporite units in the Barberà sector only display one of the two lithofacies associations: association A for the units of the Valldeperes Fm, the Pira Fm and the Rauric Fm; and association B for the upper subunit of the Sarral Gypsum, the Aguiló Gypsum and the Talavera Gypsum (Fig. 10).

Successions reflecting the progressive development of evaporitic environments are found in several of the units and subunits characterized by the massive gypsum association A. These successions, whose thicknesses oscillate between few metres and few tens of metres, display cycles composed of red lutites at the base and massive gypsum at the top, with a thickening upward trend. Such successions are interpreted as the result of the progressive development of saline lakes on preexisting mud flats. The cyclicity of the Vilaverd Gypsum (lower subunit) is shown in Fig. 5A.

A number of modalities of individual cycles were recorded: cycles in which a lacustrine body develops on a lutite horizon with edaphic structures (Fig. 11A1); cycles in which massive facies of gypsum and carbonate are developed on a lutite horizon; moreover, meganodular anhydrite has partly destroyed the sedimentary structures in these cycles (Fig. 11A2); and cycles with clastic influences (gypsarenites) at the base, and chert; meganodular anhydrite is also present in these cycles (Fig. 11A3).

Another type of cycle is developed in the thick lower subunit of the Sarral Gypsum (Fig. 12), where each cycle comprises three terms: 1) the basal term consists of gypsiferous red lutites; 2) the intermediate term is an alternation between gypsiferous red lutites and banded gypsum bearing gypsum micronodules and some nodules; and 3) the upper term consists of thick layers of massive gypsum bearing chert, which has been pervasively transformed into gypsum meganodules and irregular gypsum masses. The same cycles are developed in the Pira Gypsum, in the quarries close to this village. At first sight, the cycles in Fig. 12 could be assigned to sabkha cycles. However, the study of the meganodular lithofacies (see above) suggests a burial diagenetic origin for such particular type of anhydritization. In fact, the presence of typical sabkha cycles, i.e. nodular (primary anhydrite) facies overlying laminated facies, was not recorded in the units dominated by the massive gypsum association.

In these units, however, it is common to observe dissolution effects, some vestiges of karstification, and edaphic features at the top of the layers. By way of an example, Fig. 11A2 shows an erosional/dissolution surface at the top of a cycle, and the infilling of these irregularities with carbonate of possible edaphic origin. All these features suggest the existence, at the top of these cycles, of exposure conditions different from those leading to the formation of sabkha anhydrite. These conditions were related to dilution of the interstitial brines.

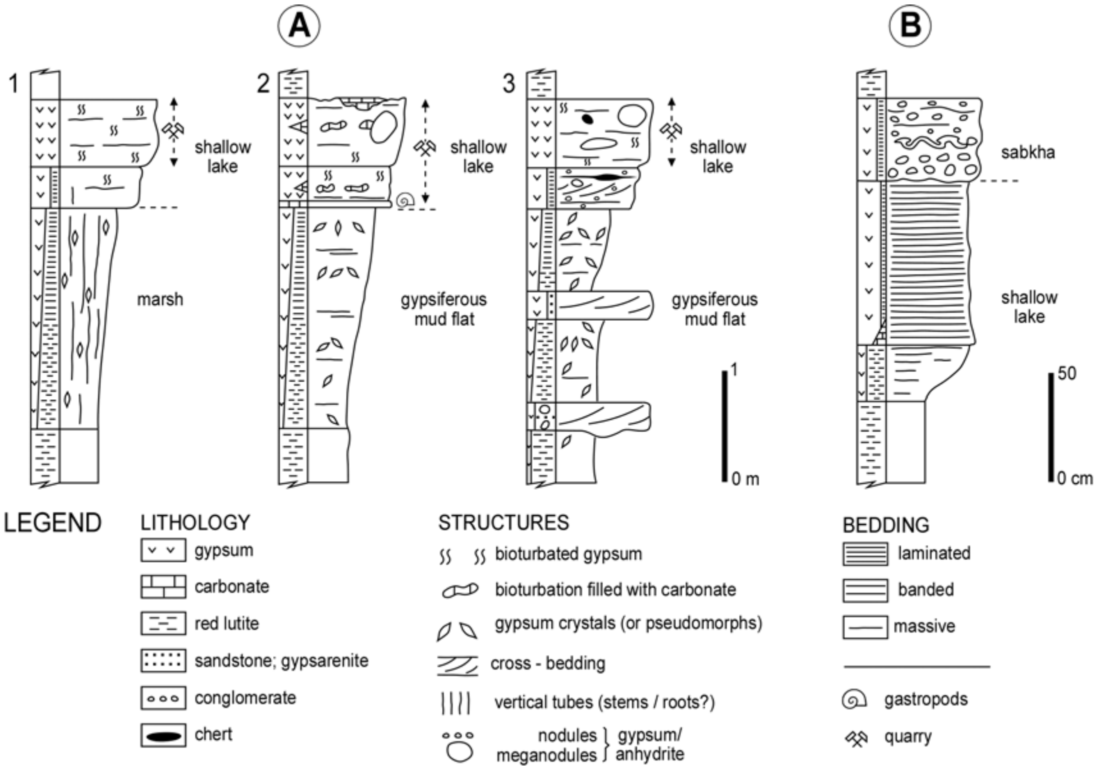

FIGURE 11 | **Some types of individual cycles recorded in the evaporite units of the Barberà sector. A) Cycles A1, A2 and A3 belong to units characterized by the massive gypsum lithofacies association. A1: cycle with tubular structures (stems or roots?) at the base; lower subunit of the Vilaverd Gypsum (see Fig. 5A). A2: cycle with bioturbation structures preserved as carbonate in the gypsum layers; lower subunit of the Sarral Gypsum, in the quarries to the north of Pira. A3: cycle beginning with gypsiferous, clastic intercalations; lower subunit of the Sarral Gypsum, in the quarries to the NW of Ollers. B) Cycle belonging to a unit characterized by the alternations of laminated gypsum and nodular gypsum (lithofacies association B): sabkha cycle in the Talavera Gypsum, near Talavera.**

In contrast, in the units characterized by an alternation of banded-nodular gypsum and laminated gypsum layers (lithofacies association B), typical sabkha cycles are common (Fig. 11B).

DEPOSITIONAL ENVIRONMENTS

Both the lithofacies associations and the cyclicity recorded in the evaporite units allow us to interpret the sedimentary environments in the sector under study (Fig. 13).

In the units characterized by association A, these environments are shallow saline lakes with low-concentrated brines of the calcium sulphate type (Fig. 13A). The lake centre is occupied by banded to massive gypsum sediment, which is severely disrupted by the activity of a number of organisms. In this setting, chert (or its possible silica-gel precursor) grows interstitially as an early diagenetic product, which replaces gypsum forming nodules and thin horizons. The lake margin is constituted by gypsiferous red lutites (saline mud flat) either devoid of, or colonized by vegetation (marsh). Within these red lutites, macrolenticular crystals of gypsum form and, in the most marginal zones, also isolated nodules and micronodules of anhydrite may develop.

During the lake dilution stages, some carbonate sedimentation (including gastropod shells) occurs in these lakes, and the carbonate mud fills and preserves the bioturbation structures within the gypsiferous sediment. Besides the sandstone and conglomerate layers, some gypsarenite beds also intercalate within the red lutites in the lake margin. Less commonly, these clastic layers can reach the lake centre. During the exposure stages, dissolution holes and erosional features form, as well as some carbonate infillings of edaphic origin

When the evaporite units characterized by the association B form (Fig. 13B), the lake centre is occupied by laminae of fine-grained gypsum. Also, small selenitic domes can intercalate within these laminae. Chert does not precipitate in these lake centres. In the lake's margin, nodular and enterolithic layers of anhydrite are common, as well as anhydrite pseudomorphs after macrolenticular gypsum; these anhydritic features correspond to a sabkha setting. During the exposure episodes, the sabkha facies expand towards the lake centre resulting in typical sabkha cycles.

Sodic salts were probably deposited in the units characterized by association B, as is usual for this type of Oligocene-Miocene units throughout the Ebro Basin

(Ortí, 1997a, 2000). Waters sourcing from one of the gypsum horizons composing the Talavera Gypsum in Rubinat, close to Santa Coloma de Queralt, have sodium sulphate content over 96 g/l (IGME, 1944). In the Rubinat area, Colldeforns and Mata-Perelló (1987) reported the presence (presumably in surface samples) of gypsum, anhydrite, thenardite, glauberite, mirabilite, and vestiges of epsomite and hexahydrite. Also, the presence of halite (sodium chloride) casts is known in the Clariana Gypsum (Ortí, 1997b).

CONTROLS ON THE EVAPORITIC SEDIMENTATION

The main controls on the evaporitic sedimentation in the area under study are climatic, structural and paleogeographic. A semiarid climate can be deduced from the mineralogy (gypsum/anhydrite) of the most common evaporite units. In fact, the abundant supply of calcium sulphate dissolved in the influx waters -from the evaporitic Triassic terrains in the source area- resulted in the predominant precipitation of gypsum under moderate evaporative conditions. On the other hand, the intense bioturbation activity in the original sediments of a number of gypsum units (lithofacies association A) suggests a very low chloride content in the brines.

The site of maximum evaporite accumulation of the gypsum units suggests a tectonic control on the sedimentation. Probably, the Francolí fault induced a high subsidence rate in the area, leading to the formation of an “evaporitic trap”. In fact, a number of features suggest a structural control in the various gypsum units making up the Pira Fm (Figs. 6 and 7): a) a thickness increase to the SW (to the Francolí fault); b) the cartographic inflexions selectively affecting some of the units, which presumably have a syntectonic origin; c) the frequent reactivations of the alluvial fan systems adjacent to the evaporite units, leading to common interfingering between evaporites and coarse siliciclastics; and d) the continuous shifting of the depocenters in the various units and subunits.

The last feature (d) is also observed in the evaporite units of other formations, such as the Valldeperes Fm in the Vilaverd depression (Fig. 5). Moreover, similar evaporitic accumulations are known in other sectors of the SE margin of the Ebro Basin. This is the case of the thick gypsiferous sequence in the Montsant sector (Fig. 1), which is constituted by the Ulldemolins Complex (Fig. 2); this complex is integrated by three evaporitic units: the Ulldemolins Gypsum, the Cornudella Gypsum, and the Vilaverd Gypsum.

As discussed above, some evaporite units display association A, whereas others display association B. This distribution seems to reflect mainly a paleogeographic control (Fig. 10), i.e. a position closer to the basin margin for the lakes characterized by association A and a more distal position for the lakes characterized by association B. Moreover, the thick alluvial fan deposits of the Sant Miquel de Montclar Fm seem to have influenced the development of units with association A to the SW of these deposits and with association B to the NE.

Other units, however, show a lateral facies change from one association to the other. This seems to be the case of the Rocafort Gypsum, composed of association A, and of the Aguiló Gypsum, made up of association B.

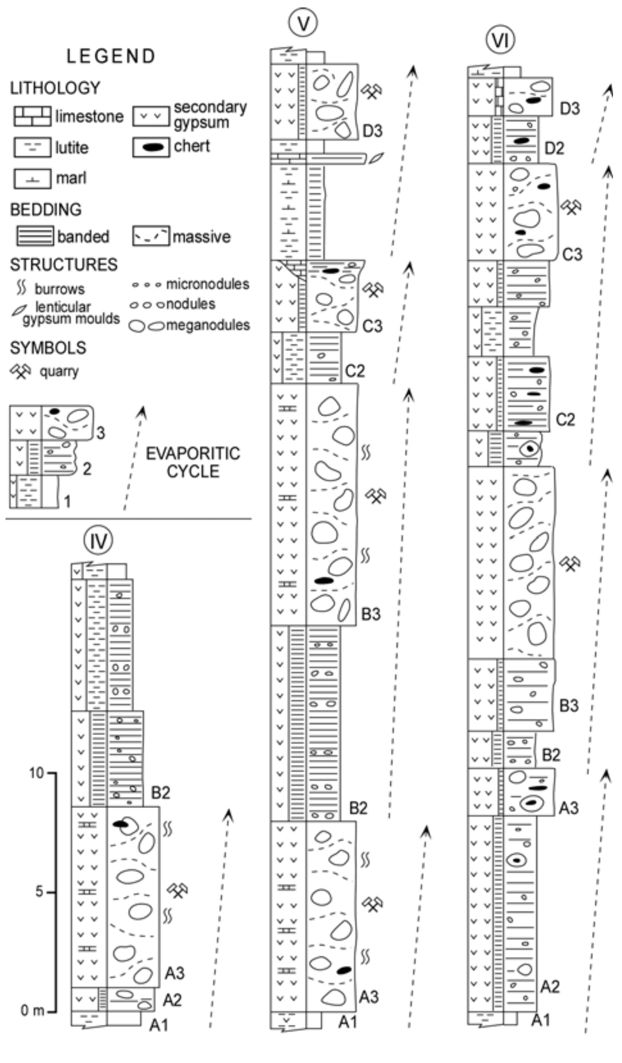

FIGURE 12 | **Main type of evaporite cycle present in the lower subunit of the Sarral Gypsum (see legend); lithofacies are numbered 1 to 3 (see text for explanation). Correlation between three quarry sections: IV: quarry to the N of Pira (this section corresponds to a part of the Section IV in Fig. 7); V: quarry to the NE of Ollers (Fig. 6); VI: quarry to the SW of Sarral (quarry of the “Roman dam”; this section corresponds to section VI in Fig. 6). Cycles are labelled with letters A to D in this Figure.**

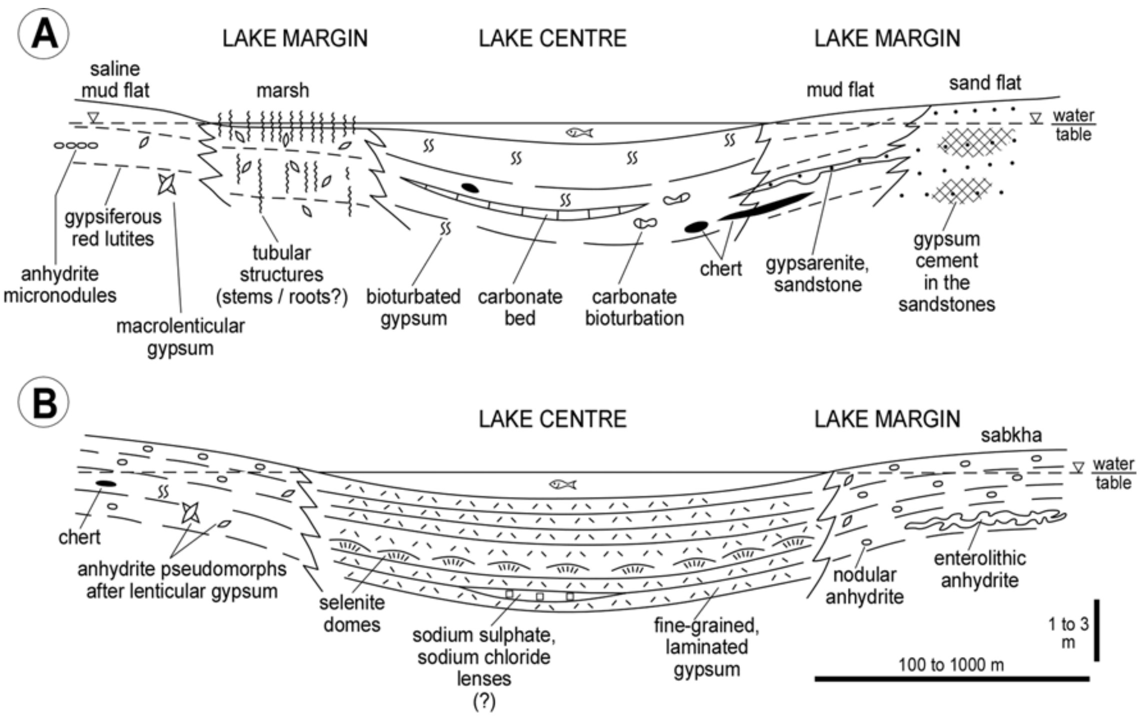

FIGURE 13 | **Interpretation of the depositional lithofacies and subenvironments in the saline lakes of the Barberà sector during the Paleogene. A) Lake characterized by association A. B) Lake characterized by association B; the possibility of a local gradation of this association to nodular gypsum and chert is shown (left part of the scheme).**

This is also the case of the Clariana Gypsum (Fig. 9) and the Sant Martí de Tous Gypsum (Fig. 10), in the Anoia sector. These units change from the predominant association B in the inner parts to nodular (and meganodular) gypsum lithofacies bearing chert nodules in the southwestern outer rims.

The lateral change between the Rocafort Gypsum and the Aguiló Gypsum can be assigned to the gradation from smaller lakes with low salinity located closer to the basin margin to larger lakes with higher salinity in more distal position. Similar changes between the two lithofacies associations are known in other evaporitic units of Miocene age along the Iberian margin of the Ebro Basin (Salvany, 1989; Ortí 1997a), as well as in the Miocene evaporite units of the Calatayud Basin (Ortí and Rosell, 2000). Furthermore, the lateral change from the inner to the outer part of the Clariana Gypsum can be assigned to different salinities between the centre (more concentrated brines) and the margin (less concentrated brines) of the lake. This change is also observed in other Miocene units of the Ebro and Calatayud basins. Unfortunately, the lack in the Barberà sector of outcrops of the evaporite units in a NW–SE direction prevents any observation of the evolution of their lithofacies towards the centre of the basin. In all cases, the low saline waters seem to have exerted a barrier influence for chert formation.

CONCLUSIONS

An important lacustrine evaporitic sedimentation occurred during the Eocene and the lower Oligocene in the Barberà sector of the southeastern margin of the Tertiary Ebro Basin. This sedimentation involved a number of gypsum units, of individual thicknesses of up to 100 m. The distribution and sedimentologic characteristics of these units were controlled by climatic, structural and paleogeographic factors.

The Valldeperes Fm comprises two evaporite units; in the Pira Fm, four evaporite units can be differentiated, this assemblage being thicker toward the SW and thinner to the NE; and the Talavera Gypsum contains a number of evaporitic horizons. The rest of the gypsum units are composed of single evaporitic episodes. All the units are composed of secondary gypsum in outcrop.

The gypsum units belong to two main lithofacies associations: A) massive gypsum bearing chert nodules and gypsum meganodules locally, and B) alternation of banded-nodular gypsum and laminated gypsum, devoid of chert. In some units, the lateral gradation from one association to the other can be observed; in this case, association B occupies the inner part of the unit and association A forms the outer rim.

The units characterized by association A formed in shallow, low concentrated saline lakes, which were located closer to the margin of the basin. These lakes have the following characteristics: bioturbated gypsum was the main primary sediment; some exposure and palustrine features are commonly present; the formation of primary (sabkha) anhydrite is limited; sabkha cycles are absent; and meganodules of anhydrite formed in the thickest layers. Cyclicity in some of these units reflects the progressive development of saline lakes on preexisting red mud flats.

The units characterized by association B formed in saline lakes with a higher ionic concentration, which were located in a more distal position with regards the basin margin. In these lakes, episodes of subaqueous precipitation of laminated gypsum alternated with episodes of interstitial precipitation of banded-nodular and enterolithic anhydrite under exposure conditions (sabkha cycles). Precipitation of sodium-bearing sulphate (and chloride) minerals could occur locally.

The low concentrated brine bodies, from which association A derived, exerted a barrier influence for silica precipitation. Chert was formed as an early diagenetic, lacustrine product in the units characterized by this association. In the units characterized by association B, chert only formed locally in the outer rims.

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