NONMARINE EVAPORITIC SEDIMENTATION AND ASSOCIATED DIAGENETIC PROCESSES OF THE SOUTHWESTERN MARGIN OF THE EBRO BASIN (LOWER MIOCENE), SPAIN

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ABSTRACT: **In the southwestern margin of the Tertiary Ebro Basin (northeastern Spain) several evaporitic units are found among distal alluvial-fan deposits. They are made up of bioturbated microlenticular primary gypsum, secondary nodular and meganodular gypsum after anhydrite, chert nodules, and charophyte limestones.**

These evaporites formed in shallow saline lakes along the basin margin during the early Early Miocene (Autol gypsum unit) and the late Early Miocene (Ablitas, Gravalos, and Ribafrecha gypsum units). The lakes were fed principally by deeply circulated groundwaters loaded with dissolved salts from the old evaporite formations (mainly Triassic rocks) that make up the surrounding mountain chains. Shallow meteoric waters of low concentration also reached the lakes episodically. Concentration of these waters led to deposition of microlenticular gypsum and charophytic carbonates, which were then intensely bioturbated. Early-diagenetic chert nodules and nodular anhydrite also formed. In the early stages of burial large anhydrite nodules (meganodules) overprinted these sedimentary and early-diagenetic deposits. With more advanced burial the primary gypsum was profoundly anhydritized in some areas. With subsequent exhumation the anhydritized zones were transformed to secondary gypsum.

Marginal lakes acted as preconcentrators of drainage waters coming from the surrounding mountain chains, causing early precipitation of low-solubility salts as Ca-carbonates, gypsum, and silica. The remaining dissolved salts then drained toward the basin center, where gypsum, anhydrite, glauberite, polyhalite, and halite precipitated in contemporaneous high-salinity lakes.

INTRODUCTION

There are a number of Tertiary nonmarine evaporite formations in the western Ebro Basin, all with extensive and varied distributions of sulfate and chloride facies (Fig. 1). Most of these evaporites form thick (several hundred meters) and wide (on the order of 80–100 km long by 30–50 km wide) formations in the basin center, made up of gypsum, anhydrite, and halite, and smaller quantities of other sulfates, like glauberite and polyhalite. Minor nonmarine evaporites made up only of salts of relative low solubility, like gypsum, chert, and limestone, are also found along the southern basin margin. These marginal evaporites form several small units with thicknesses never exceeding several tens of meters and with widths of a few kilometers.

Many earlier studies have established the stratigraphy of the western part of the Ebro Basin (Riba 1964; Crusafont et al. 1966; Quirantes 1978; Castiella et al. 1978; Muñoz et al. 1986–87; Pérez 1989; Pérez et al. 1989a, Pérez 1989b; Salvany 1989a, 1989b; Muñoz and Salvany 1990; Muñoz 1992). These studies point out that central evaporites are almost continuous throughout the nonmarine sedimentary succession with periods of marginward expansion and retraction, whereas marginal evaporites are limited to certain periods during basin evolution. These marginal evaporites were deposited principally during two periods of the Early Miocene (Fig. 2): (1) during the Agenian (nonmarine mammal stage equivalent to the Aquitanian), with the deposition of the Autol gypsum unit, contemporaneous with the central evaporites of the Lerín Formation; (2) during the middle Aragonian (equivalent to the Burdigalian), with deposition of the Ablitas-Monteagudo, Grávalos, and Ribafrecha gypsum units, related in this case to the central evaporites of the Zaragoza Formation.

Our purpose is to document the occurrence and significance of these marginal gypsiferous units, with emphasis on their depositional and diagenetic origin as well as their paleogeographic and paleohydrologic relationships with the contemporaneous basin-center evaporites. Petrologic and sedimentologic descriptions of both marginal and central evaporites of the western Ebro Basin have been given by González and Galán (1984), Mandado (1987), Pérez et al. (1988), Salvany (1989a, 1989c), Salvany and Muñoz (1989), and Mandado and Tena (1989), but ours is the first detailed overview of the marginal gypsum units.

GEOLOGICAL SETTING

The Ebro Basin is an Alpine foreland basin whose evolution is directly related to the uplift of the Pyrenean chain that forms its northern margin (Riba et al. 1983). The basin is bordered on the south by the Iberian Chain, which also acted as an active margin, although of less importance (Fig. 1). The Pyrenees are formed mainly of Paleozoic and Mesozoic rocks with a wide variety of igneous, sedimentary, and metamorphic rocks. Lower Tertiary marine sediments are also found in their southern part. The Pyrenees and the nonmarine Ebro Basin are in contact along large reverse faults with hundreds of meters of slip (Muñoz et al. 1983). The Iberian Chain is made up of Paleozoic and Mesozoic rocks that have been put on nonmarine Tertiary rocks by overthrust faults with large displacements (Guimerá and Alvaro 1990; Casas 1992). Some transverse structures are superimposed across these major thurst faults; these are more or less normal to the first set and have acted as wrench faults.

Between the Pyrenees and the Iberian Chain, the nonmarine deposits are mainly Oligocene to Miocene. with thicknesses locally reaching 5000 m. During this time the Ebro Basin, isolated from the sea, was a closed intermontane basin where the erosion products of the surrounding mountain chains accumulated. The nonmarine sedimentation was mainly detrital, involving alluvial-fan systems at the margins of the basin and wide mudflats in the central areas. The lacustrine deposits (evaporites and carbonates) accumulated mainly on the mudflats at the center of the basin, as well as on the distal alluvial-fan areas. Fluvial systems of variable length were also present between the alluvial fans and lacustrine systems of the central basin area.

In the studied area, the Miocene deposits, including the marginal gupsum units and their host detrital units, form a succession 450 m thick that unconformably overlies the Mesozoic sediments of the Iberian Chain and the Paleogene deposits of the Ebro Basin. The succession consists principally of alluvial deposits (conglomerates, sandstones, and lutites) that have a characteristic red color (Muñoz 1992). Oligocene rocks crop out extensively in the central and northern basin areas, forming a succession more than 4000 m thick (Salvany 1989b).

Stratigraphic studies based on tectono-sedimentary analysis have divided the nonmarine Tertiary succession of the study area into nine genetic units (Pérez 1989; Muñoz 1992), limited by erosional breaks in sedimentation; four are Paleogene and the rest are Miocene (Fig. 2A). The breaks are the result of tectonic activity that affected the western sector of the Ebro Basin. They are expressed as angular unconformities in the margins of the basin and as changes in direction of the sequential evolution in the most central areas (González et al. 1988; Pardo et al. 1989). The marginal evaporites were deposited in the earliest Miocene, coinciding with major expansion of the basin center evaporites of the Lerín and Zaragoza For-

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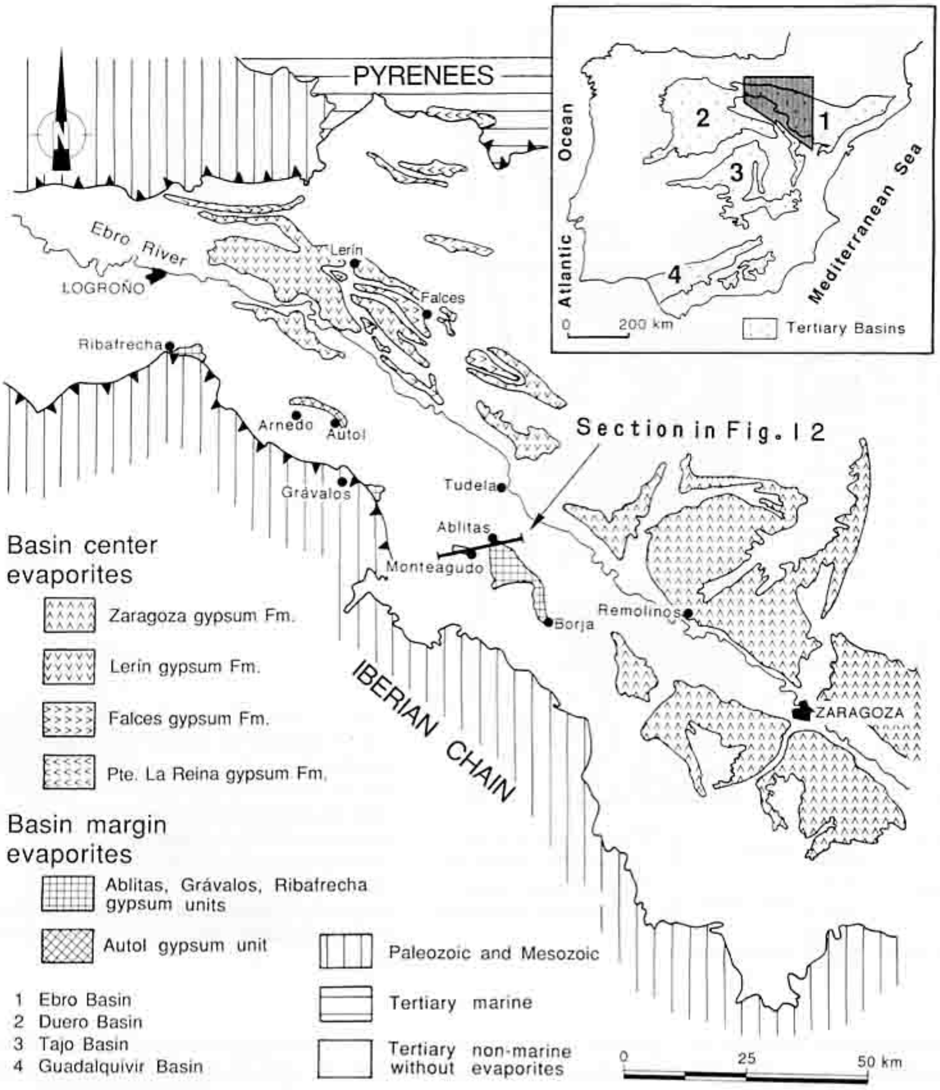

FIG. 1.—Regional distribution of the Tertiary nonmarine evaporite outcrops in the western half of the Ebro Basin.

mations (Fig. 2B). Pérez (1989) and Muñoz (1992) interpreted these stages of major lacustrine deposition to have resulted from a decrease in alluvial activity at the basin margins caused by minor tectonic activity in the surrounding mountain chains.

PETROLOGY OF THE EVAPORITES

In the marginal gypsum units the following facies types may be distinguished: (1) primary gypsum: gypsilutite, gypsarenite; (2) secondary gypsum: micronodular-nodular, lenticular rosette-like pseudomorphs, meganodular; (3) limestones; (4) chert nodules; (5) host siliciclastic sediment. (We use the term "primary" to refer all evaporitic minerals precipitated directly from brines, irrespective of whether they formed in free water or were intrasedimentary.) Figure 3 summarizes for each gypsiferous unit its facies association and relative abundance.

Primary Gypsum

Primary gypsum forms massive beds with microlenticular texture, bioturbation structures, and chert nodules. It contains variable proportions of limestone and/or clays as matrix as well as rare small celestite crystals (less than 50 μm in size). Two varieties can be distinguished:

Fine-grained microlenticular gypsum (gypsilutite) forms dark-brown massive beds up to 2 m thick, whose microlenticular nature can be determined only by petrography. This is a pure gypsum but in many cases it shows clear brown irregular bands and zones of mixed limestone-gypsum composition. These mixed zones probably originated by bioturbation of initially well-stratified gypsum and limestone beds on the order of tens of centimeters thick that alternate in the succession. The microlensoids are 100–500 μm in size, and together form a dense microlenticular aggregate with a nonoriented structure (Fig. 4). Each microlensoid constitutes an optically homogeneous monocrystal that in many cases shows interpenetration boundaries and syntaxial overgrowths.

On the basis of these characteristics we interpret this gypsum as a lake-bottom sediment that grew at the sediment-water interface or interstitially in lake-bottom sediments. These lensoids do not show fractures or erosional marks, or any other type of preferred orientation or sorting, as would be the case if they had undergone transportation before sedimentation.

Coarse-grained microlenticular gypsum (gypsarenite) is found as millimeter-size crystals and can be observed in hand specimen. They form massive greenish or reddish beds several meters thick. The beds contain considerable clay matrix, which is also responsible for their color. Under the microscope the lensoids are seen as monocrystals of variable size and

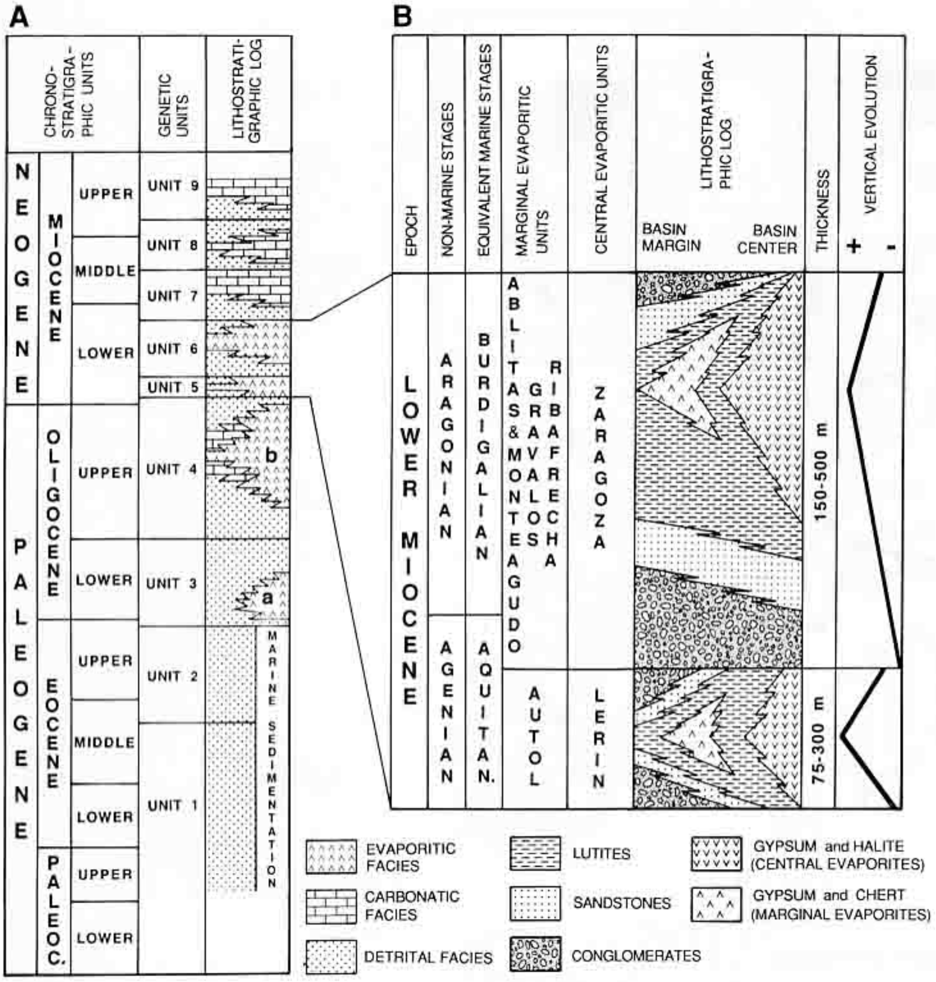

FIG. 2.—Stratigraphy of the nonmarine evaporitic deposits in the western half of the Tertiary Ebro Basin. **A)** General stratigraphic section showing the genetic units and evaporitic units distribution: (a) Puente La Reina gypsum formation, (b) Falces gypsum formation. **B)** Detailed stratigraphy of the Lower Miocene in the southwestern Ebro Basin, showing both marginal and central evaporitic units as well as their relationships with surrounding detrital deposits.

nonoriented structure. They show flattened morphologies (discoidal or spatulate) with perpendicular cleavage planes, and interpenetration boundaries (Fig. 5). Twinned crystals are also common.

Coarse microlenticular gypsum beds in some cases show small-scale cross-stratification structures (current ripples and oscillation ripples) and erosional scars, suggesting a detrital origin. These structures are commonly disrupted by later bioturbation. In thin section it can be seen that some gypsum microlensoids have grown by cutting across current-generated and bioturbation structures. Although the gypsum has been transported or remobilized to some extent, we believe that most of it has formed *in situ* as intrasedimentary growths within the soft lutitic sediment of the lake margins. A similar microlenticular gypsum of intrasedimentary origin has been described in Bristol Dry Lake in California (Rosen and Warren 1990). The gypsum precipitated in this nonmarine shallow saline lake as a diagenetic mineral within the near-surface sediments in the saline mud flat around the lake. Their precipitation from shallow brines is demonstrated by petrologic and isotopic data (Rosen and Warren 1990).

LOCATION	UNIT / AGE	FACIES ASSOCIATION		
		DOMINANT	ABUNDANT	SCARCE
MONTEAGUDO	6 Aragonian	Gl, Ga	Bt, Ch	L
ABLITAS		Gl, Ga, Gn	Bt, Gm, Ch, L	GL
GRAVALOS		Ga	Bt	
RIBAFRECHA		Gn	Gm, Ga, L	Bt, Ch, Gl
AUTOL	5 Agenian	Gn		Gm, Ch

Ga = Gypsarenite (primary gypsum)
Gl = Gypsilutite (primary gypsum)
Gn = Nodular-micronodular secondary gypsum
Gm = Meganodular secondary gypsum
GL = Lenticular rosette-like pseudomorphs in secondary gypsum
Ch = Chert nodules
Bt = Bioturbation
L = Limestone

FIG. 3.—Facies associations in the marginal evaporitic units in the studied outcrops.

Between the two types of microlenticular gypsum (gypsilutite and gypsarenite) there exists an intermediate facies that corresponds to the transition from the marginal area to the inner lake area. In this facies, isolated millimeter-size crystals are present within the gypsilutite, or the two forms of gypsum alternate in the same bed.

Bioturbation is common in both varieties of microlenticular gypsum. It consists of burrow structures, several millimeters in diameter, that cross the gypsum beds mainly vertically (Fig. 6). Whole gypsum crystals are tangential to the burrow walls, and form inside a characteristic structure of concentric arcs aligned in the same direction as the burrow (Fig. 6C). Also common are bioturbation traces filled by gypsum cement, which forms a fine crystalline equigranular mosaic that occupies void spaces (Fig. 6D).

From these observations it is clear that bioturbation was more or less contemporaneous with precipitation of gypsum, and that the gypsum crystals are part of the burrow structures and also grew on top of them. By

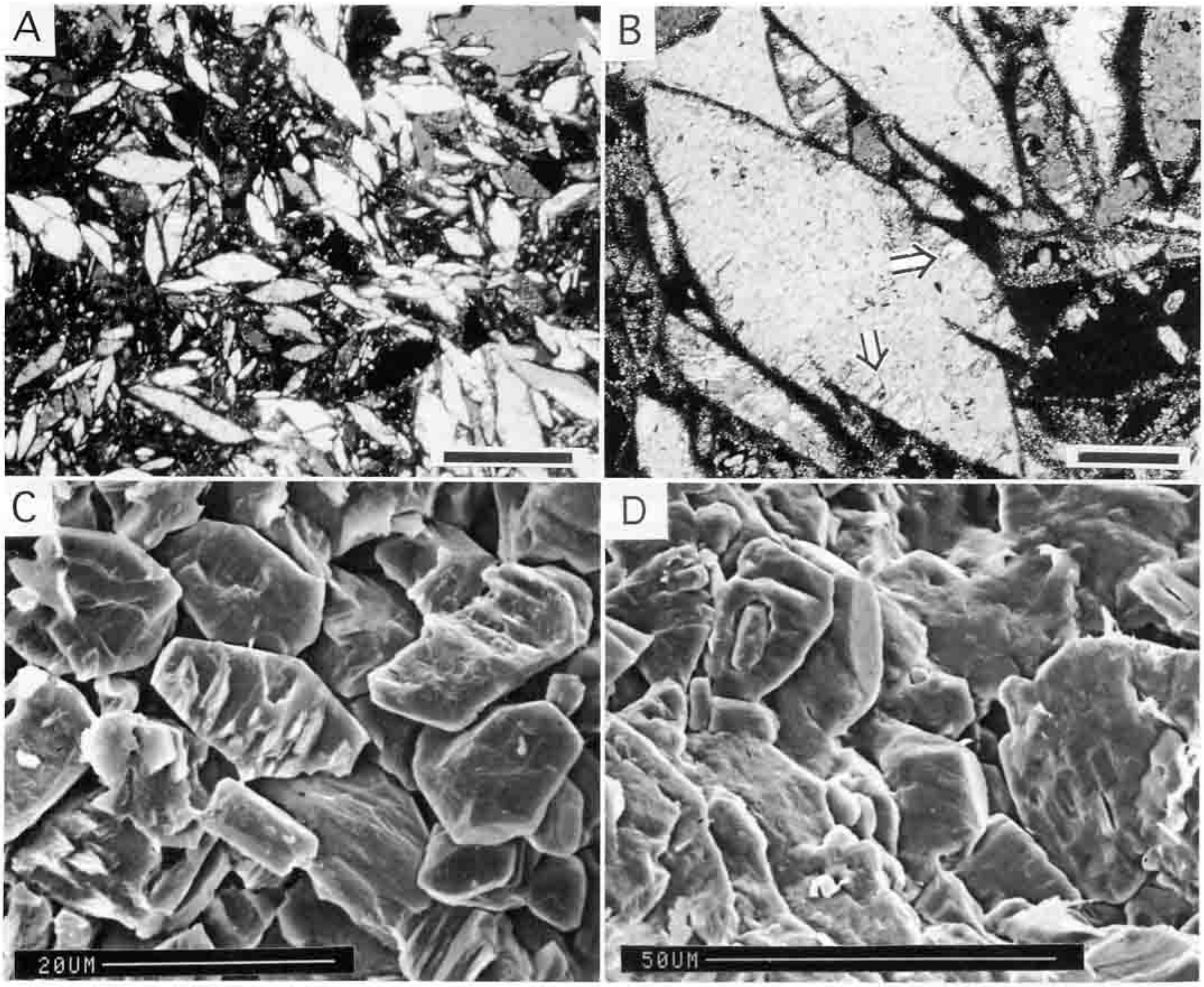

FIG. 4.—Gypsilutite fabrics. **A)** Thin-section photomicrograph of typical nonoriented gypsilutite aggregate. Scale = 500 μm. **B)** Detail in thin section of microlensoids with small calcite crystals growing on their crystalline boundaries. Scale = 100 μm. **C, D)** microlensoid morphologies in scanning electron micrographs.

their size and characteristics, the burrows could have been formed by small aquatic animals tolerant to a certain level of salinity, like worms or insects, that have not left any fossil remains.

Secondary Gypsum

Secondary gypsum is present in its typical alabastrine, porphyroblastic, and megacrystalline fabrics as described in many petrologic studies on gypsum (Holliday 1970; Mossop and Shearman 1973; Ortí 1977; among others). Primary gypsum, described above, is readily distinguished by its textural characteristics as well as by the type of facies it presents. In the various facies studied, the secondary gypsum arises from the transformation of anhydrite to gypsum. The residual anhydrite can be recognized under the microscope as relict inclusions in many crystals of secondary gypsum (Salvany 1989a, 1989b). Anhydrite was transformed to secondary gypsum during exhumation of the deposit. This process, common in the many ancient calcium-sulfate rocks now at the surface, is true also for the secondary gypsum described here, as shown by (1) absence of anhydrite in outcrop and (2) presence of anhydrite at depth, observed in boreholes and mines. These deeper deposits show the same facies as the studied secondary gypsum (transformation from deep anhydrite to secondary gypsum at or near the surface has not caused changes in the lithofacies shape and volume). This anhydrite commonly shows early indications of rehydration in the form of early crystals of secondary gypsum (porphyroblasts) and veins of secondary gypsum. Nevertheless, in some cases secondary gypsum might have formed by hydration of anhydrite during early diagenesis, and was preserved until now, in the same way that primary gypsum has been preserved.

The anhydrite from which the secondary gypsum originated may have formed in either of two scenarios: (1) as early-diagenetic anhydrite in the sedimentary evaporite system or (2) by dehydration of the gypsum sediment during burial of the deposit (late diagenesis). Early-diagenetic and late-diagenetic anhydrite (now secondary gypsum) form clearly different facies. The early-diagenetic anhydrite formed as a nodular facies that has displaced the host sediment and has destroyed the original microlenticular gypsum fabric. However, late-diagenetic anhydrite has not altered the original structure of the gypsum, and keeps its primary characteristics:

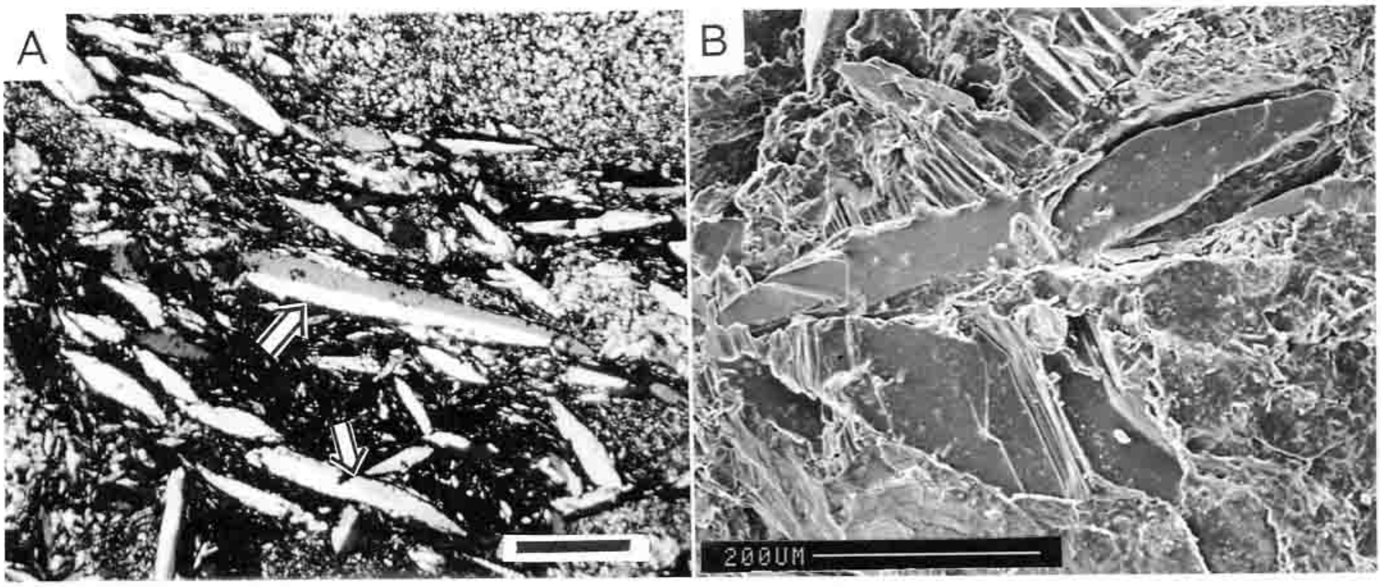

FIG. 5.—Gypsarenite fabrics. **A)** Thin-section photomicrograph of flattened lensoids scattered in a fine carbonate mudstone. The arrow indicates a typical twinned crystal in this gypsum facies. Scale = 500 μm. **B)** Lensoids showing their common cleavage planes perpendicular to the flattening direction of the crystal in scanning electron micrographs.

color, bioturbation, etc. In this anhydrite the microlenticular gypsum is still easily recognizable as pseudomorphs.

In the studied evaporites, the anhydrite formed principally during early diagenesis and/or during the initial phase of burial. Only some gypsiferous facies from Autol and Ribafrecha suffered anhydritization by burial. In the case of Autol, its altered layers were confined below a thicker Miocene succession. In Ribafrecha, anhydritization was driven by the compressive effects of the overlying thrust sheets of the Iberian Chain.

Secondary gypsum is found as the following facies:

Micronodular and nodular gypsum. This forms most of the known gypsum in the study area. Nodule size is variable, although the micronodular variety (less than 1 cm in diameter) is the most abundant, forming massive meter-thick beds with chicken-wire structure. These micronodular beds are normally white, although they may be green, red, or brown where clay or limestone is present as host sediment.

We consider that these nodular and micronodular gypsum facies originated as early-diagenetic anhydrite in the lake system by transformation of microlenticular gypsum during dry periods. The transformation totally destroyed the original structure of the sediment, and relics of the primary gypsum microlensoids are never found. Pseudomorphs after microlenticular gypsum, however, are always recognizable in chert that formed before anhydritization and commonly accompany these nodular and micronodular gypsum facies.

Lenticular rosette-like pseudomorphs. In the Ablitas area there are layers of rosette pseudomorphs in alabastrine secondary gypsum. These rosettes are found within lutites, forming layers with considerable lateral continuity. They have also been observed in carbonate beds as lenticular casts following dissolution of gypsum (Fig. 7). These rosettes originated as displacive primary gypsum between lutites or carbonate sediments. Their anhydritization (before secondary gypsum) was during early diagenesis, because no anhydrite was formed by burial in the Ablitas gypsum unit.

Meganodular gypsum. This is a characteristic element of these basin-margin evaporites, between both primary and secondary gypsum facies. The size of the meganodules varies between 20–30 cm and 1–2 m, and they are found isolated or in well-formed discontinuous layers parallel to stratification (Fig. 8A). The meganodules are superimposed on all sedimentary and early-diagenetic structures, slightly deforming (Fig. 8B) or cutting through them (Fig. 8C). They therefore grew after sedimentary and early-diagenetic processes of the saline lake but before complete compaction and lithification.

The origin and significance of these meganodules is not exactly clear. They may be related to the first stages of burial of the evaporite deposit, growing as nodules of anhydrite, probably as a result of the circulation of deep groundwaters saturated with calcium sulfate.

Limestone

Limestone, always minor to sulfates, is present as the matrix surrounding gypsum or as thin (up to 20–30 cm) massive or bioturbated beds. Its texture is always the same: wackestone-packstone of calcitic and rarely of dolomitic composition. The components are micritized but are easily distinguished. In order of importance they are (Fig. 9A, B) micritic mud, aquatic plant fragments (mainly charophyte stems), peloids, ostracods, and gastropod fragments.

Superimposed on these components, diagenetic calcite crystals of prismatic or fusiform habit have grown to a size of 100–300 μm (up to 500 μm in some cases). They are present as individuals or as aggregates. Similar calcite crystals developed also in the microlenticular boundaries of gypsum and micronodular boundaries of anhydrite (Figs. 4B, 9C, 9D). The cause of development of these calcites is not entirely clear. Similar textures have been described in Pleistocene playas of southern Australia (Warren 1982). There, lensoids of gypsarenite are partially or totally replaced by low-Mg calcite in vadose profiles. Replacement derived from the evaporation of downward-percolating rain water.

Chert

Chert is found in primary and secondary gypsum and in the carbonates, forming nodules from centimeter scale to more than a meter in size (Fig. 10A). The greater the size of the chert nodules the more irregular the shape. Commonly they show contorted structures (Fig. 10B) and in many cases follow irregularities in the gypsum beds. They are dark brown, although lighter tones are common (white nodules). In thin section they show growth zones, pseudomorphs after microlenticular gypsum (Fig. 10C), and impurities of carbonate and clay.

Chert nodules seem to be more abundant in the inner lacustrine deposits and decrease in quantity and size toward the marginal zones. Different

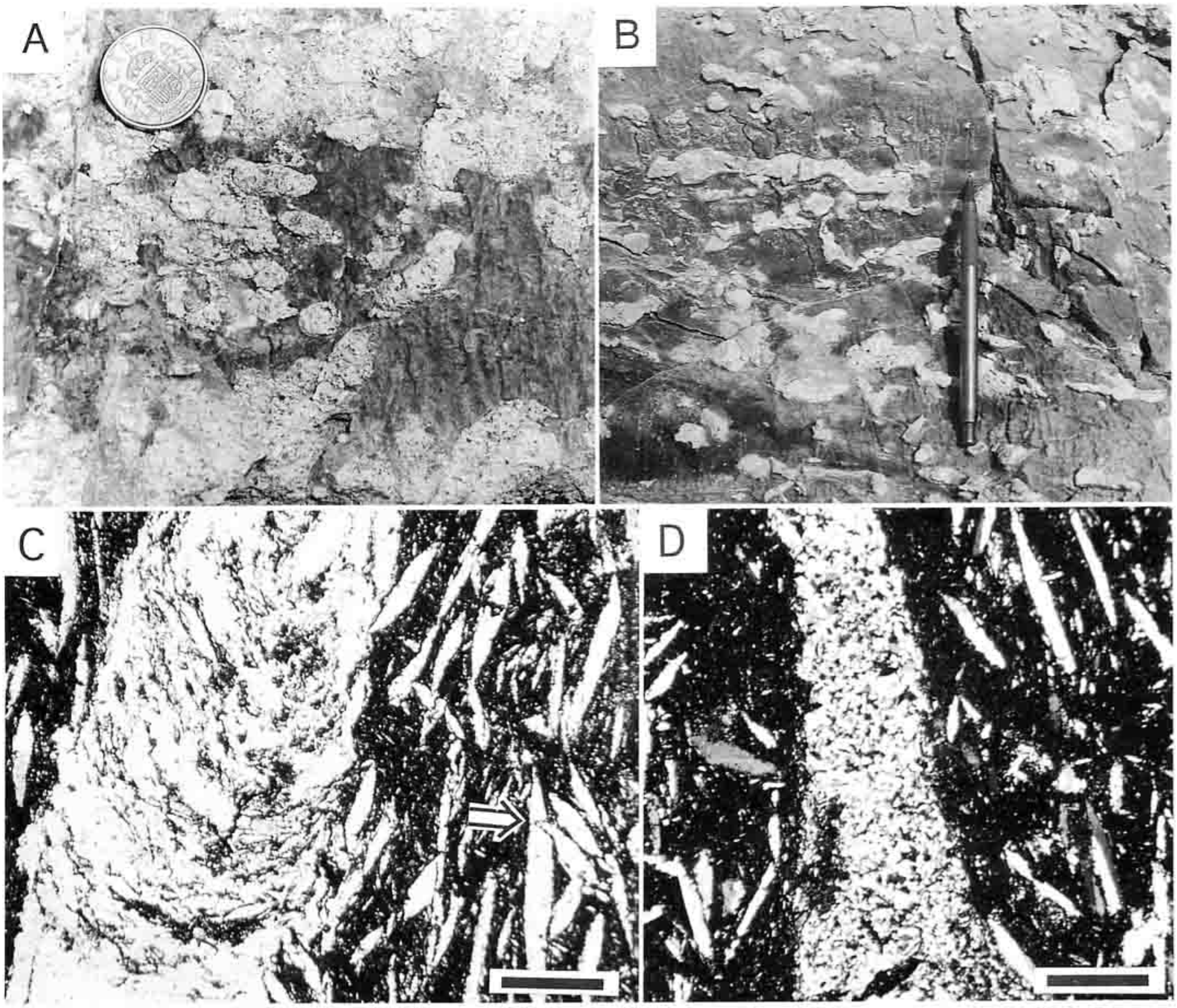

FIG. 6.—Bioturbation in microlenticular gypsum. **A, B)** Bioturbation facies in the Ablitas quarry outcrop (see Figure 12 for location). Dark zones correspond to pure brown gypsum and light zones are of mixed limestone-gypsum composition. **C)** Thin-section photomicrograph of a burrow showing the microlensoid arrangement in concentric arcs following the growth direction of the burrow. Scale = 1 mm. **D)** Thin-section photomicrograph of a burrow filled by fine microcrystalline gypsum as cement. Scale = 1 mm.

textural varieties can be distinguished in thin section: in order of importance, microcrystalline aggregates, spherulites of fibrous-radial structure of lutecite and quartzine 200–500 μm in diameter, equigranular mosaic (cement?), and opaline zones.

The usual presence of microlenticular pseudomorphs in chert nodules in both primary and secondary gypsum facies points toward their replacive origin from primary gypsum before early-diagenetic anhydritization. Replacement was probably as an opaline soft precipitate that recrystallized and later formed other textural varieties before consolidation.

Siliciclastic Host Sediment

The detrital sediment that encloses the various evaporite facies is dominantly clay. In all the samples analyzed, the clays are of similar mineral composition, characterized by the association illite-smectite-chlorite-kaolinite, with variable proportions of quartz, feldspar, calcite, and dolomite. González and Galán (1984) have further detected sepiolite and interlayered illite-smectite. The relative abundance of smectite is of particular importance, because this mineral is very rare in the basin-center evaporites.

For the most part these clays are detrital, derived mainly from alteration of Mesozoic sedimentary rocks from the Iberian Chain with subsequent transport to the basin across alluvial fans. Some clays may, however, be authigenic, like the magnesian smectites and sepiolites that were generated in alkaline waters with high contents of Si and Mg (González and Galán 1984). The high crystallinity of these clays as deduced from XRD diagrams suggests regeneration after deposition in brine-saturated sediments.

RELATIONSHIP BETWEEN EVAPORITE FACIES AND SEDIMENTARY INTERPRETATION

The lateral relationships between the various facies can be established in detail in the Ablitas-Monteagudo area (Figs. 11, 12).

FIG. 7.—Lenticular rosette-like casts (after gypsum) in a limestone bed in the Ablitas unit.

Near Ablitas, beds of fine and coarse microlenticular gypsum with intense bioturbation are dominant, forming a continuous interval 5–10 m thick. Chert nodules and meganodules of secondary gypsum are also present scattered between both fine and coarse microlenticular gypsum. Chert nodules are largest and most abundant in this area. Toward the southwest, in the Monteagudo area, gypsum continues to be primary but is less well developed, forming several thin layers interbedded with relatively proximal alluvial facies (lutites and paleochannels of siltstones, sandstones, and conglomerates).

To the east and southeast of Ablitas there is major lateral facies change: primary gypsum passes into secondary nodular gypsum in all its varieties (micronodular, nodular, and meganodular). This succession extends over a much greater distance than the primary gypsum. Peripheral to this zone, the nodular gypsum beds wedge out within the distal alluvial facies (very pure lutites) until they disappear completely. Layers of lenticular gypsum (rosettes) and charophyte limestones can be distinguished in the lutites. In this area of marginal lacustrine facies, chert and meganodules of secondary gypsum are small and scarce.

The outcrops of the other gypsiferous units of the basin margin allow only partial observation of facies distribution, although in general the facies associations and the observed trends are similar. Only the characteristics of the Ribafrecha gypsum appear to differ greatly from the other outcrops studied. In this unit, bioturbation is almost absent and silica and carbonate layers are poorly developed.

On the basis of these facies relationships, we believe that the studied gypsiferous units can be interpreted as having originated in a marginal saline lake system formed by two depositional subenvironments (Fig. 12): (1) A shallow saline lake, relatively stable and fed regularly by groundwaters loaded with dissolved salts from the evaporite formations that make up the Mesozoic basement of the Iberian Chain. The lake was subjected to dry and humid periods that produced fluctuations in water salinity and expansions and contractions of the lake. During dry periods, waters reached moderate to high salinities, and gypsum precipitated as both fine and coarse microlensoids. The fine microlenticular gypsum nucleated on the surface of the lake bottom while coarse microlenticular gypsum grew in the soft sediment of the lake margins. During humid periods, meteoric waters supplied the lake, causing brine dilution and lake expansion. The lake was then colonized by aquatic plants (mainly charophytes) and other organisms like ostracods and gastropods, which were also responsible for

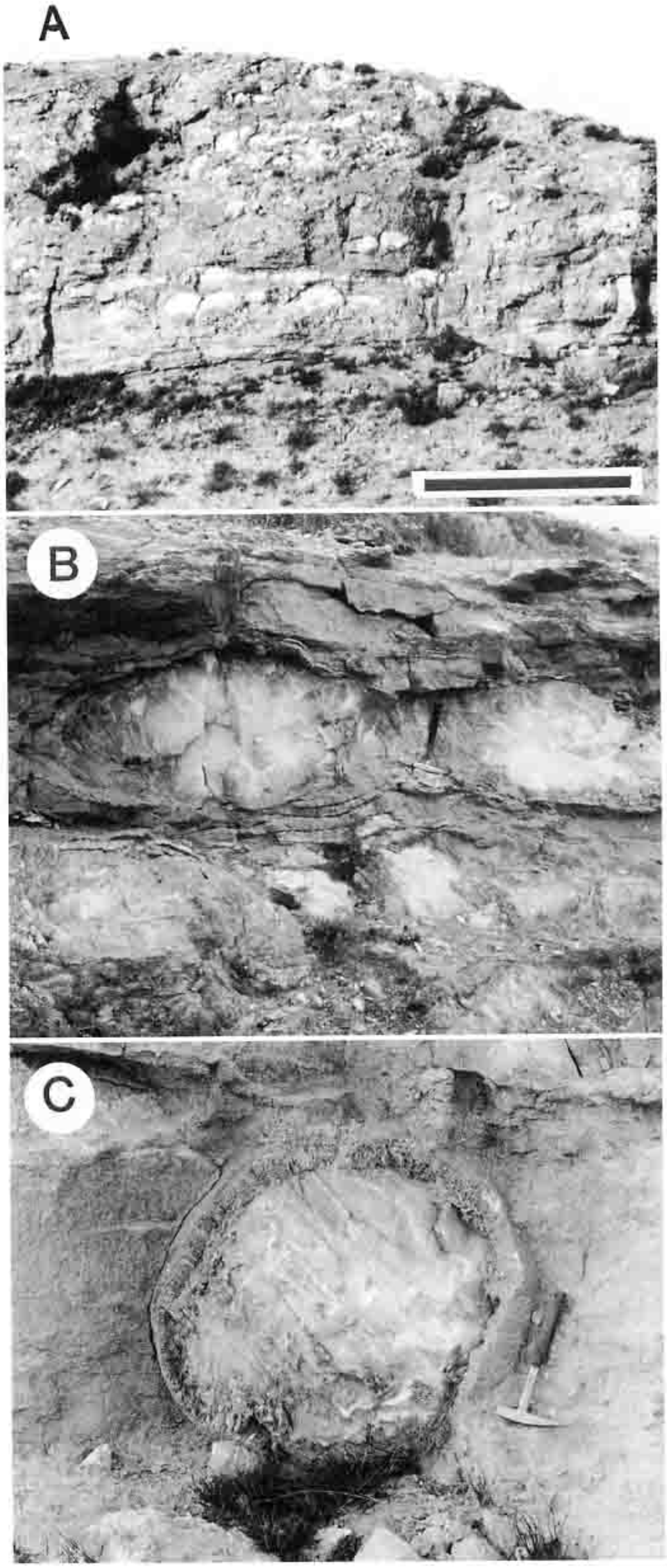

FIG. 8.—Meganodular secondary gypsum in the Ablitas unit. **A)** General view showing the meganodular distribution in El Portillo outcrop (see Figure 12 for location). Scale = 4 m. **B)** Meganodules in a micronodular secondary gypsum bed showing compaction of the surrounding material. **C)** Replacive meganodule in a primary microlenticular bed with no distortion in the surrounding material.

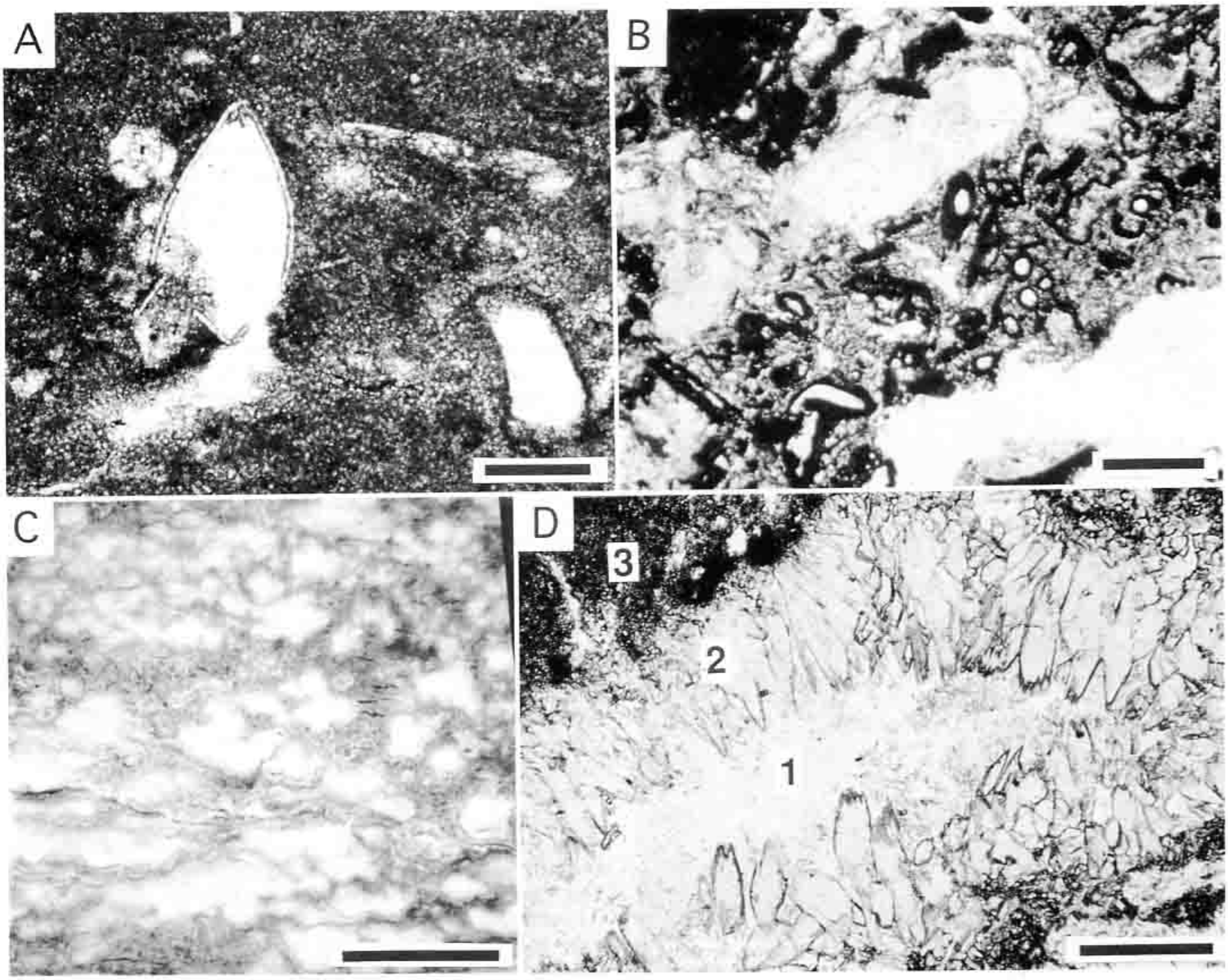

FIG. 9.—Carbonate components. **A)** Thin-section photomicrograph of an ostracod section in a carbonate mudstone sample in the Ablitas unit. Scale = 100 μm. **B)** Thin-section photomicrograph of stem sections of aquatic plants in the Ablitas unit. Scale = 1 mm. **C)** Micronodular secondary gypsum (white) from the Ribafrecha unit (in hand specimen) showing their common microcrystalline calcite matrix (dark zones). In part, calcite crystals replace the micronodular boundaries, creating their irregular shapes. Scale = 2 cm. **D)** Thin-section photomicrograph of a micronodule from the preceding sample: (1) micronodular core with secondary gypsum containing small relict inclusions of anhydrite; (2) micronodular boundary replaced by calcite crystals; (3) carbonate mudstone host material. Scale = 500 μm.

the bioturbation of the previously precipitated gypsum. (2) A peripheral saline mudflat, where the intrasedimentary growth of anhydrite dominated, caused by evaporation of shallow groundwater. This saline mudflat was inundated during episodes of lacustrine expansion, permitting precipitation of gypsum, which was later anhydritized during stages of desiccation.

The Autol marginal evaporites were contemporaneous with the central evaporite system of Lerín, which formed an extensive lacustrine system, elongated northwest-southeast, in the western sector of the Ebro Basin (Fig. 13A). This central system had three concentric sedimentary subenvironments, each with gradational transitions (Salvany 1989a): (1) A central shallow saline lake, with precipitation of laminated halite and gypsum facies. In these laminated facies grew subordinate diagenetic nodules and crystals of anhydrite, glauberite, and polyhalite, which demonstrate the unstable character of a lake that suffered periodic desiccation events. (2) An internal saline mudflat, where laminated gypsum and diagenetic products of gypsum, anhydrite, and glauberite alternate in variable proportions. The diagenetic evaporites came from dry stages of the saline mudflat and laminated gypsum from periodic inundations at times of lake expansion. (3) An external saline mudflat, where only diagenetic nodular anhydrite formed, indicating that the lake proper did not extend to this area. This last facies passes gradually into a dry mudflat with subordinate sandstone channels, corresponding to the distal area of the alluvial systems. Also developed on the periphery of the central evaporite system were palustrine carbonate zones with abundant charophyte and ostracod sedimentation.

The Ribafrecha, Grávalos, and Ablitas marginal evaporites were contemporaneous with the Zaragoza central evaporite system (Fig. 13B). This central system, now shifted toward the east of the basin, also consisted of a central saline lake and a peripheral saline mudflat with characteristics similar to the Lerín lacustrine system. However, the positions of the marginal evaporites remained in the western sector of the basin. In this new paleogeography the Ablitas lacustrine system surrounded the Zaragoza

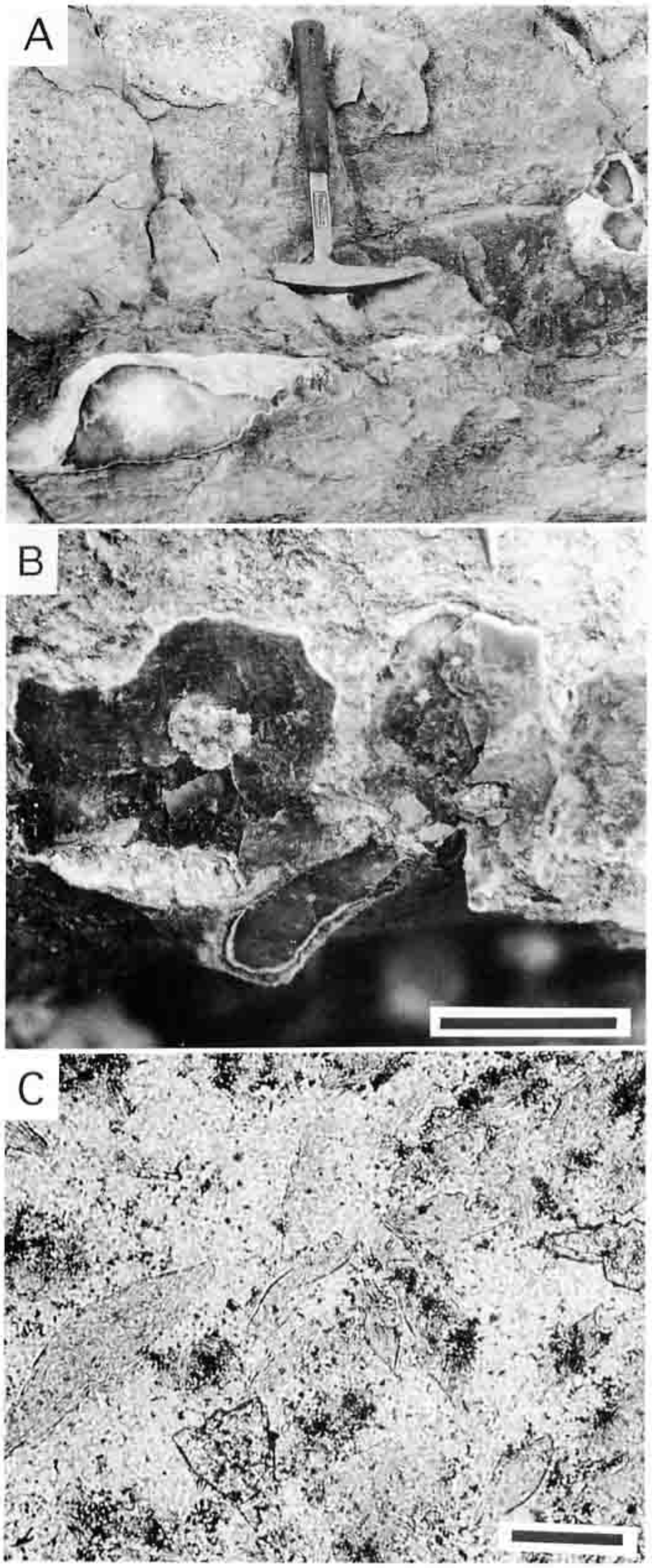

FIG. 10.—Chert nodules. **A)** Common chert-nodule arrangement in a gypsum bed in the Ablitas unit. **B)** Detail of a chert nodule with contorted structure in the Ablitas unit. Scale = 5 cm. **C)** Thin-section photomicrograph of chert showing pseudomorphs after primary gypsum in the Autol unit. Scale = 100 μm.

central system, similar to the relationship of the Autol marginal system to the Lérin lake system. The Grávalos and Ribafrecha evaporites, however, were completely enclosed by the fluvial and alluvial clastic sediments of the western sector of the basin and were far away from the basin-center evaporites.

Deposition of the marginal evaporites was related to the dynamics of the southwestern margin of the basin, and they adapted in time to the evolving paleogeography created by alluvial-fan migration. Nevertheless they seem to be independent of the position of the central systems as determined by the movements of the depocenter of the basin.

DISCUSSION

Ancient evaporitic formations with characteristics similar to those described here are common in other areas of the Ebro Basin, and also in other nonmarine Tertiary basins of the Iberian Peninsula, for example the Tajo, Duero, and Calatayud basins (Ortí 1992; Rodríguez-Aranda 1992). It is not always easy, however, to interpret the sedimentology and petrogenesis of these deposits owing to the scarcity of comparable present-day models.

Current works that discuss saline lakes of nonmarine origin (Hardie et al. 1978; Eugster and Hardie 1978; Smoot and Lowenstein 1991; among others) describe mainly perennial or ephemeral lakes of high-solubility salts. Some of these lakes (e.g., Bristol Dry Lake in California) show primary gypsum facies similar to those described here, but in general they have sedimentary and diagenetic features rather different from those of the marginal evaporites in the Ebro Basin. Examples of low-salinity nonmarine lakes are found in Australia, however (De Deckker 1988; Burne et al. 1980; Warren 1982).

Burne et al. (1980) described diverse types of modern nonmarine saline lakes with development of charophytes and evaporites (mainly gypsum) in southern Australia. The charophytes that live in these lakes have a great tolerance to the salinity of the waters, with some species able to grow in waters with 70 g/l concentration. As a whole, these Australian lakes are in a semiarid climate, with hot summers and relatively wet winters, and have a sedimentary record that reflects the hydrology and chemistry of the waters. The charophytes are most abundant in winter. Their activity ceases in very hot summers, when the lake becomes partially or totally desiccated and the salinity becomes high, but they can easily regenerate after long periods of desiccation (up to several years).

Large parts of the saline lakes described by Burne et al. (1980) are relatively stable, situated in zones of groundwater discharge that maintains the water-table level and the salinity typically between 20 and 50 g/l. Charophytes may grow across the saline lake during humid periods or in more arid settings only in more dilute marginal lacustrine areas that are partially isolated from the more saline center of the lake. In these cases the evaporitic sediment is gypsum, deposited as discoidal crystals or lensoids of variable size that grew on the lake bottom and were deposited together with charophytes, gastropods, ostracods, and nonmarine foraminifera.

In general terms, the saline lakes described in Burne et al. (1980) are similar in sedimentary characteristics to the evaporitic formations of the southwestern margin of the Ebro Basin. The "temporary saline lake" was fed by groundwaters, with gypsum or charophyte sedimentation depending on the seasonal fluctuations of water salinity. Anhydrite nodules are not found in the Australian examples, however; this may reflect less arid conditions than in the Tertiary Ebro Basin.

The existence of saline lakes at the foot of the Iberian Chain during the Miocene that were fed regularly by groundwater is in complete agreement with hydrogeologic studies of Sánchez et al. (1992), Martínez-Gil et al. (1988), and San-Román et al. (1989), who pointed out the importance of subsurface drainage from the Iberian Chain as the present-day supply for

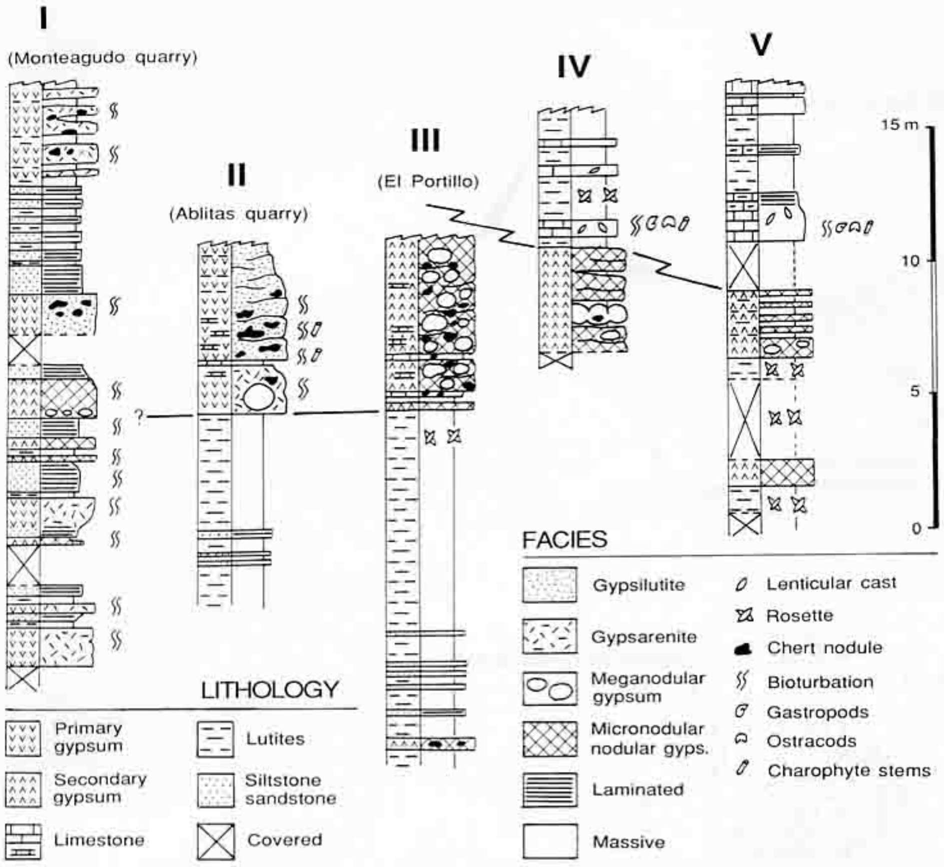

FIG. 11.—Representative logs of the Ablitas unit showing the lithology and facies arrangement.

the springs and lacustrine areas along the southern margin of the Ebro Basin. They considered that this was also true for a large part of the Tertiary (at least for the Miocene, when the structural configuration was not very different from that of today). Underground drainage is favored by regional aquifers that exist in the margins and the basement of the Ebro Basin. The basement consists mainly of stacked thrust sheets aligned in northwest-southeast and strike-slip faults perpendicular to them (Casas 1992). The thrust sheets are partly covered by Tertiary alluvial sediments (Fig. 14).

The waters of these deep aquifers are mainly of calcium-sulfate type,

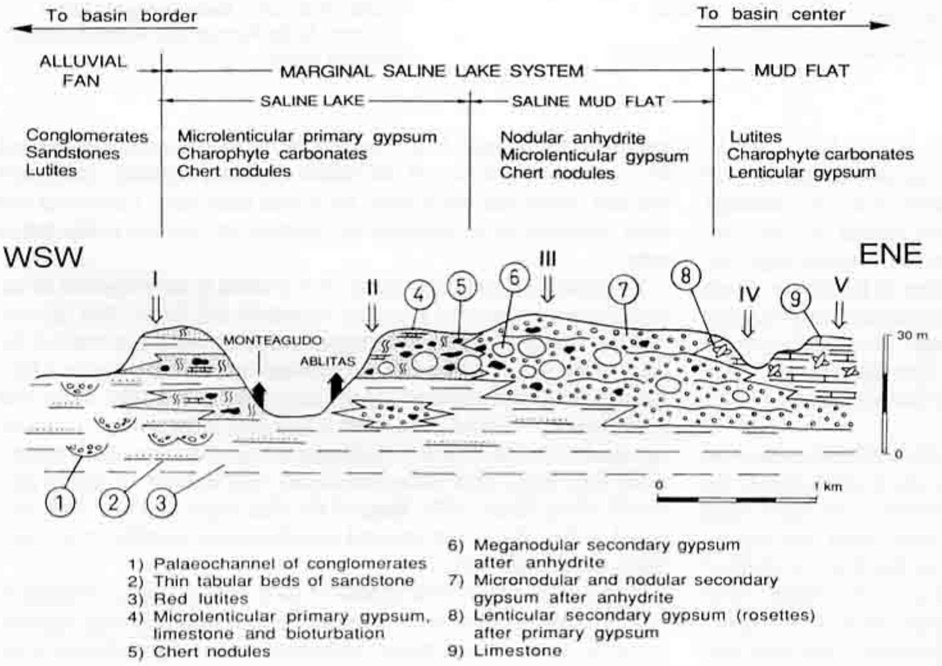

FIG. 12.—Schematic cross section through the Ablitas unit, showing the relationship between the various evaporite facies and their paleoenvironmental interpretation. Roman numerals indicate the location of logs in Figure 11.

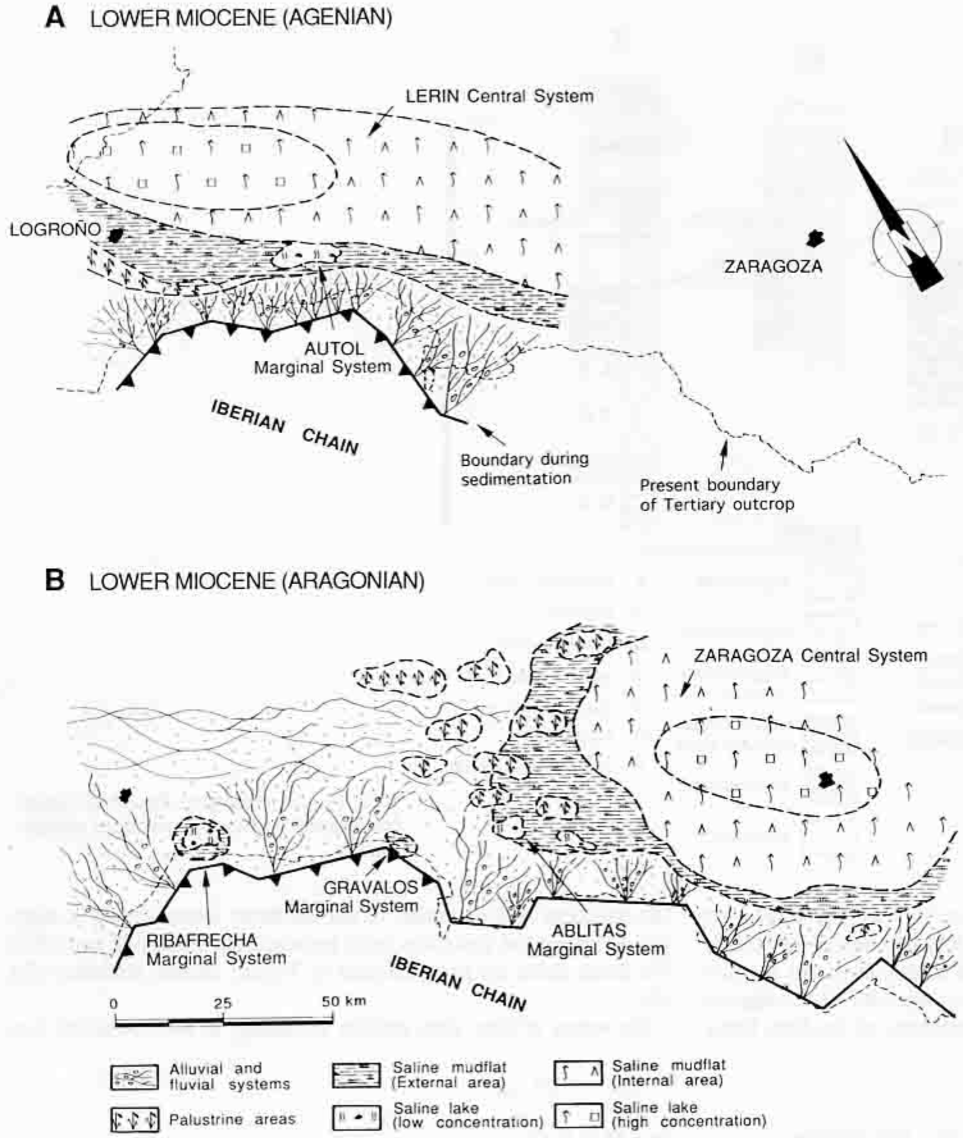

FIG. 13.—Paleogeographic distribution of lacustrine evaporite systems in the southwestern margin of the Ebro Basin during the Lower Miocene: **A)** the Agenian and **B)** the Aragonian mammal stages.

with minor concentrations of HCO_3^-, Cl^-, Na^+, Ca^{++}, Mg^{++}, and Si, and total dissolved solids of 1000–3000 mg/l. Emanation temperatures of spring waters oscillate between 22 and 25°C (Sánchez et al. 1992) although in some cases may reach 40–45°C (e.g., thermal springs of Fitero and Arnedillo; Albert 1979). The high temperatures and relatively high concentrations are a result of slow and deep drainage of the Iberian Chain aquifers, and the dissolution of the Triassic evaporites (anhydrite and salt) that are very abundant below the Iberian Chain. The recycling of the Triassic evaporites through the Tertiary of the Ebro Basin has also been confirmed using sulfate isotopes (Birnbaum and Coleman 1979; Utrilla et al. 1991).

Hydrologic studies by Martínez-Gil et al. (1988) and San-Román et al. (1989) were used to construct Figure 14, which shows schematically the hydrologic system that controlled the development of the saline lakes during the Miocene in the southwestern Ebro Basin. There was deep regional underground inflow that rose toward the surface from the fronts of the thrust sheets buried below alluvial deposits of the Ebro Basin. These waters, warm, mineralized, and of relatively constant flow, were the principal suppliers to the marginal saline lakes. Surface waters may have been responsible for periodic dilution and drainage of the marginal lake waters toward the basin center. In the central zone the waters, newly concentrated by evaporation, precipitated the sulfates (gypsum, anhydrite, glauberite) and salts (halite) that characterize the central saline lakes. Carbonates and silica, deposited earlier about the lake margins, are very rare in this central zone.

The abundance and large size of chert nodules in the evaporites of the basin margin are not easy to explain. Mandado and Tena (1989), Salvany (1989b), and Ortí et al. (1991) suggested that the silica that reached the basin margin was dissolved in the drainage waters of the Iberian Chain and that the source sediment was the major Mesozoic detrital formations (Buntsandstein, Utrillas, Weald, etc.). This idea is supported by present-day dissolved silica content in underground waters of the southern margin of the Ebro Basin, with values that usually vary between 10 and 40 mg/l (IGME 1982; Albert 1979). Some of the silica might also have been generated in the lake by clay-mineral transformation (Bustillo et al. 1989; Inglès and Anadón 1991).

Precipitation of the silica appears to have been inorganic. Progressive concentration of brines in the evaporite environment and their rapid dilution by meteoric fresh waters would have caused sharp changes in the physicochemical conditions (pH, temperature, concentration), and could

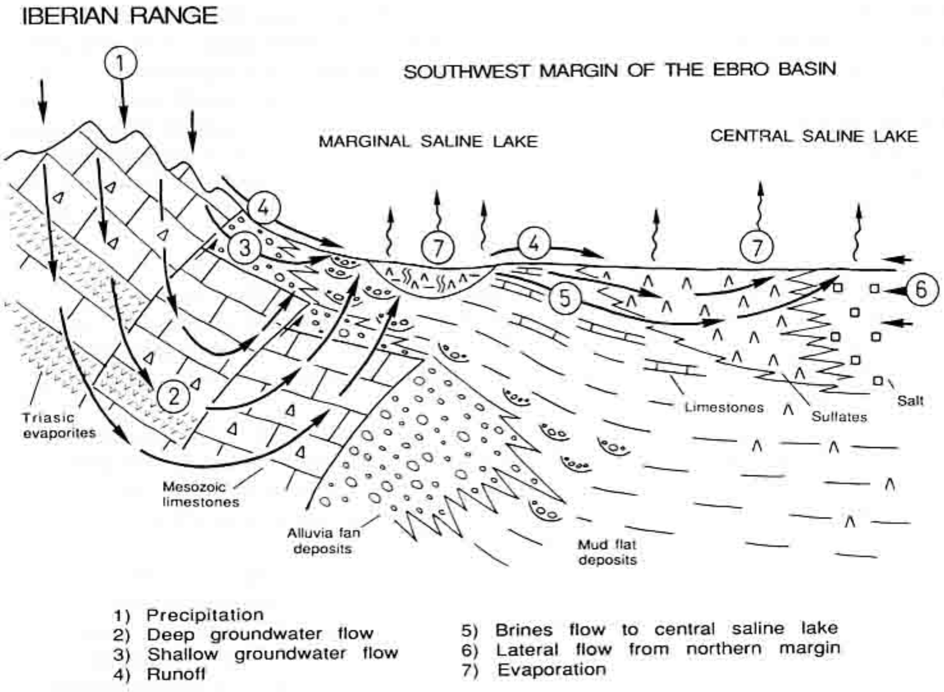

FIG. 14.—Paleohydrologic pattern for the southwestern margin of the Ebro Basin during the Miocene, showing the role of the marginal evaporitic systems as saline lakes before the greater evaporitic sedimentation occurred in the basin center (based on the hydrologic studies of Martínez-Gil et al. 1988).

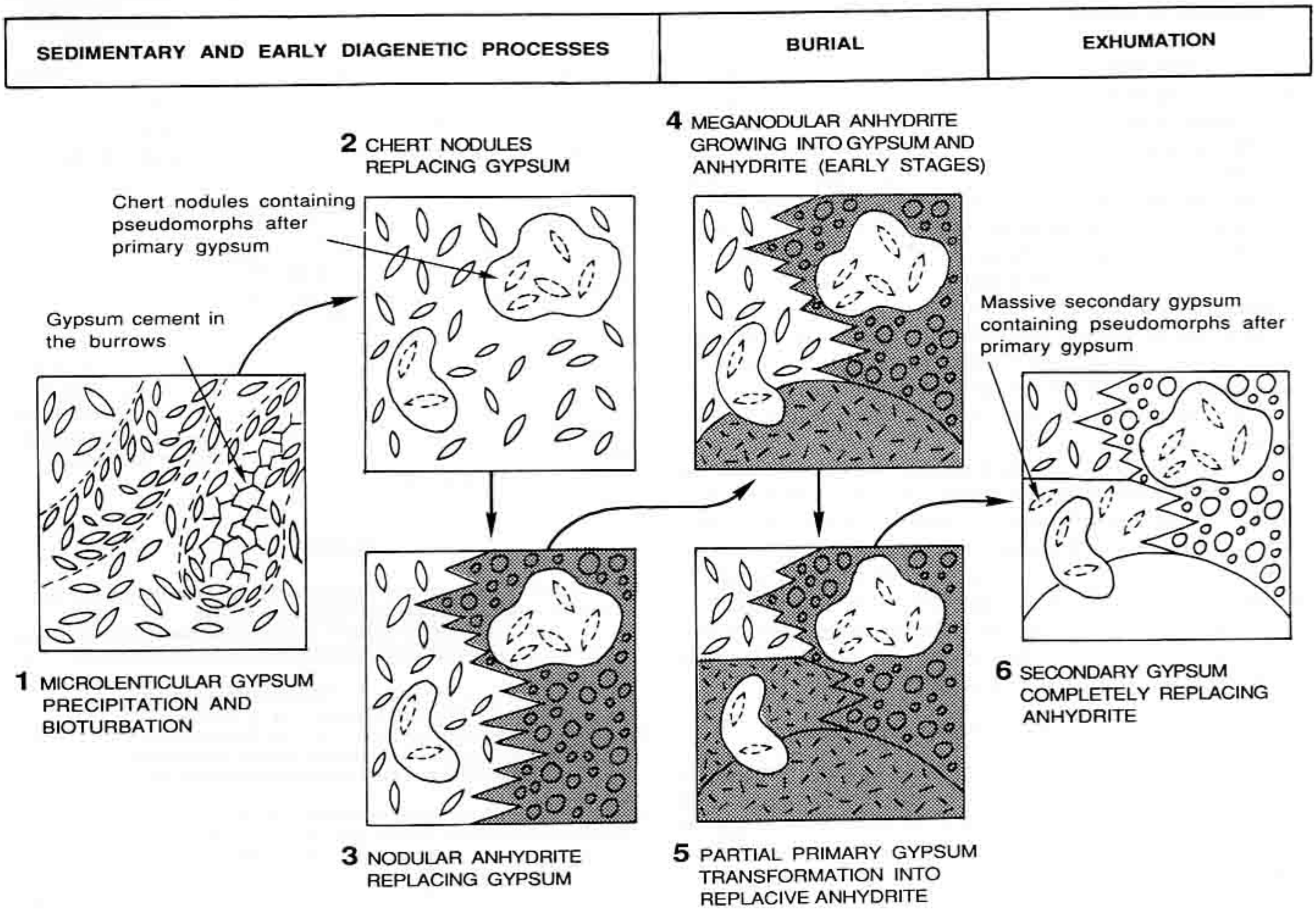

FIG. 15.—Diagram showing the diagenetic evolution of the marginal saline lake evaporites of the southwestern Ebro Basin from their deposition to the present day.

have been the cause of silica precipitation. Precipitation occurred mainly in the saline lake and its most proximal marginal zone, replacing microlenticular gypsum and carbonates. Chert precipitated first as a soft interstitial material (as gel) mainly along discontinuities in the sediment. Later it recrystallized to form chert with the hardness and textural varieties observed today. Mandado and Tena (1989) believe that during the initial period lenticular gypsum crystals were replaced by opal and that this in turn recrystallized to quartz-lutite. As oversaturation with respect to silica decreased, other varieties of chert, like quartzine, microquartz and macroquartz, could nucleate.

In the Ebro Basin chert has formed only in nonmarine lakes with waters of low concentration, either in the saline lakes that form the marginal belt of the basin or in the carbonate lakes (with charophytes and ostracods) of the margin and basin center. No chert nodules were observed in evaporitic formations precipitated from high-concentration waters in the basin center.

One final genetic aspect to discuss are the meganodules of secondary gypsum. They formed as diagenetic nodules of anhydrite during the first stages of burial of the evaporitic deposit under the influence of deeply circulated brines that were saturated with calcium sulfate. This is supported by: (1) the pure nature of the meganodules, their large size, and the absence of growth zones, suggesting slow and continuous growth under stable conditions; (2) the rarity or absence of distortion in the enclosing materials, which represents an advanced stage of consolidation of the host sediment; and (3) growth that overprinted different sediment facies as well as early-diagenetic products.

Meganodules are well represented throughout the whole of the marginal evaporitic belt of the Ebro Basin (Ortí et al. 1989) and in other Tertiary nonmarine basins of the Iberian peninsula, such as the basin of Calatayud (Ortí 1992) in the Iberian Chain, the Garumn facies of the Tremp Basin in the Pyrenees (García-Veigas 1988), and the Campo Coy Basin in the Betics (Salvany and Ortí 1990). However, none of these meganodules have been studied in detail to ascertain their origin and significance. At some locations in the central sector of the Ebro Basin (Azaila, Gelsa, and others) meganodules have also grown within clays, underlining their "primary" origin; they do not replace any former sulfate, as happens in other cited examples. In the study area the meganodules may appear as dispersed, irregular, or well-formed horizons parallel to stratification. In other gypsiferous formations columnar bodies have been observed that cut the host material more or less vertically. These columnar structures support the idea that the meganodules were formed by ascent from deep waters toward the surface along fractures or other rock discontinuities (Ortí, personal communication).

Figure 15 synthesizes the proposed sequence of diagenetic events that occurred in the evaporites of the southwestern margin of the Ebro Basin from their deposition in the basin to the present day. During sedimentation and early diagenesis, microlenticular gypsum and carbonates precipitated and were bioturbated. Chert nodules and nodular anhydrite formed. At the beginning of burial anhydrite meganodules grew, and at a more advanced stage the primary gypsum was profoundly anhydritized in some areas (Ribafrecha, Autol). As a final process, during exhumation all the anhydrite facies were transformed to secondary gypsum.

CONCLUSIONS

(1) Along the southwestern margin of the Ebro Basin, diverse evaporite deposits of small dimensions are found within the distal alluvial-fan facies. They are present at two different levels in the Lower Miocene and correspond to periods of relative tectonic quiescence in this sector of the basin within a compressive tectono-sedimentary framework.

(2) Marginal evaporites formed in shallow lacustrine systems characterized by low concentrations of salts. There, calcium sulfates formed as microlenticular gypsum and nodular anhydrite. Also, carbonates rich in charophytes, ostracods, gastropods, and silica in the form of chert nodules formed. Gypsum and carbonate suffered intense bioturbation.

(3) The development of these marginal saline lakes coincided with stages of great expansion of the lacustrine evaporite systems of the basin center. These much larger systems were characterized by high brine concentrations and consequent thick accumulations of sulfates (gypsum, anhydrite, glauberite) and halite. Locally (Autol, Ablitas) the marginal lakes connected with central lakes via an intermediate zone with the development of interstitial evaporites (anhydrite nodules). In other areas (Ribafrecha, Grávalos) the marginal lakes were totally isolated from the central evaporite basin by alluvial and fluvial sediments.

(4) The marginal lakes acted as preconcentrators of drainage waters from the Iberian Chain, precipitating salts of low solubility: carbonates, calcium sulfate, and silica. After precipitation of these salts, the brines drained toward the central lacustrine systems, where they were further concentrated by evaporation to precipitate the more soluble salts, including glauberite and halite.

(5) From the facies distribution, a lacustrine configuration is interpreted, constituted by a relatively stable lake colonized by charophytes, ostracods, and gastropods, with sedimentation of gypsum and carbonates, and a peripheral saline mudflat with diagenetic growth of nodular anhydrite and lenticular gypsum.

(6) This lacustrine system was regularly fed by groundwaters loaded with dissolved salts from the evaporite formations in the Mesozoic basement of the Iberian Chain. Episodically, shallow meteoric surface water of low concentration also reached the basin edge. In humid periods the higher water level expanded the lake as lower-concentration waters precipitated carbonates, gypsum, and chert. During dry periods, the major part of the lake became desiccated, causing transformation of gypsum to anhydrite.

(7) The large nodules of secondary gypsum (meganodules) formed during the early stage of burial as advanced diagenetic nodules of anhydrite.

(8) Exhumation of these marginal evaporite formations produced the transformation of the various anhydrite facies to secondary gypsum.

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